ATZ/MTZ-Fachbuch

Klaus Bengler
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UR:BAN Human Factors in Traffic

Approaches for Safe, Efficient and Stress-free Urban Traffic

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Preface UR:BAN MV

This book contains the results of the research project UR:BAN “Human Factors in Traffic”. The complex interaction of various road users in city settings with future driver assistance and driver information systems, makes this research project unique.

Since the beginning of the research project, the actual research activity and the appearance of this book, the development of driver assistance systems for various reasons has drastically accelerated and the first automated driving features have already been developed. Undoubtedly, future technical development of sensors and algorithms will lead to a rise of driver assistance functionality. To benefit traffic safety, transport efficiency and user comfort, special efforts in human factors are required make these systems usable, useful and controllable for the broad variety of traffic participants.

The work presented in this book shows that, first and foremost, the use of driver assistance systems and automated systems in urban areas requires special care and methodology in design and evaluation. For the whole team of UR:BAN Human Factors in Traffic, these aspects were the center of their activities. Interaction design, methodological and technical topics were considered in cooperation with the accompanying UR:BAN projects: Cognitive Assistance and Networked Traffic System. The various contributions from five subprojects report a variety of experiments in various experimental vehicles and simulators, and developments in the field of examination and evaluation methods developed for this purpose. Moreover, the shift to urban traffic situations showed that a systemization of traffic scenarios where users use driver assistance and information systems is required for such research. Additionally, guidance regarding assistance systems and beyond are provided. It is increasingly important to understand the behaviour of weaker road users who interact in traffic with these assistance systems and in future automated systems. The investigations presented here, in simulators and field observations, represent an important foundation for future technology.

We greatly thank the Federal Ministry for Economic Affairs and Energy for their willingness to promote and support these activities over a period of four years, in a broad cooperation of partners from industry, universities and research institutes. This lead to unique project in this area of research, bringing basic research results to application in industrial processes.

My thanks go to the team of coeditors, leaders of the sub-project and the group of authors contributing to this book. We thank Springer for their willingness to publish this book. First and foremost, we thank Mrs. Elisabeth Lange and Mr. Axel Garbers for their very good and insightful service and Walter Scholl and Susanne Bohnacker for leading the Project Office that supported us in an outstanding way. My personal thanks go to Christian Lehsing for his excellent support in project management and Armin Eichinger for his support during the project planning phase. Both are reflected in this book by the diversity and quality of the results obtained. Also I want to thank Martin Götze for guiding the publishing process of this work, conducted in parallel to his various research activities. His excellent management skills in addition to his research activities deserve special thanks.

I also thank leaders and employees of the neighboring projects: Cognitive Assistance and Networked Traffic System. Thank you, Ulrich Kressel, Michael Ortgiese and Stefan Feit for a great cooperation that we will remember for a long time. This network and cooperation was engaged and motivated by our excellent project coordinator Eberhard Hipp.

This book shall make the results and methodological findings achieved in this project available to a wide national and international readership. The versatile author teams will inspire more cooperation and remind the contributors of a superb and inspirational project time and research. Thus, this book also serves to motivate and inform interested persons on the potential of human factors.

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Introduction

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Eberhard Hipp, Klaus Bengler, Ulrich Kressel, and Stefan Feit

1.1 Motivation

The automobile and road traffic have made in the course of their joint development great progress. Still, to be ready for the future, the entire transport system has continuously to meet new and higher requirements. Each trip shall be traveled safely, efficiently and comfortably. The progressive urbanization leads to more and more people living in urban areas. The additional large number of commuters and supply transport should not be underestimated. This moves mobility spaces increasingly into the urban space and individual traffic using cars represents the majority.

Heterogeneous user requirements lead to conflicts and reduced efficiency in a limited urban space. In industrialized countries such as Germany 85% of the population live in the urban area. While especially outside Europe but partly also in Southern Europe a clear trend toward megacities with several million inhabitants can be observed, urbanization in Germany happens in a variety of medium-sized cities, as well as some major cities. These agglomerations are adjacent to a core city and reach out to a far area. They are characterised by strong commuter flows with mixed traffic (car/motorcycle/bicycle, passengers

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of public transport, pedestrians, etc.). This leads to increasing mobility needs in the urban context and suggests to focus research activities towards an efficient urban mobility.

Previous research projects had the goal to increase security and improve traffic management on motorways and rural roads. This resulted in a considerable number of essential driver assistance systems and traffic management systems. Since the year 2000, the number of persons injured in road traffic, is decreasing which is due in large part to the growing market penetration by active and passive safety systems (see Fig. 1.1). But the reduction rate on city streets is significantly weaker than that in rural and motorway traffic.

As active driver assistance systems for the urban area are not yet available, there is a remarkable need for action to reduce the number and severity of accidents in urban areas. Complex traffic present new challenges for existing assistance functions. Methods of longitudinal and lateral control that are successful deployed on highways reach their limits in the city. Therefore extensions must be created so that assistance can be continued successfully in the city.

The importance of urban regions as a habitat will continuously increase parallel to increasing demands of environmental and climate protection. In particular, the usage of the transport network will be characterised by ecological aspects; topics are increasing requirements on climate protection, reduction of CO_2, NO_x and noise. Cooperative systems for infrastructure and vehicles can positively contribute. Especially by making transport and driving more efficient on the strategic and tactical level, if multiple requirements of pedestrians, cyclists, vehicles and public transport will be integrated leading to a more harmonic and smoother traffic flow. Future vehicles with new drivetrain systems have to be considered. This is a new challenge for the cooperation between intelligent infrastructure and intelligent vehicles. Today vehicles with internal combustion engines determine the traffic, but this will change greatly in the future. In particular electric vehicles gain public

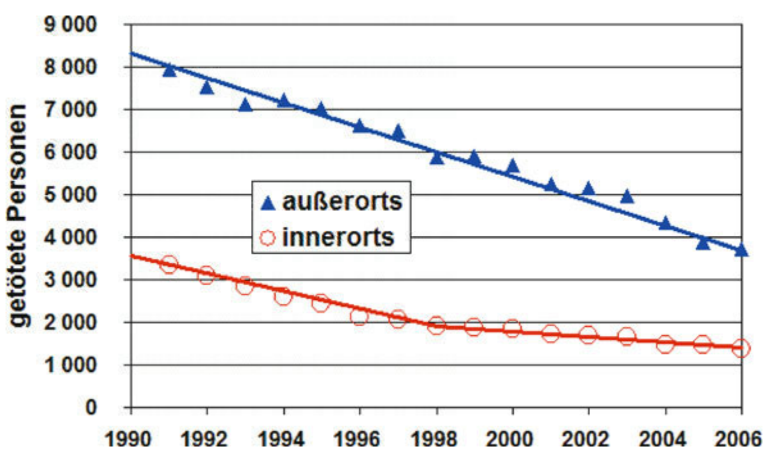

Fig. 1.1 Development of fatalities in German traffic. (Source: Statistisches Bundesamt, Fachserie 8, Reihe 7)

interest and appear more and more in the cities. Shorter distances, especially in the urban areas are the main deployment area of electric vehicles. A future transport system will be based on a mixture of drivetrain concepts and lead to new demands for network planning, supply and presentation of information.

1.2 The UR:BAN Research Initiative

As a consequence of these challenges 32 partners from the automotive and supplier industry, electronics, communications and software companies as well as insurance companies and research institutions together with cities form research initiative UR:BAN (urban space: user oriented assistance systems and network management) to develop driver assistance systems and traffic management systems for the urban area. The focus is on humans in their various roles in the transport system.

UR:BAN organizes the complex research tasks in three thematic areas:

Urban Traffic Safety
Today new technologies allow to implement a comprehensive perception of the complex traffic situations via machine perception in the city. In UR:BAN especially the perception of pedestrians and cyclists, as well as an assessment of their behaviour is provided. The driver is continuously supported in complex urban traffic situations such as bottlenecks/narrowings, oncoming traffic and lane changes. Collisions are avoided by automatic swerving and braking.

Economic and Energy Efficient Driving
New information and communication facilities such as Galileo, GPS, UMTS/LTE and C2X enable new ways for the cooperative traffic management in cities. Through the development and expansion of intelligent infrastructure and networking with intelligent vehicles. In the future innovative driver assistance systems can directly react to measures or recommendations of the strategic traffic management. Thus it is possible to take into account the different drivetrain concepts in modern vehicles such as electric and hybrid in traffic management. Goals are the optimization of transport efficiency, avoiding congested streets and reduction of emissions in the urban space.

Anticipative and Stress-free Driving
New assistance systems will provide the driver with relevant information in complex traffic situations. But this must not lead to a flooding with information. Therefore, high workload or inattention of drivers are detected by the new systems and adequately adaptively supported. Through appropriate design of operation and displays drivers can be informed significantly earlier and be motivated to an anticipative driving style so that the drive in the city will get safe, efficient and relaxed.

Three topic areas form the main pillars of UR:BAN.

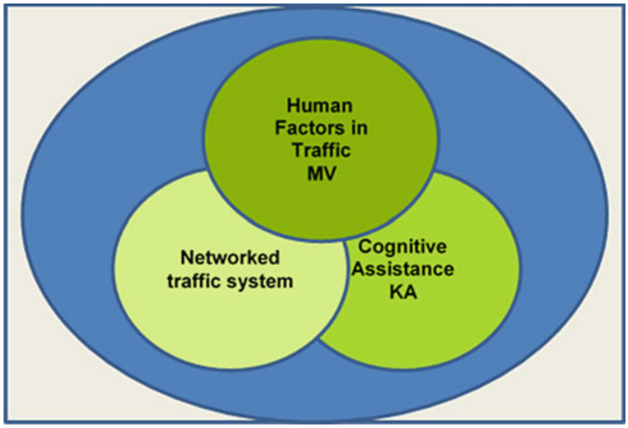

Fig. 1.2 The project pillars forming the UR:BAN project initiative

The project of "Cognitive Assistance" driven developments, be rich to have a clear focus on improving road safety in the inner city. In parallel, the project focuses on technologies, which make a contribution to the consumption-optimized traffic flow "Networked Transportsystem". In the third pillar of the project "Human traffic" behaviour examines the reverse – sweeping participant in an increasingly interconnected system, the requirements to meet and not to overload the driver with the perception of complex traffic system functions. It is based on the results of previous projects such as INVENT and AKTIV. With a novel approach integrating the three original project columns UR:BAN offers a view onto the intelligent cooperative interplay of vehicles and infrastructure in the future. The introduction of so-called "cooperative systems" will make a significant contribution to the emission driving in urban areas where vehicles communicate and interact with the infrastructure, as well as with other vehicles in the environment to inform the drivers, to reduce the risk of accidents and to ensure a smooth traffic flow throughout.

A significant contribution to improving safety in inner-city traffic makes UR:BAN through the continuous support of the driver in complex situations such as bottlenecks, oncoming traffic and lane change collisions are avoided by automatic swerving and braking. New technologies allow to create a comprehensive perception of the complex traffic situation with visibility in the city – also taking into account pedestrians and cyclists – and to develop appropriate security features. Instead of flooding the driver by means of innovative assistance systems with information, who the overburdened or inattentive driver of the new systems recognised and adequately supported. By appropriate design of operation and displays the driver can much earlier be informed and motivated to a forward-looking driving-wise so that the drive in the city can be safe and relaxed.

The development of new driver assistance and intelligent transport systems is considered by the Federal Government as a technology of the future and is therefore also key component of the national development plan for the accelerated introduction of intelligent transport systems. Close cooperation in this area between public administrations, academia and industry in the "Economic Forum" "verkehrstelematik", as well as the national working group in its supported these new technologies. That promote his technical new requirements and innovations not only in Germany but throughout Europe plays an important role, prove the directives of the European Parliament on the framework for the introduction of intelligent transport systems in road transport. Furthermore, a policy and an action plan for the fast-track a set of intelligent transport systems (its) was submitted by the EU, which requires subsidiary activities in federal and State.

In July 2010 by the Federal Cabinet decided that "high-tech strategy 2020, ideas. Innovation. Growth." aims, inter alia, to create lead markets and to deepen the cooperation between science and industry. As one of five required fields the topic is mobility and transport technologies in the central point, manifested in the 3rd transport research program of the Federal Government. It focuses on inter alia the protection of man and environment, mobility in the demographic change and the management of traffic. Methodically it goes faster to make about new research and innovations to twists. In UR:BAN co-operating companies and institutions are obliged this goal for a long time and therefore have many years of experience in the cooperation between science and industry. They will bring this expertise in the project.

In a further demand field of the 3rd transport research program – "Intelligent infrastructure" – to by making efficient use of the infrastructure negative impact-gen of the intermodal transport be reduced or completely avoided. Especially the municipalities must be enabled therefore technically and organizationally, to meet these challenges. For this purpose appropriate guidelines and tools are required, so far not or only occasionally and are transferable so not on other application areas. At this point the UR:BAN project column "Interconnected transport system" offers an important contribution to the implementation of the conveying and transport policy objectives.

1.3 Relation of UR:BAN to National Research Strategies

Mobility of society is an important prerequisite for progress, prosperity, growth and employment. The transport policy is still tagged the task – is to make this mobility as safe, as environmentally friendly and as efficiently as possible. Against the background of limited resources but also of the demographic development is need for action, through technical measures to take care, that mobility is affordable and environmentally friendly possible permanently for all. The driver or driver behaviour pose an enormous potential for the reduction of CO_2 and increasing security.

In UR:BAN to developing driver assistance systems support the development goals of the 3. Verkehrsforschungsprogramms of the Federal Government. The "car of the future" is the active helper in dangerous situations. Based on the development of security-related technologies, as in game way bottlenecks, oncoming traffic – and lane change assistance with all-round visibility and their rapid implementation in products to support the political targets given will be on existing foundations. Sensor-based assistance systems for the city significantly increase vehicle safety. Systems that take into account the demand for accident mitigation and accident prevention are developed. Appropriate information and communication genuine, liability issues, as well as individual conduct behavioural play an important role here.

A well-developed and efficient transport infrastructure is a central prerequisite implementation for a needs-based mobility of persons and goods. It is a location factor, which significantly influences the economic development. It is therefore important to improve the efficiency of the existing transport infrastructure and thus to adapt it to new requirements. It is the existing infrastructure through the use of intelligent technologies and organizational forms to use. Fluid transport and anticipatory driving results in positive impact on energy efficiency and environmental conservation (fuel- and CO_2 reduction).

1.4 Work Program

The close link between the driver and the assistance systems in urban traffic is an important feature of the research initiative UR:BAN. The additional project column "Human Factors in Traffic" plays a prominent role, because the intentions of the driver as well as the intuitive interaction with the vehicle HMI are examined for the first time, cross-functional and holistic. Interaction with the traffic infrastructure provides on the one hand the necessary information from the roadside traffic system. At the same time this opens up new opportunities, to optimize infrastructure control using the specific characteristics of drivetrain. Last but not least, the maturity and the approval of the proposed systems are taken into account for the first time and prepare their implementation.

In the light of the overall range of UR:BAN the various scientific and technical goals of three UR:BAN project columns "Cognitive Assistance", "Networked transportation system", and "Human factors in traffic" are presented in detail:

1.5 Human Factors in Traffic (MV)

The project column "Human Factors in Traffic" focuses on the users of future ADAS and IVIS. As for driver assistance systems for the urban area not only comfort, but above all the safety is crucial, user orientation is not only restricted on the acceptance of the user. The new features of the UR:BAN assistance systems bring high requirements with them regarding their controllability by the user. This is due to the fact, that the systems cannot cover all potential situative constellations. Definitely system limits will exist and also system failures can occur. Here, the driver is required to detect, to correctly interpret and act appropriately in the given situation with adequate performance. While this question is already intensively investigated and successfully solved for many systems related to driver assistance on motorways and rural situations, a variety of questions rises about the controllability in the urban area because of other time budgets and parameters of situation complexity. Often only a fraction of the time is available in the suburban traffic compared to highways that remains the driver for the successful acquisition of a situation or a system fault.

Urban driving is also much more influenced by vulnerable road users. In summary urban assistance means to integrate a variety of functions to manage the complexity of the situation in a vehicle. The interaction between longitudinal and lateral control are combined with traffic management, navigation system and active security systems for this purpose. Many previous research demonstrators show interaction concepts that are specialized and limited to the interaction with a single function or a selection of function. Successful urban assistance requires HMI concepts that are able to integrate many functional aspects without overwhelming or distracting the user. That will be no longer possible by pure design of the information presentation. Rather, the understanding of timing and time budgets in urban scenarios plays a decisive role.

The extremely short time budgets also related to warnings in urban scenarios require that the driver is informed as early as possible and in a recognizable way. This shall support anticipatory driving and gain valuable seconds. Recognition of the driver's intention and the prediction of future driver behaviour based on observable data will increase the accuracy of the systems, individual driving performance and in particular the acceptance of the ADAS function.

Especially urban scenarios are characterised by their complexity and are very difficult to reproduce. Often reproducible conditions are needed for efficient system development and evaluation. In addition, a variety of different road users in interaction with assisted drivers should be regarded to assess the effectiveness of a new function. Interactions between traffic participants and especially several assisted road users are not sufficiently represented in present simulations. But also consumption optimized driving will depend on the cooperation and successful interaction of several motorists in encounter and platooning. This is one reason why statements for tests and simulation runs in urban scenarios are of reduced validity. Therefore existing simulation environments have been adapted to these requirements. Through networking of simulators a new type of driving simulation can help to analyse the interaction of multiple users in a risk-free and reproducible way. The integration of a "real" interacting pedestrian in driving simulation was another innovation.

The collection of standardised driving data helps to improve driver and pedestrian behaviour models in macro simulations of the connected project VV.

It is a target to provide technical solutions and appropriate interaction concepts for a synthesis of comfort, efficiency and safety. The development of navigation systems in the 1990s can serve as an historical example. It shows that the usage and presentation of additional map based information in meaningful representation leads to a significant reduction of consumption and a significant increase of traffic safety and comfort, but not to increased driver distraction. Similar effects can be expected for future information and assistance systems, if the user centered design is the approach.

The activities in the project "Human factors in traffic" (MV) are performed in following five subprojects:

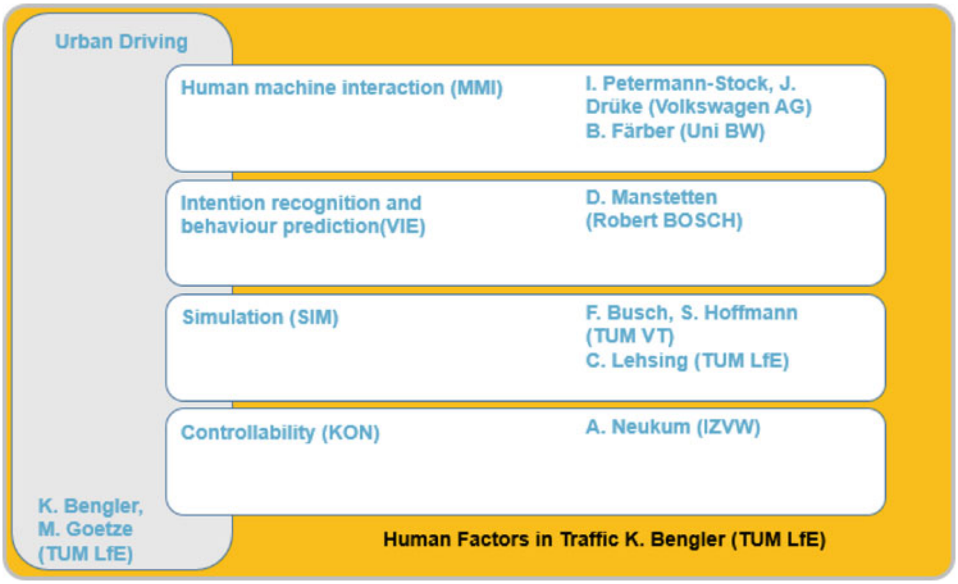

Fig. 1.3 UR:BAN project structure – Human Factors in Traffic with subprojects

1.5.1 Urban Driving

Urban traffic and the corresponding scenarios are extremely heterogeneous compared to motorway. It is therefore crucial that investigations as well as data collection used in experiments are based on comparable scenarios and user properties. Therefore the part of the sub-project "Urban driving" (abbreviated UF for "Urbanes Fahren") serves as a platform between the different subprojects. Goal is to unify assistance scenarios and provide project internal data standards. An Assistance scenario is determined by the properties of the present assistance/information systems, such as, for example, reliability, interference characteristics and field of application; continue due to the type of assistance/information case: navigation, manoeuvres or stabilization; through the in use of user: permanent, intermittent, modality-specific requirements on schedule and operating forces. Already, at the beginning of the project, these three dimensions will contribute to the efficient coordination of partners.

In MV and its neighboring projects big data sets are collected at great expense for critical traffic situations. It is therefore useful to coordinate these activities and to use applicable formulation data multiple times, and to increase the interpretability through collecting and evaluation standards. Preparatory work of the EU projects FESTA and Euro-FOT, but also SimTD provide valuable input for this. Here data collection standards have been developed, that can be met with reasonable technical effort of various partners. For example, standards of sampling rates, video formats to perform synchronization and situation encodings have been defined. This opens the possibility that a small sample by adding additional data can be extended or validated and valuable experimental time can be saved.

1.5.2 Human-Machine Interaction

Previous projects have already investigated aspects of the human-machine-interface (HMI) and often shown specific interface solutions for dedicated functions. This no longer sufficient for two reasons: the increase in functionality could overburden the driver by too many competing, uncoordinated information. In addition, the likelihood of notices, warnings, and interventions is significantly higher in urban areas compared to highways or rural roads. For these reasons, following three objectives are pursued in the HMI (abbreviated MMI for "Mensch-Maschine-Interaktion") project:

Objective 1: Design and development of a generic HMI tool kit including generic, integral HMI components evaluated for the urban space and assistance or security functions. Aspects such as the efficiency of the older drivers and the requirements of future individual mobility are incorporated in the requirements. The central idea of the integrated, cross-functional concept of the warning concept is not to point out dangerous situations only, but to trigger a dedicated action (e. g. "braking"). Because the more different alerts occur, the bigger problems of the driver will be to distinguish them, to develop an action strategy and to act properly. The adaptation of this warning concept to the needs in urban areas finds special consideration. The integration of navigation information and environment knowledge leads to an optimization of warning type and time as well as to support anticipative driving. Risks that are not visible for the driver are displayed using haptic feedback on accelerator pedal and steering. The challenge is to find a meaningful and safe way to convey the knowledge of an intelligent vehicle to the driver.

Objective 2: Integration of applications of KA and VV. Starting from the concept designed in objective 1 the HMI concepts can be derived for partners in UR:BAN.

Objective 3: Review and demonstration of HMI solutions. Over the entire development process the resulting HMI concepts are evaluated using the appropriate methods (e. g. model-based evaluation/simulation, expert test, experiment). Starting with preliminary investigations and iterative test the overall concept is tested in a final evaluation.

1.5.3 Intention Recognition and Behaviour Prediction

Driver assistance and transport systems have enormous potential to increase road safety through targeted support of the driver – Especially in stress situations. To achieve this goal and at the same time to get the driver's acceptance the system has to be in accordance with the plans of the driver. Especially in urban traffic with its high complexity, the diversity of situations and options for action for the driver, it is of particular importance to use the lower time budget as efficiently as possible for correct decisions. If the intervention strategies of vehicle systems collide with the intentions and actions of the driver and lead to unclear situations, important time would be lost to defuse by reverse sweeping conflicts. It is therefore of great importance for the correct behaviour of driver assistance systems, to detect the driver's intentions as early as possible, as well as to determine future driver behaviour. This requires an individual, situation-dependent behaviour prediction and Intention recognition. The central objectives of the sub-project VIE (abbreviated VIE for "Verhaltensprädiktion und Intentionserkennung") are:

- systemization of driver's intentions in the urban space,
- demonstration of real time capable modules for the prediction of the behaviour and intention recognition in experimental vehicles of the subproject,
- integration of modules in corresponding applications of project KA,
- demonstration of benefits for user oriented design.

The project develops detailed procedures for the prediction of behaviour and intentions in the urban space based on a requirements analysis and empirical data. The quality of the process is systematically checked and shown in own experimental vehicles.

1.5.4 Simulation

Objectives of subproject SIM are analysis and corresponding descriptive modeling of behaviour and interaction of traffic participants – other vehicles (with/without UR:BAN technology) as well as cyclists and pedestrians.

For the interaction between vehicle and vehicle, it is considered how current models (e. g. vehicle sequence model) represent the reality and what models are necessary to describe the interactions between drivers using new ADAS. The interaction between two or more cars in the application cases of lane-changing behaviour and overtaking while approaching an intersection.

Pedestrian behaviour has a very strong impact on the traffic situation in the urban environment. For the functional analysis of UR:BAN technologies no mathematical models are available so far. The first step is to examine and improve the modeling of pedestrian behaviour itself and to make appropriate statements about the interaction of vehicles with pedestrians.

In urban areas cyclists take in addition to the pedestrians an important role. In the focus are the improvements of the modelling of motion behaviour of cyclists as well as modeling of the interaction with the motorized vehicular traffic for an existing cycle route, or if the cyclist shares the car lanes.

1.5.5 Controllability

The challenge to ensure controllability is getting bigger facing the rapid development of complex assistance systems. The current situation is characterised by the fact that the issue of controllability is increasing to the extent, in which the new systems are "smarter" and "more efficient". The stronger the support by a system the harder it is to master the error case. This simplistic rule is in contradiction to the fact that the driver without the system would have not been to prevent a potential accident in a comparable situation. Thus, it is obvious that controllability of an ADAS must not be considered without its overall efficiency for traffic safety, which in turn strongly depends on the acceptance, which ultimately decides on take rates and usage rates.

Special requirements for the controllability come from driving and traffic situations, in which the parallel processing of multiple sources of information is necessary in a short time and thus producing a high driver workload. Goal of the subproject KON (abbreviated KON for "Kontrollierbarkeit") is therefore to develop a uniform methodology to be able to assess the controllability of urban ADAS systems with a focus on time-critical situations in an efficient and valid way.

The subproject KON provides methods and develops in the project – where necessary – additional methods including system boundaries, system errors, potential abuse.

The project works out procedures for the review and improvement of the system behaviour in borderline and error cases as well as the examination of the control by the driver for the proper use. Application areas come mainly from the applications of the project of "Cognitive Assistance", but are not limited only to these applications. The systematized knowledge, supplemented by the new findings with regard to the control of driving and traffic situations, is summarized in a driver performance database that allows a first assessment of controllability.

1.6 Cognitive Assistance (KA)

The UR:BAN – KA project takes on the challenge of developing assistance systems for urban areas, whereby the following four main focuses have been jointly identified by the participating partners:

Robust perception, modeling, and interpretation of complex traffic conditions as the prerequisite for safety-relevant driver assistance functions in urban areas, interdisciplinary function for processing "environment detection and modeling" common to all urban assistance systems.

Development of cognitive and user-friendly assistance systems for effective and predictive "protection of more vulnerable road users" in urban areas dedicated on the one hand to the reliable detection of pedestrians and bicyclists and their behaviour while at the same time developing a predictive assistance system for their protection.

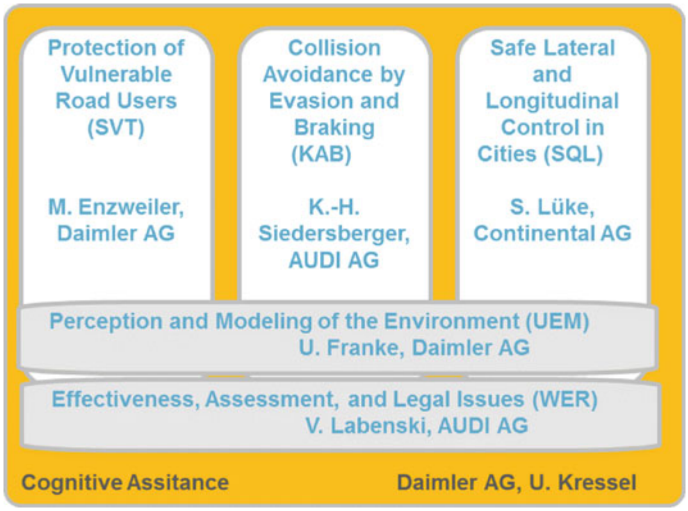

Fig. 1.4 UR:BAN project structure – Cognitive Assistance with subprojects

Cognitive assistance systems in urban areas for performing last-minute accident-avoiding manoeuvres are addressed in the application package "collision avoidance through evasion and braking".

Relief for drivers in narrow urban spaces through early information on clearance width as well as continuous support of lateral and longitudinal control in the application project "safe lateral and longitudinal guidance in cities" with various assistance systems such as the narrow passage assistant, oncoming traffic assistant, and lane changing assistant.

The development of the new technologies is accompanied by the competent consideration of legal issues as well as the designed systems' effectiveness.

In addition, topics such as accident causes and effects analysis as well as legal issues are being investigated in the UR.BAN – KA project column.

The resulting structure of the Cognitive Assistance project is then as follows:

1.6.1 Environment Detection and Modeling

Due to its complexity, the urban traffic environment completely overwhelms currently available detection and evaluation systems. A prerequisite for capable accident avoidance systems in urban areas is that they have a reliable "image" of their environment on the basis of which they can "understand" even difficult situations with multiple participants and boundary conditions. In addition to a comprehensive all-around view, this also requires efficient modeling of the static and dynamic vehicle environment – independent of the various applications which will be based upon this description.

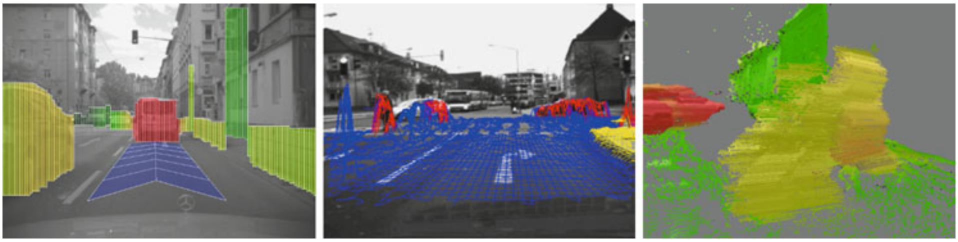

Fig. 1.5 Different representations of space-time perception

This task demands an interdisciplinary project whose function is to develop the basics of an integral all-around view and precise modeling to form the foundation of the application projects of UR:BAN KA. The goal is the realization of generic representations which decouple the intelligent sensors from the applications, thus permitting a multitude of sensor variations and configurations and simultaneously presents a stable foundation for future driver assistance systems.

Within the interdisciplinary project "Environment detection and modeling", the "all-around" environment shall first be detected rigorously and consistently. The goal is to develop common 360° environment models for applications which will not only be able to integrate the information from the implemented sensors, but also that from future maps as well as other data sources.

Complex situations in urban areas often have the characteristic that relevant objects partially occlude one another. Their detection and the tracking required for the precise determination of their motion state presents a problem which to date remains unsolved. Major progress regarding this issue is expected from this interdisciplinary project. The same expectation applies to the development of a systematic approach for dealing with uncertainties in the signal processing from the raw data to the representation. The currently most common heuristics will not meet the critical safety requirements of future systems. The subsequent steps of fusion, interpretation and prognosis require reliable degrees of confidence which describe both the uncertainty as well as the plausibility of the measurements.

1.6.2 Protection of Vulnerable Road Users

The primary goal of this subproject is the development of cognitive user-friendly systems for passenger and utility vehicles for the effective and predictive protection of vulnerable road users in complex urban scenarios. For passenger vehicles, the focus is on active and predictive systems with the potential to recognise dangerous situations involving vulnerable road users prior to likely accidents in order to initiate protective measures to avoid

Fig. 1.6 Child at risk in an urban scenario

the accident or reduce its severity. For utility vehicles, a system to significantly improve the all-around view in critical situations shall be developed.

The research activities in the subproject are concentrated on urban scenarios (short and medium range sensor detection, vehicle velocities up to 60 km/h) during the day and at night because that is where the majority of accidents with vulnerable road users occur. The appearances of persons in traffic vary widely, the motion sequences are highly dynamic, visibility is often limited due to occlusion (parked vehicles, baby carriages, etc.) and the relevant scenarios for accidents are extremely complex.

Key technologies for robust operation of such a protective system are the sensor-based detection of relevant traffic participants (video sensors, beam sensors, etc.) as well as deeper situational understanding combined with object-specific behavioural prediction in order to initiate situation-dependent action strategies (warning or autonomous reaction). Compared with systems which were developed in the preceding AKTIV project and current state-of-the-art technology, the main focus of the research is on the significant improvement of the protective function of active predictive systems by:

- Significantly increasing the number of applicable scenarios for the system, i. e., addressing of traffic participants and accident scenarios which previously were not included, as well as improving system availability under various weather conditions.
- Greatly enhancing the effectiveness and robustness of the systems in the included applicable scenarios by developing high-performance algorithms for sensor-based detection, classification, behavioural modeling, and behavioural prediction for vulnerable road users.

1.6.3 Collision Avoidance Through Evasion and Braking

In urban environments, driver assistance systems for collision avoidance have great potential for reducing injuries and material damage. The question regarding in which situation

Fig. 1.7 Automatic emergency braking taking evasive action by the driver into account. (From AKTIV-AS AGB)

a single or combined autonomous braking or steering intervention might most effectively or most safely prevent a collision is at the focus of this research project. The analysis will be directed toward determining which functional configurations are principally suited, with high probability under urban conditions, to avoiding an imminent collision. Critical parameters in this regard are the degree of support of the assistance function, the scale of the intervention, and the timing of the intervention.

The decision as to whether an accident can be avoided by an evasive action or by braking is made by an alert driver with a good overview of the situation based on diverse influencing factors. These include, for example: relative velocity, overlap with the obstacle, and direction of motion of the traffic participants involved. For optimal support which starts at the right time, all relevant factors must be included in the decision whether to intervene.

When this function is implemented, its degree of support is purposely not specified beforehand. This is based on the background that it must first be determined whether a warning for driver action is already leading to positive results. An evaluation of more intrusive functions ranging up to automatic evasion and braking is only possible after comparing the various function configurations.

The close coordination with UR:BAN *Human Factors in Traffic* project guarantees that the assistance systems developed in this subproject will be optimized precisely for driver requirements in urban scenarios. This applies in particular to the design of the human-machine interface (HMI).

1.6.4 Safe Lateral and Longitudinal Guidance in Cities

The primary goal of this subproject is the prevention of serious accidents in cities as well as the increase of urban traffic efficiency while simultaneously maintaining the mobility of the elderly. This is achieved through a combination of powerful and innovative assistance functions through which drivers in narrow urban spaces are provided relief through early information on clearance width and drivability as well as continuous lateral and longitudinal guidance.

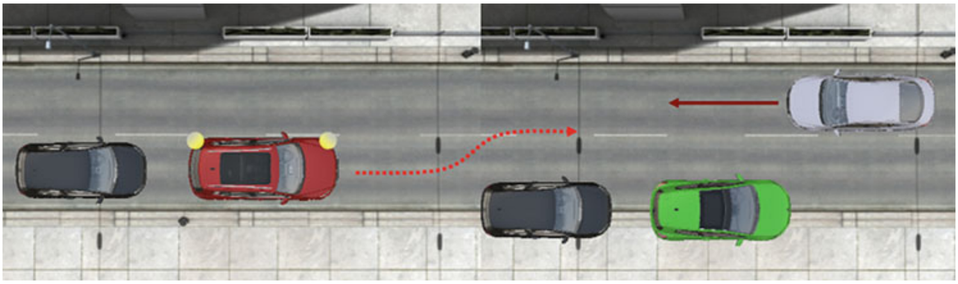

Fig. 1.8 Schematic representation of a bottleneck with oncoming traffic

Collisions at bottlenecks result in blocked traffic and long traffic jams. Avoiding accidents at bottlenecks therefore immediately leads to an enormous increase in efficiency and to a reduction of pollution in dense urban traffic. Equally important is that assistance systems which provide lateral and longitudinal guidance for urban scenarios have a positive effect on the maintenance of mobility and the social integration of the elderly. For example, they can provide significant support in the event of a physical handicap or emotional insecurity. Elderly citizens can thus continue to take part in society as before and need not forego independent transportation with their own vehicle.

Within the scope of the safe lateral and longitudinal guidance subproject, the following assistance systems are being analysed and prototyped:

Narrow Passage Assistant

Lateral guidance in flowing traffic to support the driver when driving through a bottleneck or when passing vehicles in neighboring lanes, stationary obstacles, or parked vehicles. A warning sounds if the width is too narrow to drive through safely.

Oncoming Traffic Assistant

Oncoming vehicles are evaluated as to whether they could become a problem when driving through a bottleneck. A warning sounds if passage through the bottleneck is not possible with oncoming traffic.

Lane Changing Assistant with All-around View

The position of the driver's own vehicle in the lane is determined and, in addition, all lanes are monitored, also to the rear, to determine whether a safe lane change is possible. This provides relief to drivers in urban scenarios with multiple lanes in a single direction.

Effectiveness, Assessment, and Legal Issues

The complexity of urban accident scenarios leads to a corresponding complexity in the design and development of driver assistance systems for active safety in urban areas. These processes require quantitative estimates of traffic safety impacts right from the start. There

Fig. 1.9 Accident Analysis in UR:BAN

are numerous tradeoffs and optimization issues in the design of safety functions. It is essential to focus on the goals of maximal accident avoidance and reduction of injury severity while taking into account how real accidents occur "in the field."

This subproject supports the three application projects in system design. An integrated computer simulation toolkit is created based on real world accidents (GIDAS as well as video-documented accidents), with the purpose of predicting the potential effectiveness and the future benefit of safety systems addressing these accident samples. This toolkit is used to help optimize the design of the application functions for maximum safety effectiveness.

In addition, the addressed applications are considered from a legal perspective. As part of the development process, systems with a direct influence on longitudinal or lateral control of the vehicle, ranging up to fully autonomous intervention, require the analysis of relevant legal consequences. The issues pertain both to product liability laws as well as laws regulating driving behaviour. For example, an international treaty known as the Vienna Convention on Road Traffic mandates control of the vehicle by the driver.

The national traffic code of Germany also contains provisions regulating driver behaviour and control. Legal requirements and constraints have been considered in the concept and design of safety applications developed in UR:BAN-KA. The aim was to develop functions which eliminate those situations most likely to cause legal conflicts.

1.7 Networked Traffic System (VV)

The development of applications for energy- and traffic-efficient driving in urban areas lies at the core of the UR:BAN project "Networked Traffic System" (UR:BAN-VV). The primary goal of the project is the development of new approaches to solve the following scientific and technical issues:

- Monitoring of complex urban situations for information and assistance systems to support energy efficient, comfortable, safe, and most of all traffic efficient mobility.
- Consideration of the requirements of alternative propulsion systems in the design of networked traffic applications.
- Optimization of infrastructure management and networking with innovative vehicle concepts and systems.
- Cooperative environment systems in complex urban situations.
- Complex co-modal network management in order to also satisfy more far-reaching mobility requirements of the post-fossil era.

New information and communication possibilities such as GSM/GPRS (2 G/2.5 G), UMTS (3 G) and C2X allow new possibilities for cooperative traffic management in urban areas. Through the construction and expansion of intelligent infrastructure and the networking with intelligent vehicles, future innovative driver assistance systems can profit directly from the information and recommendations supplied by strategic traffic management while at the same time generating valuable information. These means will also allow appropriate consideration of the various propulsion systems of modern vehicles, such as electric and hybrid drives, when controlling traffic flow and optimizing traffic behaviour. The goals are the optimization of traffic efficiency, avoidance of traffic congestion, and thus the reduction of emissions in urban areas.

The "Networked Traffic System" project takes into account that along with the present variation in vehicles, the number of propulsion systems will increase in the future and the vehicles can be managed with greater sophistication dependent on their characteristics. Particularly in urban traffic, the variety of vehicles with different propulsion concepts and ensuing concept adaptations will increase significantly. Only through vehicle-specific adapted solutions can the potential of such specialization be efficiently taken advantage of by the infrastructure.

For the prototypical realization of the set goals, the participating partners defined four fields of activities within the project. The following figure presents an overview of the central focus of each subproject and how they are interrelated.

In the process, the various aspects of urban traffic in the three traffic subprojects are tightly intermeshed: beginning with a large-scale view of the regional network and the strategic routing of traffic, over anticipatory energy- and traffic-efficient driving on urban roads, all the way to adaptive control of smart intersections and the support of the driver (tactical assistance) in the vehicle. The interaction of the traffic applications from the three subprojects will be demonstrated in a common test area in a realistic traffic environment with the participation of the responsible municipal authorities in Düsseldorf. The "Cooperative Infrastructure" subproject represents the brackets around the traffic subprojects. The creation of a guideline for introducing cooperative systems opens up the possibility of implementing the traffic solutions developed within the project into other municipal and regional jurisdictions. The traffic evaluation of the interacting applications as well

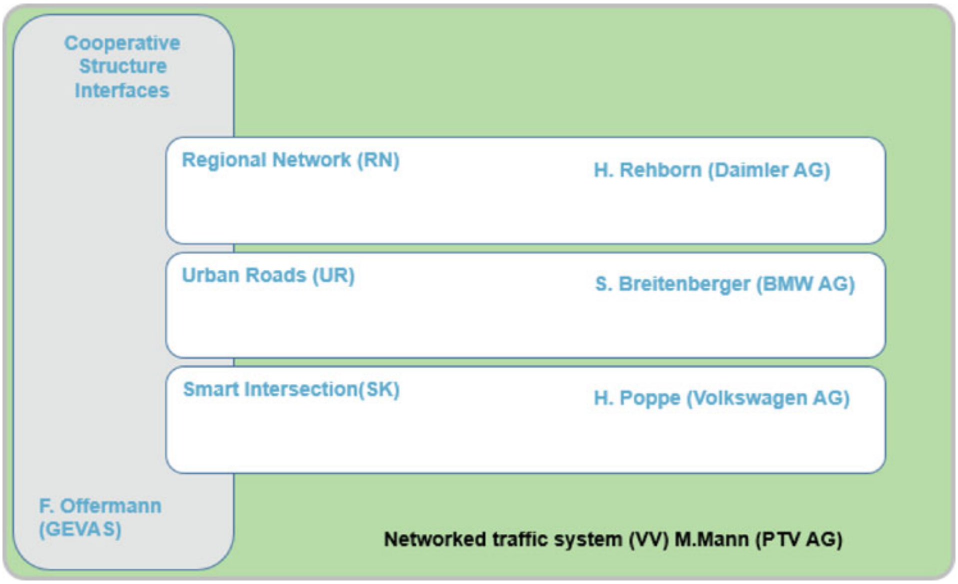

Fig. 1.10 UR:BAN project structure – Networked traffic system with subprojects

as the extrapolation of the results ultimately provide a statement on the potential of the applications implemented in UR:BAN-VV.

1.7.1 Regional Network

The "Regional Network" subproject is working on securing and sustainably developing a functional and efficient traffic network to ensure efficient and safe as well as socially and environmentally compatible mobility for people and goods. The decision for the most suitable access to or the best route through the metropolitan area is made on the network level. Up to now this decision has been based on statistical travel-time charts and a rudimentary knowledge of the current traffic conditions. Because of their lack of availability, traffic management recommendations cannot be taken into account by either traffic assistance systems or routing services.

The "Regional Network" subproject encompasses an expansion of traffic management to include environmental aspects as well as the consideration of various vehicle propulsion technologies (e. g. diesel, hybrid, or electric drives) both in the development of urban strategies as well as in the route selection in the vehicle. The resulting route recommendations – "energy-optimized routes" – dependent on the vehicle and drive type are communicated to the vehicles along with high-precision traffic information for autonomous optimization in the vehicle of the route selection. Acquisition technology in vehicles and devices with geographic positioning (GPS) and tracking systems via GSM are providing

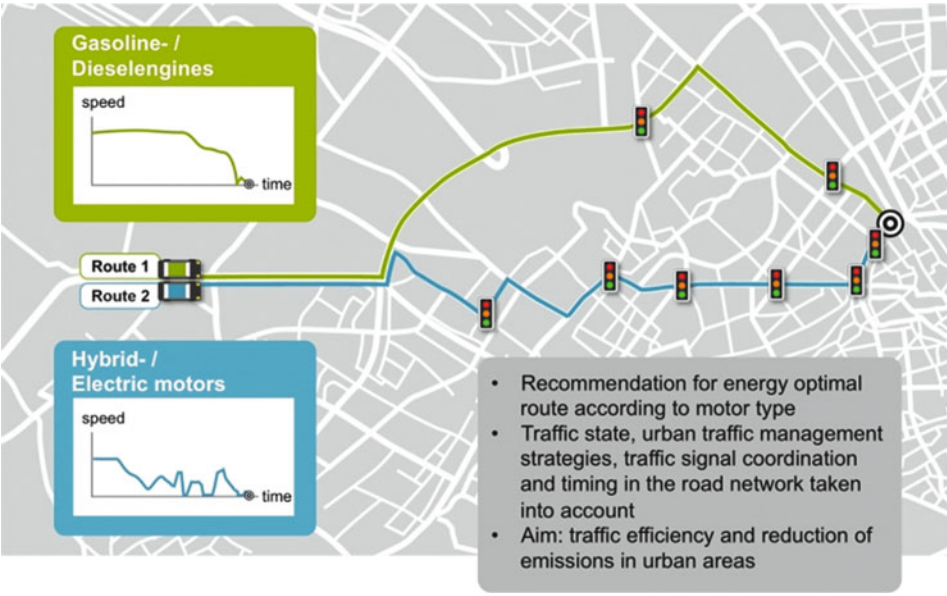

Fig. 1.11 "Regional Network" – issues and goal

traffic management with high-precision traffic information on an increasing scale. The result from the perspective of traffic management is an optimized distribution of traffic which takes global aspects such as traffic efficiency and emissions as well as individual vehicle and drive types into consideration.

1.7.2 Urban Roads

The "Urban Roads" subproject aims to develop vehicle functions for enhancing traffic efficiency and emissions reduction in motorized individual transport through traffic-signal controlled urban road networks. The close intermeshing of intelligent infrastructure with intelligent vehicles is an absolute prerequisite for reducing emissions and increasing traffic efficiency along a route.

Individual transport in urban road networks, especially on primary roads (urban streets) is currently characterised by a significant optimization potential with regard to traffic efficiency and avoidable emissions in the vicinity of intersections controlled by traffic lights. On the one hand, the lack of predictive information on traffic-light signal phase and timing prevents drivers from being provided with the best possible horizon for optimizing their driving and thus also reducing their fuel consumption and emissions. On the other hand, the potential for increasing efficiency and reducing emissions through the reduction of

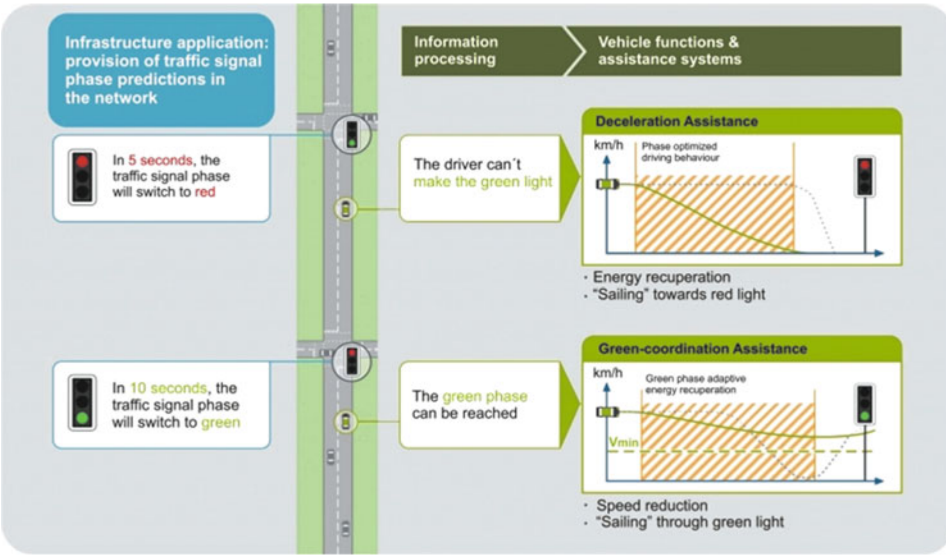

Fig. 1.12 "Urban Roads" – Adaptive vehicle functions based on traffic-signal predictions

the braking and acceleration processes of the overall traffic flow caused by not optimally synchronised traffic signals at successive intersections is currently not being realised.

The "Urban Roads" subproject is developing basic components to provide vehicles with comprehensive infrastructure data and information, with the focus on providing a prediction of the timing of the traffic signals included in the urban road network. This information is directly implemented in passenger as well as commercial vehicles by new vehicle functions for efficient, energy- and emission-optimized driving through the traffic-light controlled road network. For monitoring purposes and to further optimize the infrastructure signaling, the vehicles make their route traces available to the central infrastructure.

1.7.3 Smart Intersection

The "Smart Intersection" subproject addresses the vicinity of urban intersections. These generally have a high degree of utilization and are controlled by traffic lights. Construction in the vicinity of intersections restricts the area available for traffic as well as for traffic infrastructure. The traffic situation is characterised by overall high traffic demand from diverse traffic participants such as motorized vehicles, public transportation, cyclists, and pedestrians as well as emergency response vehicles, all with different utilization requirements.

The focus is therefore on innovative vehicle and traffic technologies which permit efficient as well as climate- and environmentally-friendly traffic through urban intersections.

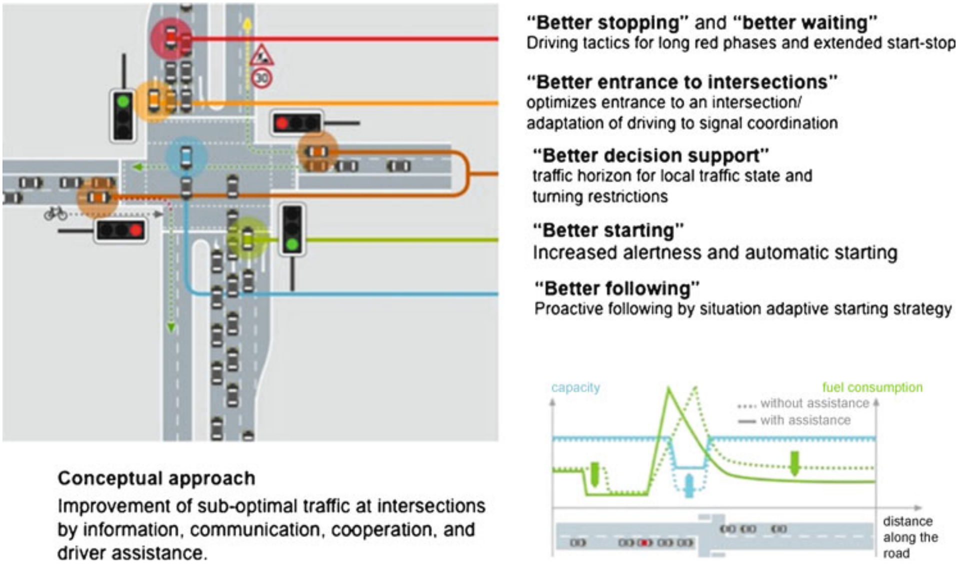

Fig. 1.13 "Smart Intersection" – "Crossing guard" driver assistance

In addition, urban areas in particular require that a balanced co-existence of completely different utilization requirements be satisfied in this restricted traffic area.

The cooperative exchange of information between local traffic lights, vehicles, public transportation, emergency response vehicles as well as cyclists and pedestrians for traffic- and energy-optimized traffic flow lies at the core of the "Smart Intersection" subproject. In this context, the subproject is focused on assistance and information systems which, in cooperation with an intelligent infrastructure, will raise the traffic capacity and lower fuel consumption and emissions as close as possible to intersection-free levels.

1.7.4 Cooperative Infrastructure

The public sector demands information on the introduction of cooperative systems and their control center components as well as their technical requirements in a cooperative system. This discussion is particularly relevant now with regard to the reference architectures, subsystems and interfaces required as well as the operational aspects.

The "Cooperative Infrastructure" subproject ensures the transferability to and development of reference systems for the public sector and thus guarantees the sustainability of the research project and the transferability of the UR:BAN-VV results into the introduction of cooperative systems in cities and towns.

The "Cooperative Infrastructure" subproject also performs the evaluation of the developed systems and applications of the Networked Traffic Systems project. The subproject coordinates the harmonization of goals, the survey methodology, planning and performance of the traffic evaluation. The traffic evaluation lies at the focus of the evaluation. Above all, it should quantitatively show whether the applications meet expectations regarding the optimization of the traffic situation. These include increased efficiency of the traffic system through the reduction of congestion and travel time on the one hand, as well as the evaluation of environmentally-relevant parameters (e. g. emissions reduction, fuel savings) in urban areas on the other. The evaluation activity is holistic and therefore complementary to the observations of detailed interdependencies within the context of the "Regional Network", "Urban Roads", and "Smart Intersection" subprojects.

1.7.5 Test Areas

All components and applications developed in UR:BAN-VV were tested and demonstrated in the Düsseldorf test area. In agreement with the city of Düsseldorf, two traffic-relevant intersections were identified as smart intersections in which especially the interaction with public transportation as well as with pedestrians and cyclists can also be shown.

The Brunswick field test area is the base for the development and test of applications for the "Smart Intersection" subproject. These tests in particular require extensive field testing in an environment which is secured both technologically and with regard to traffic. The AIM large-scale test facility of the German Aerospace Center provides the appropriate prerequisites.

The Kassel test area provides the "Urban Roads" subproject with a development and test environment which is especially necessary on account of the infrastructure which differs to that in Düsseldorf. The Kassel test area makes an important contribution to the complete transferability of the infrastructure developments into new cities and towns and as a building block for the reference architectures to be developed in the "Cooperative Infrastructure" subproject.

Whereas in Düsseldorf traffic- and time-dependent fixed-time control processes are implemented, in Kassel adaptive traffic-dependent control processes are used. This difference impacts solely the development of the switching time predictions for the infrastructure. In sum, the two methods cover approximately 80% of all control processes being implemented in Germany.

1.7.6 Communication & Standards

On the basis of the experience gained over the last few years, it is now becoming quite apparent that the future networking of traffic systems will be implemented with various communication or protocol standards dependent on the particular application. The systems will also be designed to permit flexible role configuration for institutions. The classical boundaries between the "private" service provider and the "public" infrastructure provider are no longer necessary from a technological perspective. The public sector, for example, will be able to pass information to mobile devices and vehicles, or private service providers will provide their services to the public operators.

In order to take this development into account, the applications in UR:BAN-VV supports the current standardization efforts and considerations for a comprehensive ITS system architecture. The applications in the "Smart Intersection" and "Urban Roads" subprojects will support C2I communication via short-range (IEEE 802.11p) as well as cellular network communication (e. g. UMTS). The data can be specially prepared by a service provider ("Urban Roads" subproject) or provided directly by the city ("Regional Network" subproject). The developments of the Car2X integrated network running in parallel to UR:BAN will be considered in the system architectures.

Part II

Urban Driving

A Meta-perspective on Research Activities in UR:BAN Human Factors in Traffic

2

Matthias Graichen, Verena Nitsch, and Berthold Färber

2.1 Introduction to the Project "Urban Driving"

Urban traffic scenarios are characterised by a high variety of different traffic participants, infrastructural features and diverse environmental conditions. As such, they are considerably more complex than traffic scenarios on rural roads or motorways. So far, the development of advanced driver assistance systems (ADAS) was guided by a rather disintegrated function-oriented approach. When it comes to urban traffic scenarios, however, it becomes necessary to consider the various influencing factors more comprehensibly. The design of urban ADAS should follow an approach of an adaptive and integrated HMI to support drivers according to situation- and driver-related requirements, and avoid confrontations with unnecessary information [1].

With this goal in mind, the research initiative UR:BAN conducted numerous data collections pertaining to different research foci. To support a more holistic process of function and HMI development, it is necessary to integrate the diverse research questions, synchronise individual partner activities and evaluate the obtained project results from a broader perspective. This requires a fundamental, project-spanning, structured procedure and coordination. For this purpose, the project *Urban Driving* (abbrev. UF for "Urbanes Fahren") applied a strategy, starting with the beginning of the research initiative, with the objective of monitoring research activities in the four projects *Human-Machine Interaction for Urban Environments* (abbrev. MMI for "Mensch-Maschine-Interaktion"), *Behaviour Prediction and Intention Detection* (abbrev. VIE for "Verhaltensprädiktion und Intentionserkennung"), *Simulation* (SIM) and *Controllability* (abbrev. KON for "Kontrolllierbarkeit"). Hence, research intentions were identified and correspon-

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DOI 10.1007/978-3-658-15418-9_2

ding data collections standardised by means of several systematic procedures in order to provide a meta-perspective on the project research activities and results.

2.1.1 General Approach

UF approached its objective of providing a meta-perspective with different strategies on both an operational and a conceptual level. On the operational level, procedures were developed to facilitate inter-project communication processes and inter-project relations. This is particularly pertinent for bigger research initiatives that are often conducted of heterogeneous partners from industry and academia who vary with respect to their terminology, specific background knowledge as well as their strategic research intention (short-term or long-term orientation) Instead of conducting disparate and isolated research activities, synchronised efforts should be initiated for documentation, standardisation, coordination and communication of joint or similar project phases, right from the beginning of the project. In UF this was achieved e. g. by synchronising the basic terminology, the form of representation of research objectives and measurements, and also by creating a comparative and clarifying summary of data collections [1].

On the conceptual level it was aimed to obtain a broader perspective on the investigated (assistance)-scenarios, which are composed of various aspects pertaining to the driving situation, the driver and the implemented function (as well as its user interface). With respect to the overall objective of initiating a holistic function development process, the development of a classification scheme for assistance scenarios constituted an essential part of UF. This classification scheme considers and systematically combines a priori driver charac-

Fig. 2.1 Dimensions of the classification scheme for urban assistance scenarios. (Adopted from [2]; reproduced with permission from C. Purucker and A. Neukum)

teristics, situational demands, system design as well as their interplay. Moreover, a user-oriented development and integration process for functional and informational systems can be facilitated with this classification, as well as their adaptive functioning according to current situational demands (Fig. 2.1).

Regarding the UF objective of providing an integrative meta-perspective, the stated classification scheme also allows for inter-project comparisons and discussions as well as evaluations of project results and their assignment to different effectiveness criteria. With this analytical approach, further gaps concerning urban ADAS research and development can be identified and specified [1].

2.1.2 Project Infrastructure

In order to achieve the operational and conceptual objectives, and – as mentioned above – to provide a meta-perspective on the initiative's research activities, a multi-aspect approach was applied (Fig. 2.2), which comprised the following steps:

- Synchronisation of terminology, data acquisition and data formats for the development of internal project standards and conventions.
- Systematic description of assistance scenarios to be investigated based on a classification scheme for urban driving scenarios.
- Systematic evaluation of project results using the classification scheme for urban driving scenarios.

On the operational level the communication and cooperation was guaranteed by a mandatory involvement of the project leaders (PL) in UF. For the exchange and archival of the various partner inputs, a dedicated UR:BAN server was used.

The first two steps focused on defining data standards and the systematic description of investigated assistance scenarios in order to achieve the following objectives:

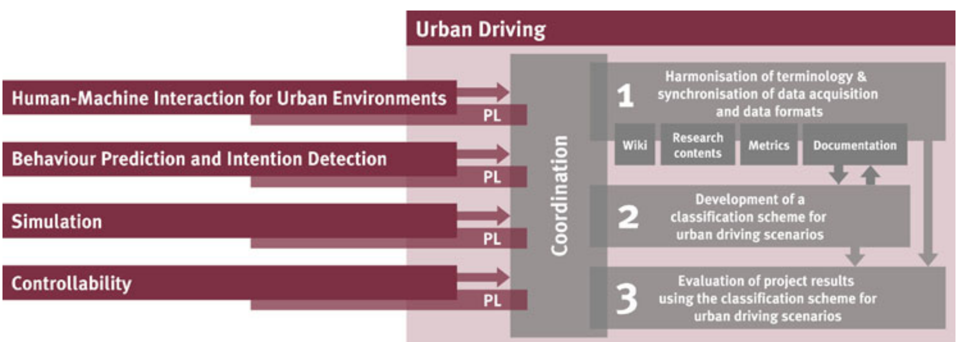

Fig. 2.2 UF objectives

- Increased transparency and comprehensibility of data acquisition.
- Internal coordination (harmonisation and synchronisation) of data acquisition activities.
- Documentation of the obtained data.
- Facilitation of the comparability and interpretability of results by utilising standardised procedures.

As can be seen in Fig. 2.2, the corresponding efforts culminate in the third step which comprises the evaluation of project results by using the developed classification scheme for urban driving scenarios, which will be the main focus of the present chapter. As such, the following section only briefly describes the methodological issues of the stated procedure, which involved several tools and standardised documents for the collection of necessary meta-information on the project activities (for more details of the conceptual development process of these tools, see [1, 3, 4]).

2.2 Methodological Approach

Several methods were applied to achieve the various objectives concerning inter-project communication and internal coordination as well as transparency and comprehensibility of data collection, which are briefly described in the following sections.

2.2.1 Harmonisation of Terminology

To ensure the utilisation of a consistent terminology throughout the project, a central information platform (Wiki) was implemented in the initial project phase. The platform contained the most important terms and definitions (and corresponding references) concerning the investigation of Human Factors and the development of ADAS, which were used identically within all subprojects. Throughout the entire duration of the project, the platform was open for continuous maintaining by any project partner [5, 6]. Experiences from coordinated activities within each subproject have shown that the platform contents were used to stimulate debates not only on formal definitions of specific terms but also on creating a consistent language throughout the project and reporting system.

2.2.2 Synchronisation of Data Acquisition and Data Formats

In accordance with the research initiative's goals, all research activities focused on data acquisition at least once over the duration of the respective projects (e. g. by means of field observation or studies with experimental manipulation). Depending on the individual research objectives, studies or experiments might have been conducted in different research environments, but would likely comprise the same types of traffic participants (motorcar, truck, motorbike, bicycle, or pedestrian). As such, it was considered useful to coordinate the planned research activities in advance of the first data acquisition phase. Thereby, planned activities could be diversified and coordinated between partners to reduce required resources, and acquired data could be shared for related research questions. For example, in projects KON and MMI, similar studies were conducted regarding driving performances in evasion manoeuvres, in order to either investigate comparability of different research environments (Chap. 25) or designing appropriate warning strategies (HMI; Chap. 5), respectively.

In order to achieve this effect of synchronised research activities, three procedures were developed, which aimed at determining consistent standards in data acquisition, and at increasing comprehensibility and transparency regarding the phase of study conceptualisation (Sect. 2.2.2.1) and the phase of data acquisition (Sect. 2.2.2.2 and 2.2.2.3). The following sections briefly outline the applied methods.

2.2.2.1 Matrix of Research Contents and Experimental Settings

The matrix of research contents was initially compiled based on the description of the intended research activities, and was continuously updated throughout the project progress. Planned research activities considered different types of traffic participants (motorcar, truck, motorbike, bicycle, and pedestrian) as well as different research environments (on-road, closed test-track or driving simulator). The different constellations can be seen in Fig. 2.3. Each cell shows the involved partners, who conducted data collections focussing

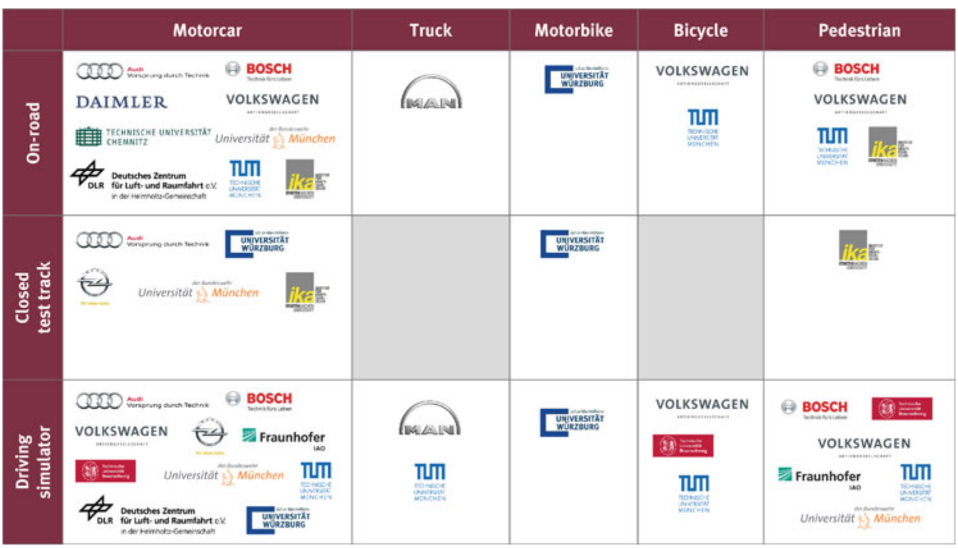

Fig. 2.3 Matrix of research contents, experimental settings and research partners. (Adopted from [1]

on the corresponding type of traffic participants and research environment. Thus, the matrix depicts the complete data pool generated over the duration of project [1].

2.2.2.2 Metrics

A list of metrics had been developed based on the matrix of performance indicators (PI-matrix) in the project FESTA ([7]; as cited in [4]), which aimed at field operational tests for assessing the impact of information and communication technologies systems on driver behaviour and – similar to UF – in an "*integrated and coordinated program of research*" (see http://www.its.leeds.ac.uk/festa/). The matrix was adapted to meet the requirements of the UR:BAN project on relevant contents [4]. Similarly to the Wiki, the list of study metrics stimulated debates within each project on determining comparable measurements (e. g. matching definitions of lane exceedances) as well as defining standards for following data analysis and modelling procedures (e. g. computations of TTC).

2.2.2.3 Documentation of Empirical Research and Data

For each data acquisition activity, partners completed a one-sided data sheet which briefly described the applied experimental or observational procedure. The electronic document required basic information concerning the research environment, traffic participants and sample size, as well as a link to the corresponding description of the investigated assistance scenario (if available). Additional information could be given, e. g. on potential deviations from the variables and measures in the list of study metrics or on special technical features [4].

2.2.3 Classification Scheme for Urban Driving Scenarios

With regard to the description of investigated assistance scenarios, UF established categories which consider various aspects of the driving situation, the driver and the implemented function (cf. Sect. 2.1.1). Table 2.1 lists specific categories within these dimensions. The following sections briefly describe the contents of the three scenario dimensions. For a theoretical derivation of the classification scheme for urban driving scenarios and a comprehensive literature review (see [1, 3]).

2.2.3.1 Situation Description

The operating principles of ADAS can be best illustrated using typical traffic situations. The situation description contains static and dynamic aspects of the environmental situation described by text or using illustrating sketches. Dynamic aspects relate to the ego vehicle (and its driving manoeuvres) as well as various aspects of the traffic situation (such as other traffic participants, traffic flow or weather). Static aspects concern the road infrastructure and environmental conditions in which the driver moves. Additionally, the core aspects of the situation were classified according to the potential conflict (or accident) situation and concerned driving manoeuvres. To allow for comparable replications of the

Table 2.1 Classification scheme for urban assistance scenarios. (Adopted from [1, 3])

<table>
<tr><td>RESEARCH OBJECTIVES</td><td>- Collision avoidance
- Controllability
- Manoeuvring assistance
- Intention detection</td><td>- Methods
- Simulation systems
- Usability
- Validation</td><td>- Efficiency enhancement
- Emission reduction
- Infrastructure development
- Effectiveness
- …</td></tr>
<tr><td>SITUATION</td><td colspan="2">DRIVER</td><td>FUNCTION</td></tr>
<tr><td>Situation description

Situation sketch (Images)

Description of conflict situation

Manoeuvre type

Traffic situation
- Description of ego vehicle
- Description of traffic participants
- Situation-dependent visibility
- Traffic flow
- Operational parametrisation

Environmental and road conditions
- Type of road
- Road condition
- Weather
- Lighting condition
- Time of day</td><td colspan="2">Driving task

Requirement level of driving task

Secondary tasks
- Sensor modality
- Type of interaction
- Interruptibility
- Information coding

Driver characteristic
- Age and sex
- Personality
- Driving skills
- Driving experience
- Driving style
- Driver state</td><td>Function description

Information/intervention depth
- Information
- Warning
- Intervention (assisted, partly/highly/fully automated)

Technical system
- Objective description
- Technical implementation
- Sensory input variables
- Description of operational sequence

HMI
- Objective description
- Technical implementation (visual, auditory, haptic)
- HMI phases</td></tr>
</table>

experimental design, all necessary parameters were documented. The results of a detailed situation analysis can be used for:

- Deduction of safety-relevant requirements for the development of assistance functions,
- Effective comparisons of functions and
- Identification of synergy effects.

2.2.3.2 Driver Description

The driver description contains the specification of the driving task and a determination of corresponding levels of task requirements. Secondary tasks while driving can also be described with various details, as these tasks can limit the driver's attentional resources and thus reduce the effectiveness of assistance systems. Moreover, additional information can be provided regarding the general driver characteristics (e. g. age, familiarity with the route or driving experience) and driver state, as these might have a moderating impact on the driving task performance as well as on the interaction process with the assistance system.

2.2.3.3 Function Description

The function description contains specifications regarding the purpose and functionality of the respective function as well as the intended extent of the intervention (e. g. ranging from just informing to warning the driver). It is further differentiated between functions that involved driver-system interactions and those that do not directly involve interaction. Examples of the former include warning or information systems, which can be described, e. g. with respect to the sensory modality of warning signals. Examples of the latter include the automatic monitoring of vehicle dynamics or environment-related sensory data.

A minimum amount of information must be provided on these three dimensions in order to describe adequately an assistance scenario and to provide a sufficient data basis for successive qualitative analyses. Elaborate details were omitted from the descriptions in order facilitate completion and processing. Some of the comprised categories aimed at providing a quick overview of the investigated assistance scenario and a mutual understanding between projects. Other categories could be filled with precise details concerning the technical implementation of a system or the specific design of a HMI interface. These were optional and aimed at a detailed bilateral exchange. The final document was implemented as a digital checklist, which allowed for easy export of into a database. This facilitated the project-spanning synopsis of the investigated assistance scenarios.

2.3 Evaluation of Project Results

In order to provide an integrative meta-perspective of the diverse research activities and project results, the obtained information from the described assistance scenarios must by condensed to their core aspects and merged with specific situation- or assistance-related key results of the individual project activities. This allows for a qualitative evaluation of the project results and potential analysis regarding the effectiveness criteria. However, not all project activities focused on situation- or assistance-related research questions. Each project also engaged in methodological and/or conceptual work (e. g. development of a HMI tool kit, potential analysis of signals for manoeuvre prediction, development of linked simulators, or the expansion of the methodological inventory for controllability studies), which was also to be considered with an integrative view on project results. In the following section, these results are referred to as "core messages".

The following sections describe the strategies for obtaining the core messages and key results, and culminate in an integrative meta-perspective on the project's research activities by means of text-based summaries and comprehensive visual representations of project results.

2.3.1 Project Core Messages

The project core messages reflect the main results of each project which focus on methodological or conceptual aspects that are independent of the specific dimensions (situation, driver, or function) of an assistance scenario. The underlying main objectives of each project are listed below (Table 2.2) and are elaborated in the corresponding chapters for each project in this book.

Despite the apparent distinctiveness of these objectives, projects exhibit mutual interdependencies. Behaviour prediction and intention detection (VIE) is a precondition for an adequate, transparent and accepted support or intervention. However, intention detection will sometimes change system behaviour. For example, a system which warns the driver of an insufficient distance to a preceding vehicle might omit this warning, if it predicts that the driver will turn right. Thus, system behaviour is not necessarily consistent over time and the driver needs to understand under which circumstances what kind of system action can be expected.

The communication of system stages, planned and actually performed actions to the driver is part of the project HMI. It offers a strategy and a toolkit for comprehensible and user-centred interaction, specifically for the challenges of urban traffic.

Even if drivers' intentions are correctly identified and system actions are displayed in a transparent and non-overloading manner, the question remains whether the system is controllable by the driver (KON); in other words, whether s/he can override the system if necessary or is willing to transfer control to the system for a while.

Table 2.2 Main objectives of the projects MMI, VIE, SIM and KON

Human-Machine Interaction for Urban Environments	Behaviour Prediction and Intention Detection	Simulation	Controllability
– Conception and development of a generic HMI-Toolkit – Development of a structure for HMI-strategies – Elaboration of the HMI strategies "Warnings and Interventions", "Lateral and longitudinal control", and "Recommended action"	– Determination of systems approaches and applications – Determination of boundary conditions – Potential analysis of signal usage – Determination of prediction quality and restrictions	– Determination of metrics for the quantification of social interaction – Development of linked simulation systems and investigation of interaction effects – Investigation of effects of assisted drivers on non-assisted drivers – Microscopic simulation of interaction behaviour	– Choice of research environment – Determination of validation and evaluation criteria – Enhancement of the methodical inventory – Differentiation from traditional criteria of controllability – Investigation of driver performance – Implications

Many aspects of driver behaviour prediction as well as controllability can be tested in specific experiments and testing environments. However, to get a deeper insight in the behaviour and mutual dependence of traffic participants' actions, simulations are necessary. SIM therefore investigates effects of the interaction of traffic participants (drivers and pedestrians/cyclists) and of interactions of drivers with highly automated and "conventional" cars.

2.3.2 Situation- or Assistance-related Project Key Results

The numerous described aspects of the assistance scenario checklist were filtered for relevant and meaningful variables, and then aggregated into core statements using an iterative strategy. Linking core statements obtained from the described assistance scenarios with scenario-specific key results constituted a particular challenge. Additional data sources were queried, such as the internal report system (e. g. [8–16]) public presentations (e. g. posters of the final presentation; see UR:BAN, [2]) as well as several partner publications, which are listed in the project reports or the projects website (see http://www.urban-online.org/de/publikationen/).

Based on the obtained data from the assistance scenario checklists and the extracted project key results, the classification scheme for urban driving scenarios was restructured with an integrative view on the developed functions. In a workshop with the participation of UF partners as well as the project leaders, this revision was discussed and the potential effectiveness criteria were identified, which aimed at the potential evaluation of the obtained project results. The workshop results are listed below (see also Fig. 2.4):

The scenario data have been aggregated into three global driving scenarios in urban environments:

- Roads without constrictions or visibility constraints.
- Roads with constrictions or visibility constraints.
- Intersections and crossroads.

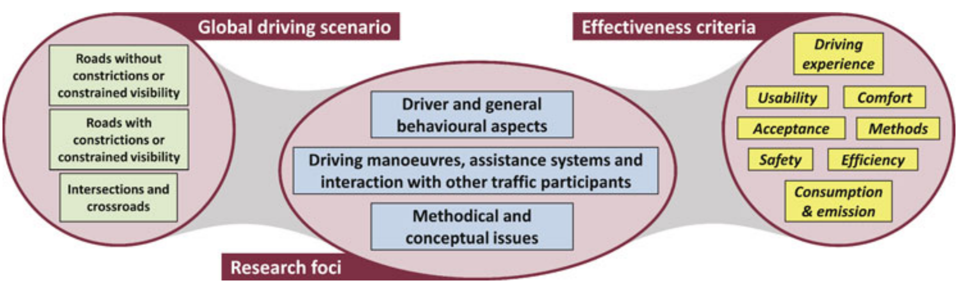

Fig. 2.4 Revised classification scheme for research activities and potential criteria for effectiveness and efficiency

Within these scenarios, research activities focused on various aspects which could be classified into three categories:

- Driver and general behavioural or cognitive aspects (e. g. individual characteristics, perception, distraction, workload, or driver experience).
- Driving manoeuvres, assistance systems and interaction with other traffic participants.
- Methodical and conceptual issues (Comparison of research environments, development of multi-party driving simulations, and development of an integrative HMI concept and toolkit).

Analogously to these categories, the following effectiveness criteria were identified:

- Driver related: Acceptance, comfort, driver experience, usability.
- System related: Safety, efficiency, consumption and emission.
- Research related: Methods.

In order to establish the basis for a qualitative analysis of project results and potential analyses with regard to the identified effectiveness criteria, an integrative and intuitive visual representation type was preferred and implemented for each global driving scenario (see Figs. 2.5, 2.6 and 2.7). Within these scenarios the specific key results can be described and assigned to the identified research foci and effectiveness criteria.

2.3.2.1 Roads without Constrictions or Visibility Constraints

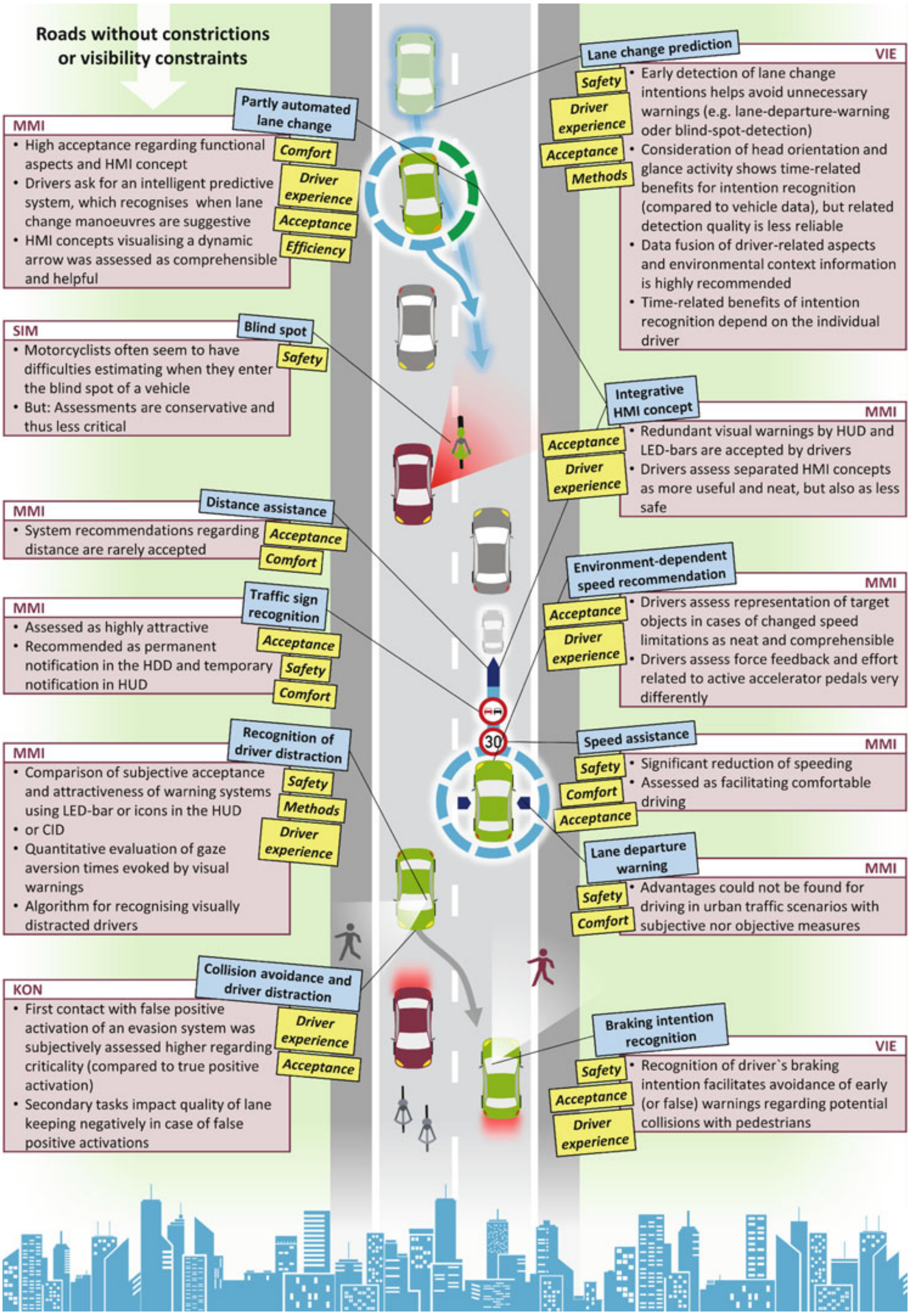

Fig. 2.5 Roads without constrictions or visibility constraints

2.3.2.2 Roads with Constrictions or Visibility Constraints

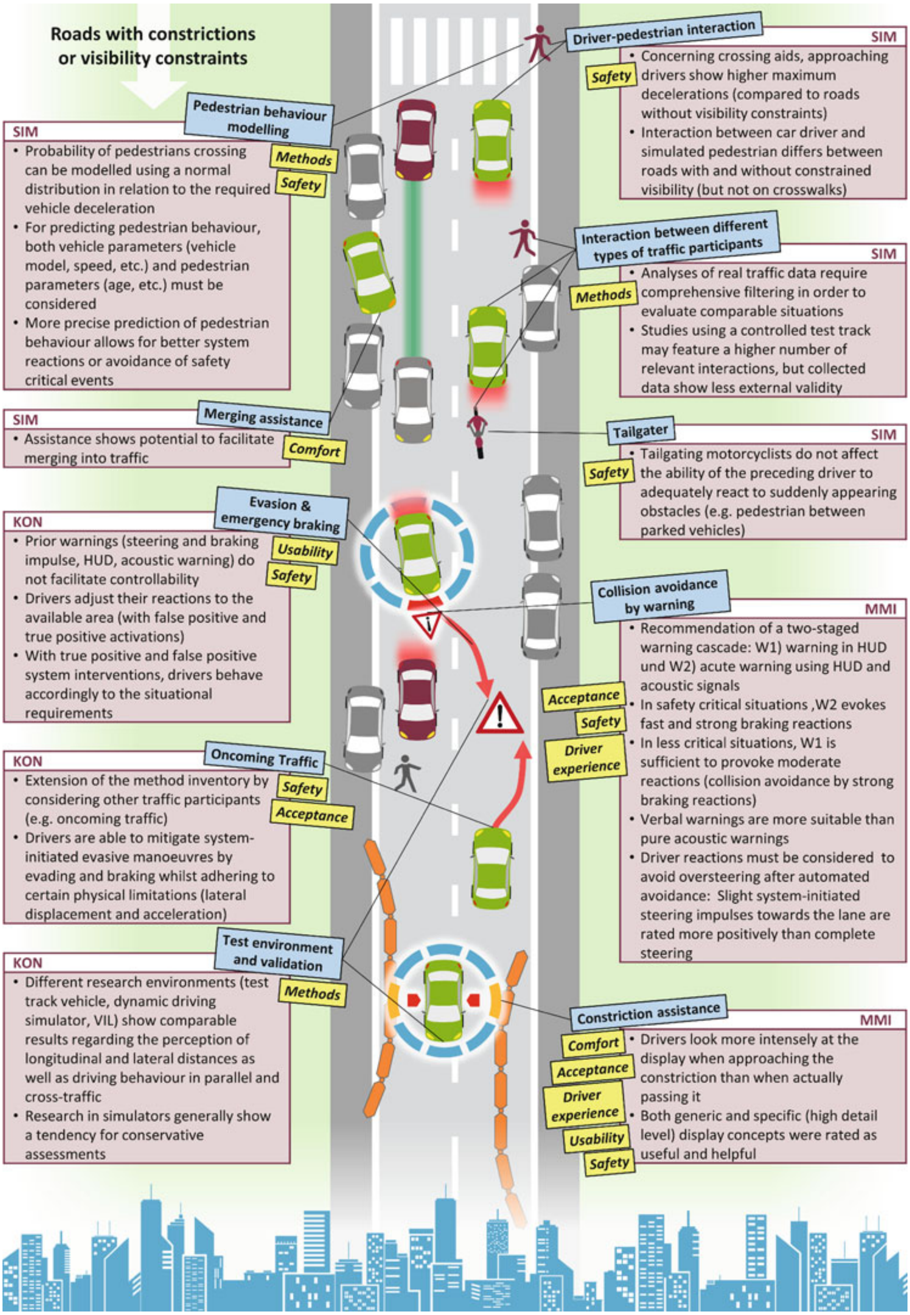

Fig. 2.6 Roads with constrictions or visibility constraints

2.3.2.3 Intersections and Crossroads

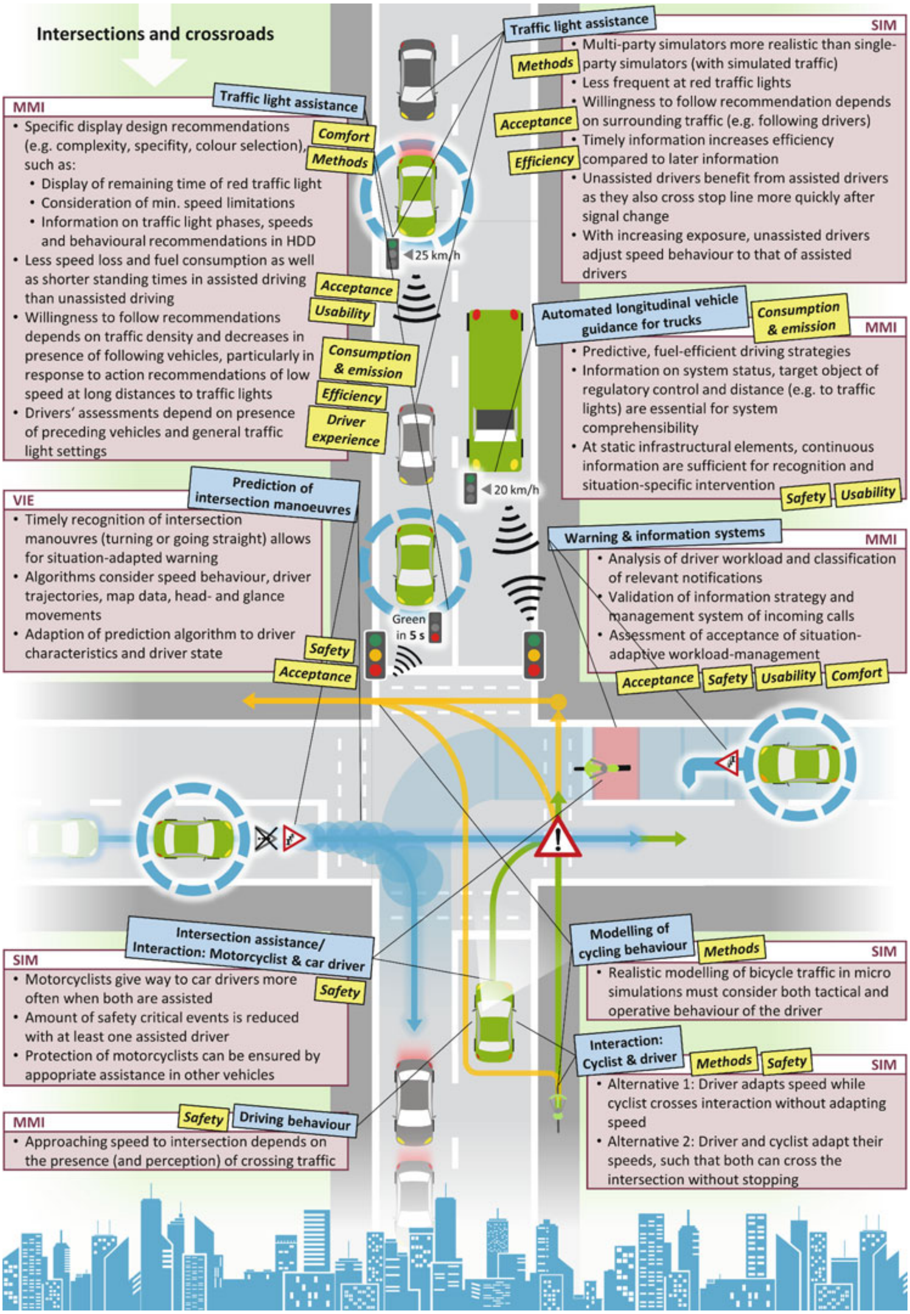

Fig. 2.7 Intersections and crossroads

2.3.3 Road Map to Key Results

Roads without constrictions or visibility constraints	*MMI*	Chap. 6: HMI Strategy – Lateral and Longitudinal Control
	VIE	Chap. 10: Predicting Strategies of Driving in Presence of Additional Visually Demanding Tasks: Inverse Optimal Control Estimation of Steering and Glance Behaviour Models Chap. 11: Lane Change Prediction: From Driver Characteristics, Manoeuvre Types and Glance Behaviour to a Real-Time Prediction Algorithm Chap. 12: Fusion of Driver Behaviour Analysis and Situation Assessment for Probabilistic Driving Manoeuvre Prediction Chap. 13: Human Focused Development of a Manoeuvre Prediction in Urban Traffic Situations Based on Behavioural Sequences Chap. 14: Application of a Driver Intention Recognition Algorithm on a Pedestrian Intention Recognition and Collision Avoidance System
	SIM	Chap. 22: A New Approach to Investigate Powered Two Wheelers' Interactions with Passenger Car Drivers: the Motorcycle – Car Multi-Driver Simulation Chap. 23: Multi-Road User Simulation: Methodological Considerations from Study Planning to Data Analysis
	KON	Chap. 29: Integrating Different Kinds of Driver Distraction in Controllability Validations
Roads with constrictions or visibility constraints	*MMI*	Chap. 5: HMI Strategy – Warnings and Interventions Chap. 6: HMI Strategy – Lateral and Longitudinal Control
	SIM	Chap. 16: Methodology and Results for the Investigation of Interactions Between Pedestrians and Vehicles in Real and Controlled Traffic Conditions Chap. 23: Multi-Road User Simulation: Methodical Considerations from Study Planning to Data Analysis
	KON	Chap. 25: Validity of Research Environments: Comparing Criticality Perceptions Across Research Environments Chap. 26: Emergency Steering Systems – Controllability Investigations with the Vehicle in the Loop Chap. 27: Considerations of the Available Evading Space for the Evaluation of the Driver Reaction to Emergency Steering Interventions

Inter-sections and cross-roads	*MMI*	Chap. 6: HMI Strategy – Lateral and Longitudinal Control Chap. 7: HMI Strategy – Recommended Action
	VIE	Chap. 9: Analysing Behavioural Data from On-Road Driving Studies: Handling the Challenges of Data Processing
	SIM	Chap. 17: Understanding Interactions Between Bicyclists and Motorist in Intersections Chap. 18: Analysis and Modelling of the Operational and Tactical Behaviour of Bicyclists Chap. 20: Encounters Between Drivers with and Without Cooperative Intelligent Transport Systems Chap. 21: The Multi-Driver Simulation: A Tool to Investigate Social Interactions Between Several Drivers Chap. 22: A New Approach to Investigate Powered Two Wheelers' Interactions with Passenger Car Drivers: the Motorcycle – Car Multi-Driver Simulation Chap. 23: Multi-Road User Simulation: Methodical Considerations from Study Planning to Data Analysis

2.4 Summary and Conclusion

UF aimed to support a holistic function development process for urban ADAS that takes situational, environmental and driver-related aspects into consideration, as they are featured in urban traffic scenarios. For this purpose, several strategies were applied that generated synergies between the research projects by integrating the various research questions, harmonising individual partner activities and evaluating the obtained project results from a broader perspective. This comprised the development of internal project standards and conventions, and a classification scheme for the investigated urban driving scenarios. On this basis it was possible to structure communication and interaction with experts working on function development in UR:BAN Cognitive Assistance and traffic information management in UR:BAN Networked Traffic System.

Moreover, particularly the classification scheme raised awareness of the numerous factors that affect driving in urban traffic scenarios and it directed efforts from a predominantly function-oriented development towards an integrative approach. By extracting core messages and aggregating obtained information, a qualitative analysis and potential evaluation could be performed – culminating in a meta-perspective on the overall research activities.

The analysis evaluated the project results in three global driving scenarios that featured in urban environments with respect to various effectiveness criteria. Integrative visualisations of the project results give insights into the main research achievements of the projects and showed in which way the obtained results will positively affect the UR:BAN objectives of safety, comfort and efficiency.

Experiences from former comparable research initiatives, such as PROMETHEUS [17], MoTiV [18], INVENT [19] and AKTIV [20], highlighted the importance and challenges of cross-project coordination and its potential contribution towards the overall project success (as well as to the public image; cf. [1]). The presented strategies and results of UF have shown that these challenges can be met by applying appropriate strategies for documenting and harmonising the diverse research activities over the entire duration of the project. Moreover, viewing the project activities and results from an integrative meta-perspective provides valuable insights, which go beyond the presentation of results in isolated project reports or public presentations and emphasise the necessities which justify research initiatives of this type a fortiori. With this holistic view on UR:BAN *Human Factors in Traffic,* it can be seen to which extent we are ready to meet the requirements of assisted urban driving and what still needs to be addressed in future research initiatives.

Acknowledgement
Sincere thanks to Andreas Pütz and Christian Purucker who developed the standards for data acquisition, the classification scheme as well as the checklist for describing the assistance scenario respectively. Moreover, Matthias Graichen thanks Julia Drüke for supporting the initial development process of the holistic perspective on the project results. Furthermore, without the support of all project partners and project leaders, and their diligent document completion and valuable feedback in numerous communication and coordination processes, the present work could not have been completed.

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Part III

Human-Machine Interaction for Urban Environments

Introduction of Human-Machine Interaction for Urban Environments

3

Julia Drüke

In the German national funded UR:BAN project numerous assistance functions supporting the driver in longitudinal and lateral vehicle guidance control up to preventing accidents by warning the driver or making evasive manoeuvres autonomously are considered in order to contribute to improve safe, comfortable, and energy-efficient driving in urban areas. Especially, the design of the human-machine-interfaces (HMIs) of all the applications together faces many challenges. For example, urban traffic is compared to highways and rural roads more complex and dynamic due to different infrastructure and the interaction with other road users (e. g. crossing vehicles, pedestrians, and bicyclists). Thus, information, warning, and system intervention concepts should be designed to minimize the conflict between the complexity of urban traffic situations and the driver's limited cognitive information processing by keeping understanding and trust in such assistance systems. The subproject "Human-Machine Interaction for Urban Environments" (named "Stadtgerechte Mensch-Maschine-Interaktion") addresses the development and design of HMIs of this range of driver assistance systems. The central goal of the subproject is to design user-oriented, integrative HMI concepts of current and future assistance systems by considering the challenges and needs in urban areas. In total, nine project partners – Adam Opel AG, AUDI AG, Robert Bosch GmbH, Daimler AG, MAN Truck & Bus AG, Technische Universität Braunschweig, Technical University of Munich, Universität der Bundeswehr München, and Volkswagen AG – rise to this challenge.

In the subproject three main objectives are considered to contribute to increase driving safety, comfort, and energy-efficient driving in urban traffic:

(1) Development and design of a cross-functional HMI tool kit including generic, integrative HMI concepts of current and future driver assistance systems by providing an organization for the prioritization of adequate HMI components (e. g. presenting in-

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formation and warnings in the display in the instrument cluster and/or in the head-up display) and its design guidelines so that the required driver's action can be achieved in the situation.

(2) Integration of the developed HMI concepts in the UR:BAN prototypes of the work packages "Cognitive Assistance" (e. g. collision avoidance system by autonomous evasive manoeuvre and braking, protection of vulnerable road users by turning and crossing assistance, constriction assistant) and "Networked Traffic System" (e. g. entrance and start assistant at intersections, intersection area view). This is done to evaluate the HMI tool kit method and the integrative HMI concepts derived from the tool kit logic as third objective in the subproject.

(3) Evaluation and review of the HMI concepts throughout the entire development process from the user perspective, using a various number of expert reviews and research studies (e. g. focus groups, expert tests, driving simulator studies, and on-road testing) with research questions regarding the effectiveness, usability, optimized design, and driver acceptance of the HMI concepts as well as the effect on driver behaviour. The aim is to obtain refined requirements of the HMI concepts, then carry out an iterative development and evaluation process, and finally continue up to an evaluation of the overall approach.

The idea of the cross-functional HMI tool kit is to define a strategy for the systematic derivation of action-oriented HMI concepts of assistance systems for safe, comfortable, and energy-efficient driving in urban traffic. The tool kit illustrates how generic information, warning, and system intervention concepts can be designed by selecting appropriate HMI output media (e. g. display in the instrument cluster, head-up display, steering wheel etc.) for the different UR:BAN applications. It defines where and how information should be positioned relative to the driver in order to achieve the required action by the driver. The tool kit also describes which driver's action is recommended in the situation. Due to the variety of cases in urban traffic differing in time horizon and priority, the HMI tool kit is structured in three paths of HMI strategies: 1) HMI strategy "Warnings and interventions", 2) HMI strategy "Lateral and longitudinal control", and 3) HMI strategy "Recommended action".

The HMI strategy "Warnings and interventions" contains HMI concepts especially for safety-critical situations, e. g. when a pedestrian is suddenly crossing the road without paying attention to the traffic. The aim is to avoid a potential collision by interventions by the driver (braking and steering) or the application (warning, steering, locking the accelerator). The UR:BAN applications from AUDI AG, Robert Bosch GmbH, Technische Universität Braunschweig, Technical University of Munich, and Volkswagen AG were used to test the developed HMI concepts derived from the HMI tool kit. Chap. 5 gives insight into the HMI strategy and describes the different HMI concepts developed from the project partners and tested in research studies.

The HMI strategies "Lateral and longitudinal control" and "Recommended action" contain assistance systems for comfortable and energy-efficient driving. The HMI strategy

"Lateral and longitudinal control" covers situations in which the driver should continuously and safely be supported in lateral and longitudinal vehicle guidance control, e. g. within narrow roads. Project partners like Daimler AG, MAN Truck & Bus AG, and Volkswagen AG worked on system functions, such as a constriction assistant, lane change assistant, and green wave assistant to enable 1) comfortable and energy-efficient driving and 2) a comprehensive awareness and understanding of the continuous operation of the system by the driver. In contrast, the HMI strategy "Recommended action" contains assistance systems which support the driver in his/her optimal route selection without active system interventions. The information is only given to the driver as recommendation. The energy-efficient navigation and the intersection area view are two examples of such assistance functions. The project partners Adam Opel AG, AUDI AG, Technical University of Munich, and Volkswagen AG address to this task in the UR:BAN project. In Chaps. 6 and 7 both HMI strategies and partner-specific HMI concepts are described.

The following section provides insight into the structure and contents of the HMI tool kit method. In addition to the aim and development of the tool kit, in Chap. 4 the HMI path structure, the three HMI strategies, and the design guidelines of the HMI components are explained in detail. The chapter ends with a generic and integrative HMI concept for the display in the instrument cluster developed in the UR:BAN project. The aim of this generic HMI concept is to aggregate relevant information and warnings of the various complex assistance systems in order to increase transparency by the driver. The generic HMI concept is exemplary applied for the constriction assistance and a collision avoidance system by autonomous evasive manoeuvre. In the Chaps. 5–7 the three HMI strategies are described in more detail. Besides the background and motivation of the HMI strategy and its HMI concepts, each project partner introduce their HMI concept of the UR:BAN application based on findings and input from the research studies conducted throughout the entire development process. Finally, it is important to mention that only a selection of results can be presented here. More detailed information and further results can be found in the references mentioned in the studies.

The "HMI tool kit" as a Strategy for the Systematic Derivation of User-Oriented HMI Concepts of Driver Assistance Systems in Urban Areas

4

Julia Drüke, Carsten Semmler, and Lennart Bendewald

4.1 Introduction

In the last few decades, the development of driver assistance systems has shown various innovation waves [1, 2]. The rapidly growing field of such systems ranges from supporting the driver in longitudinal (e. g. Adaptive Cruise Control – ACC) and lateral vehicle guidance control (e. g. Lane Assist) to the point of preventing accidents by warning the driver (e. g. collision warnings) or making evasive manoeuvres autonomously (e. g. emergency braking). While such assistance systems can contribute to increasing driving safety and comfort on highways and rural roads, in the future system limits will be enhanced to include also urban traffic. In the UR:BAN project, 31 partners comprising automotive manufacturers and suppliers, electronics, communication technology and software companies, universities, research institutes, and cities did research in this area.

The above mentioned trend also faces challenges, especially in the design of human-machine-interfaces (HMI). First, HMI concepts of existing driver assistance systems are mostly stand-alone solutions (e. g. HMI for ACC or Lane Assist). Such HMI solutions could overload the driver with additional HMIs of future and novel assistance functionalities, which could be competitive and unsynchronised to each other [3, 4]. Second, the expansion of driver assistance systems to urban roads includes many challenges with regard to the environment and infrastructure (Fig. 4.1a).

Compared to highways and rural roads, urban traffic is more complex and dynamic due to the different infrastructure and the interaction with other road users (e. g. crossing vehicles, pedestrians, and bicyclists). Due to the complexity of urban traffic, this could also result in an increased number of different information, warnings, and system interventions whose understandability and differentiation could be reduced [4]. Thus, a quick and ad-

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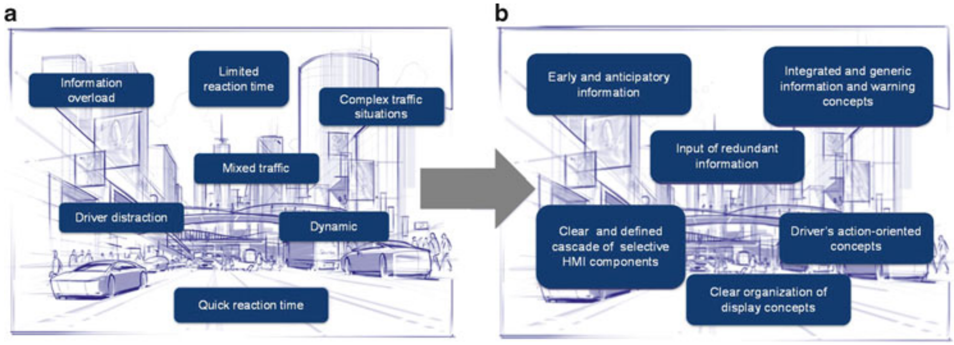

Fig. 4.1 Demands on human factor in urban areas (**a**) and the effects for HMI concepts (**b**)

equate reaction by the driver might be difficult to reach. The aim of the different HMIs should be to keep understandability and trust in such assistance systems by the design of generic information and warning concepts, with early and anticipatory information and clearly defined action-oriented concepts (Fig. 4.1b).

In the UR:BAN project [5], one aim was to design user-oriented, integrative HMI concepts of current and future assistance systems by considering the challenges of urban driving (Fig. 4.1) and to improve safe, comfortable, and energy-efficient driving. Therefore, in the subproject "Human-Machine Interaction for Urban Environments" (translated "Stadtgerechte Mensch-Maschine-Interaktion") the cross-functional "HMI tool kit" was developed, which comprises a strategy for the systematic derivation of action-oriented HMI concepts. The UR:BAN applications (e. g. emergency braking assistance, collision avoidance by autonomous evasive manoeuvre, lane change assistance, constriction assistance) are fundamental for the development of the HMI tool kit. Furthermore, novel applications supporting the driver in his/her optimal traffic flow through the urban traffic are also considered in the project and are part of the HMI tool kit. In the following, the aim and contents of the HMI tool kit are described.

4.2 HMI Tool Kit

4.2.1 Aim and Development of the HMI Tool Kit

The aim of the HMI tool kit was to develop and design user-oriented display and operating concepts in terms of a cross-functional HMI, which structure and standardise HMI concepts of current and future driver assistance systems.

The HMI tool kit comprises a strategy for the systematic derivation of action-oriented HMI concepts of assistance systems for safe, comfortable, and energy-efficient driving in urban traffic. It provides an organization for the prioritization of adequate HMI components (e. g. display in the instrument cluster, head-up display, steering wheel etc.) regarding urban cases. Furthermore, the tool kit also contains design guidelines for the different HMI components as output media so that the preferred driver's action can be achieved in situations e. g. in which the driver should be warned of a potential collision or the driver needs to become aware of the assistance system controlling the longitudinal or lateral system guidance. Overall, the goal of the HMI tool kit is to illustrate how consistent information, warning, and intervention concepts can be achieved by selecting appropriate HMI output media for the different types of applications in the urban area.

The input for the development of the HMI tool kit is shown in five key questions in Fig. 4.2, which also explains the structure of the tool kit (Fig. 4.3).

The output of the HMI tool kit is a proposal for adequate HMI concept solutions, which consider two main challenges:

(1) Dealing with different and frequent information, warnings, and system interventions,
(2) Integration of different messages from the system in a generic, integrative HMI concept to achieve an adequate reaction by the driver.

With regard to the goals of the UR:BAN project, the cross-functional HMI is based on the following key requirements:

(1) Consideration of various driver assistance systems based on on-board sensors and cooperative communication technologies with the aim to improve safe, stress-free, and energy-efficient driving in urban areas,
(2) Structuring and coordination of continuous information, warnings, and situational recommendations of driver's action,
(3) Identification of adequate and situation-adapted HMI output media for information, warnings, and situational recommendations to achieve a fast and adequate driver reaction,
(4) Definition of requirements and design guidelines of prioritized HMI output media.

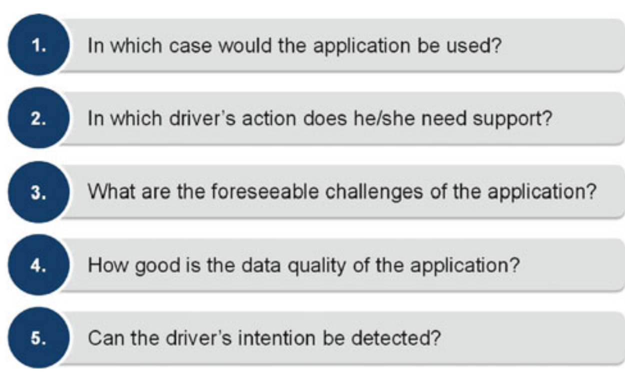

Fig. 4.2 Input criteria for the HMI tool kit

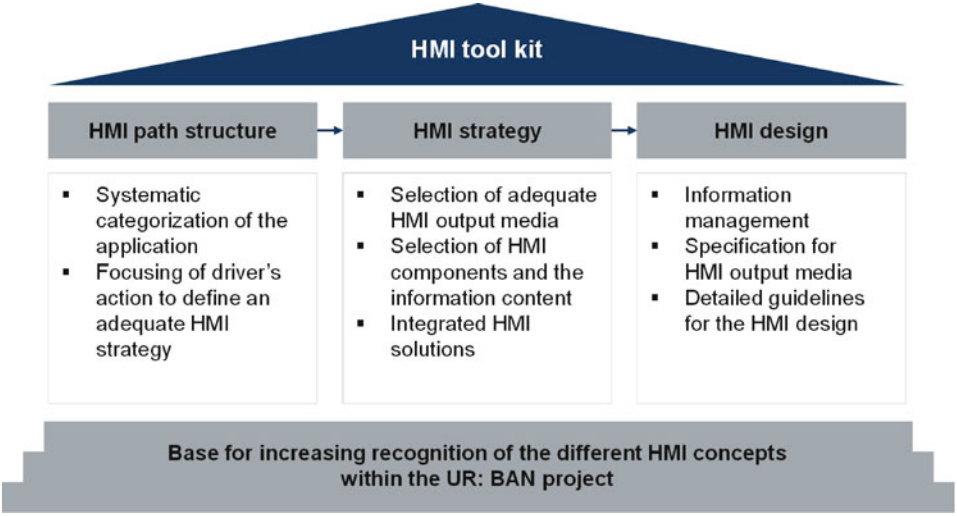

Fig. 4.3 The three pillars of the HMI tool kit

Aside from these, the subproject "Human-Machine Interaction for Urban Environments" (translated "Stadtgerechte Mensch Maschine Interaktion") includes three topic pillars, which structure the basis and key contents of the HMI tool kit (Fig. 4.3): (1) HMI path structure, (2) HMI strategy, and (3) HMI design. Within the UR:BAN project the three pillars also provide a base for increasing recognition of the various HMI concepts of the different applications of the project partners.

The "HMI path structure" contains the systematic categorization of the UR:BAN applications for safe, comfortable, and energy-efficient driving. It is also used for systematic organization of the action-oriented HMI concepts of these applications. Depending on the case, each HMI path structure defines the adequate "HMI strategy". According to the different UR:BAN applications (e. g. collision avoidance by autonomous evasive manoeuvre and by braking, constriction assistant, lane change assistant, green wave assistant, speed recommendation) it is not possible that all cases can be covered with only one HMI strategy to adequately assist the driver. On the one hand, they differ in time horizon and priority, on the other hand in the preferred driver's action (e. g. either the driver should become aware of the system behaviour or must immediately react to a critical event). Thus, the "HMI strategy" of the HMI tool kit is divided into: (1) "Warnings and interventions", (2) "Lateral and longitudinal control", and (3) "Recommended action". With the HMI strategy, the adequate HMI output media (visual, auditory, tactile), the selection of the suitable HMI components (e. g. display in the instrument cluster, head-up display, LED-bar, warning tone), and the information content to achieve the required driver's action are defined. Here, different stages of the driver's action are defined depending on the "HMI strategy". It describes that specific HMI components should only be used in later stages; other components are not recommended for each HMI strategy. Detailed information about the "HMI path structure" and "HMI strategies" are described in Sect. 4.2.2 and 4.2.3. The third pillar the "HMI design" contains detailed guidelines for the design of the HMI concept in the HMI strategy. Furthermore, it defines where and how information should be positioned and designed relative to the driver. Sect. 4.2.4 provides an insight into the design guidelines.

The examination of the HMI tool kit is based on the applications from the UR:BAN work packages "Cognitive Assistance – Kognitive Assistenz" (e. g. collision avoidance by autonomous evasive manoeuvre and braking, protection of vulnerable road users by turning and crossing assistance, constriction assistant), "Networked Traffic System – Vernetztes Verkehrssystem" (e. g. entrance and start assistant at intersections, intersection area view), and the subproject "Behaviour Prediction and Intention Detection" (translated "Verhaltensprädiktion, Intentionserkennung") of the UR:BAN work package "Human Factors in Traffic – Mensch im Verkehr". During the developing process, the HMI concepts were evaluated by a various number of expert reviews and research studies, e. g. focus groups, expert tests, driving simulator studies, and on-road testing. Research questions regarding the effectiveness, usability, and driver acceptance of the HMI concepts as well as the effect of the concepts on driver behaviour were considered within these studies. Based on the findings, the HMI tool kit was developed, advanced, expanded, and adapted by the HMI project team. It is also important to mention that the HMI tool kit should be seen as a proposal for cross-functional HMI concepts. The brand-specific details of the different concepts is left up to the UR:BAN partners.

4.2.2 HMI Path Structure

The HMI tool kit is structured in three HMI paths, resulting in three HMI strategies (Fig. 4.4): (1) "Warnings and interventions", (2) "Lateral and longitudinal control", and (3) "Recommended action". As mentioned above due to the variety of cases in urban traffic it is not possible to cover all with only one HMI strategy in order to adequately assist the driver. Especially in urban traffic, the cases differ in time horizon, priority, and appropriate driver's action. For example, in unexpected, safety-critical situations when a pedestrian is suddenly crossing the road without paying attention to the traffic, the driver needs to be adequately warned that a fast and situation-related driver reaction (e. g. braking, steering, or braking and steering) can be achieved. In other situations, in which the driver is assisted by a lateral guidance system, e. g. when driving through a narrow point on the road or constriction (e. g. constriction assistant), the driver needs to have an adequate awareness and understanding of the continual lateral control of the assistance system. As a result, the different HMIs need a structure that differentiates according to the various applications and specify the path for an adequate HMI strategy. Thus, in the 1st level of the HMI tool kit the HMI concepts are divided into "safe driving" and "comfortable and efficient driv-

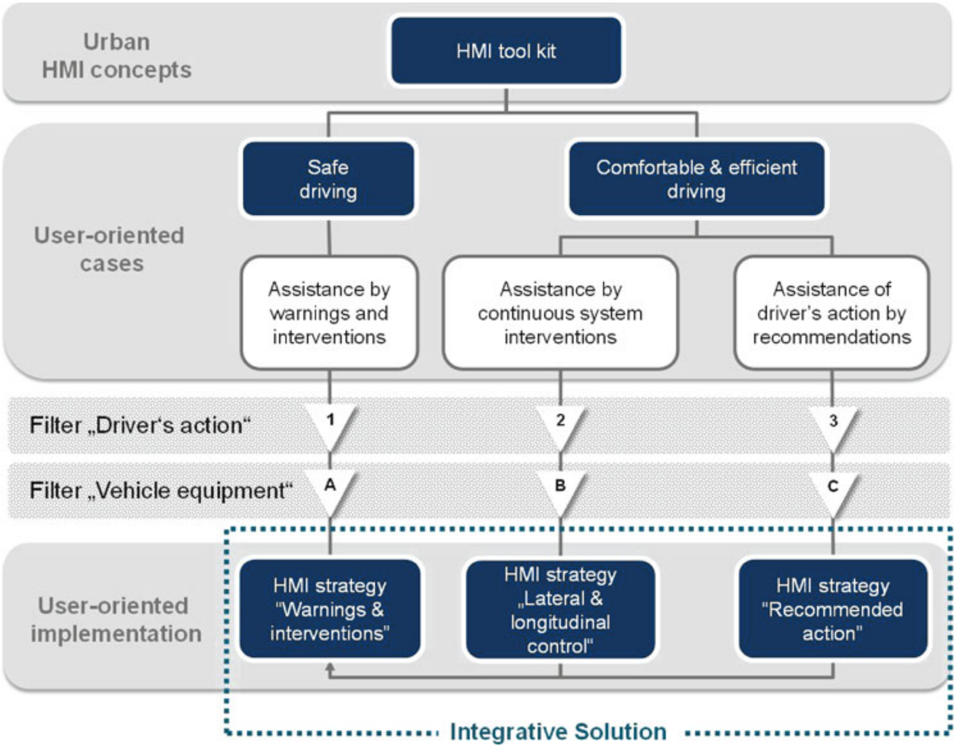

Fig. 4.4 The HMI path structure of the HMI tool kit – A systematic derivation of different HMI concepts for the applications of safe, comfortable, and energy-efficient driving

ing" (Fig. 4.4). This level highlights the question: What kind of assistance does the driver need?

As Fig. 4.4 shows, in the case of "safe driving" the driver is assisted by warnings and system interventions. For "comfortable and efficient driving", the assistance is divided into continual system interventions and by recommended driver's action. Although comfort and efficiency are indeed strongly related to each other, in detail both have different user requirements and needs. In terms of comfort, the driver should get a comprehensive awareness and understanding of the continual control and operation of the assistance system. In contrast to efficiency where it is important that the driver gets information in order to reduce consumption. As a result, the user-oriented HMI strategies are divided into (Fig. 4.4): (1) HMI strategy of warnings and interventions, (2) HMI strategy of lateral and longitudinal control, and (3) HMI strategy of recommended action.

As shown in Fig. 4.4, to finally define the precise HMI for the current traffic situation, two filter processes are distinguished: (1) driver's action and (2) equipment of the vehicle. The driver's action defines the action of the driver, which is required from the assistance system, e. g. the driver should brake or steer in a safety-critical situation. The equipment of the vehicle defines the HMI components, which are available in the vehicle. This filter also defines the adequate HMI of an assistance system in order to achieve the best driver’s action. After the two filter processes, the HMI strategies are reached. They include the user-oriented implementation of the HMI based on a scheme, which structures the HMI concepts (Fig. 4.5, 4.6 and 4.7). Detailed information about the three HMI strategies are described in Sect. 4.2.3.

It is also important to mention that the three HMI strategies are not isolated from each other. This is highlighted in Fig. 4.4 by arrows between the strategies. It can be assumed that a vehicle has assistance systems, which cover all three HMI strategies. For example, Fig. 4.4 shows a transfer from the HMI strategy “Lateral and longitudinal control” to the “Warnings and interventions” strategy. This is the case when the driver is driving through a narrow road with parked vehicles on both sides and is supported in the lateral guidance by a constriction assistance. Then, a vehicle is suddenly entering the road out from a parking spot. As a result, a “comfortable” situation has become a “safety-critical” situation and the system should hand over the control to the driver, e. g. in order to brake. The design of such safety-critical HMI has completely different requirements compared to HMIs of continual lateral guidance control systems. In such cases, user-oriented and integrative HMI concepts are necessary, which filter and prioritize the different HMIs optimal so the driver can understand and follow the system behaviour and can appropriately react.

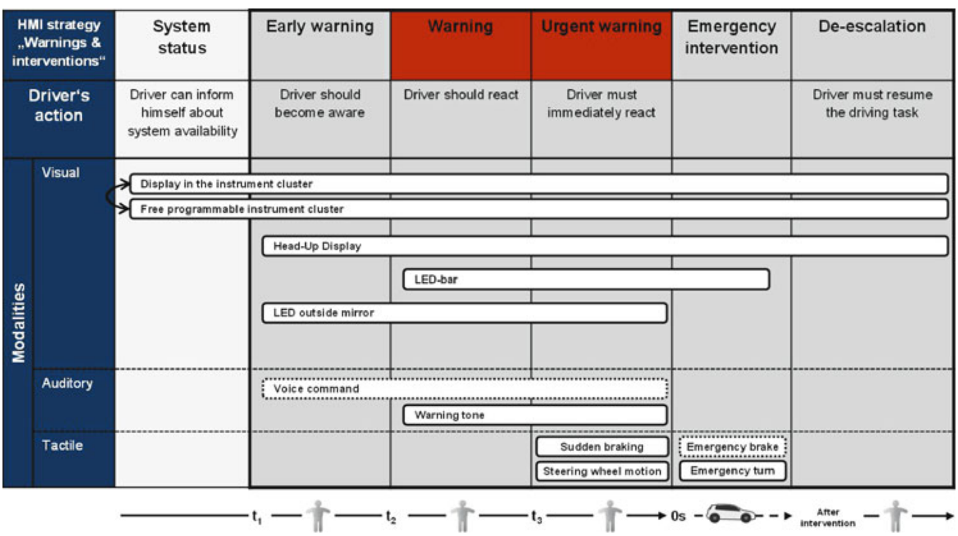

Fig. 4.5 Scheme of HMI concepts for the HMI strategy “Warnings and interventions”

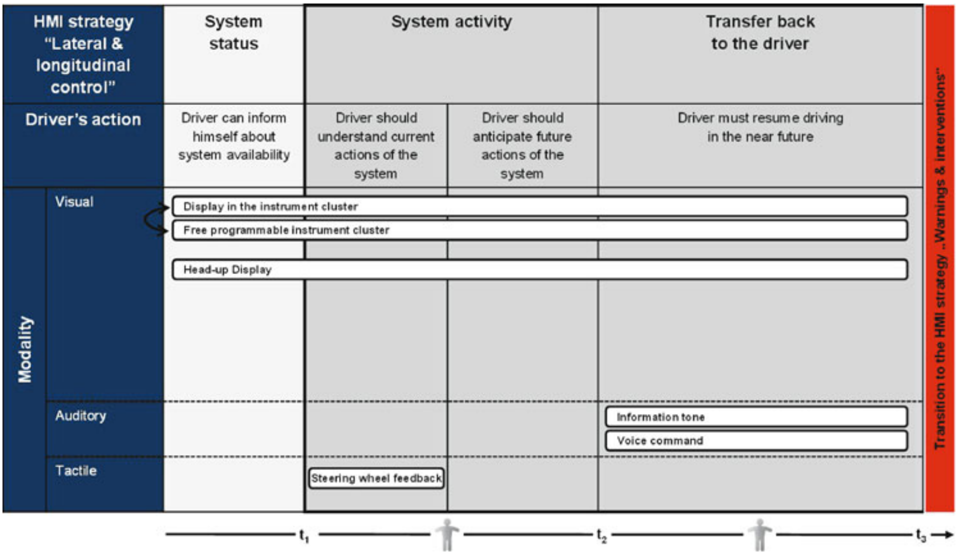

Fig. 4.6 Scheme of HMI concepts for the HMI strategy "Lateral and longitudinal control"

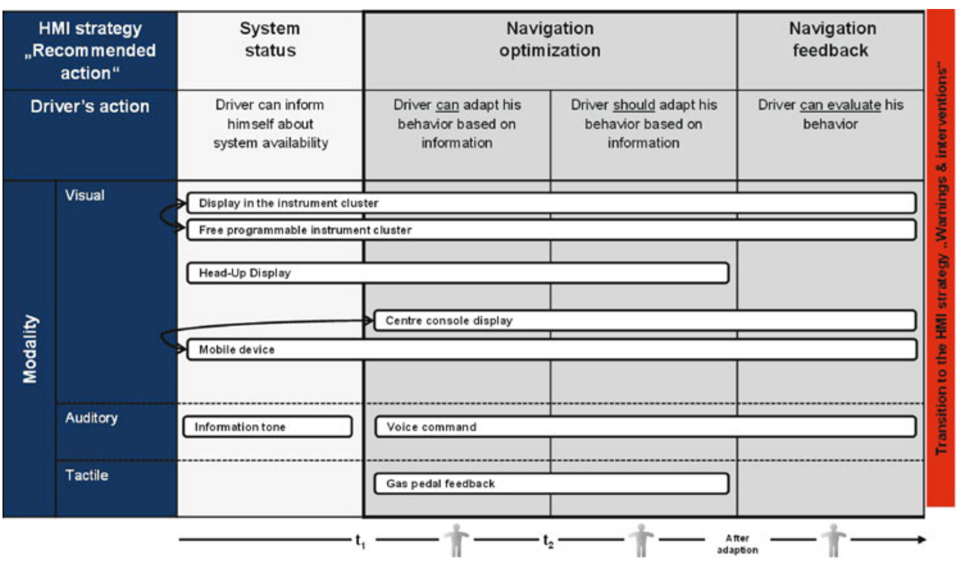

Fig. 4.7 Scheme of HMI concepts for the HMI strategy "Recommended action"

4.2.3 HMI Strategies

4.2.3.1 HMI Strategy – Warnings and Interventions

In the HMI strategy "Warnings and interventions" HMI concepts are designed especially for safety-critical situations, e. g. when a pedestrian is suddenly crossing the road without paying attention to the traffic. In such cases, assistance systems by interventions through the driver (braking and steering) or by the application (warning, steering, locking the accelerator) are developed to avoid a potential collision or at least mitigate the consequences of an unavoidable collision. With regard to the action-oriented HMI concepts of such assistance systems, the following driver's actions are differed in the HMI tool kit in the UR:BAN project:

(1) The driver should make an evasive manoeuvre as directed or rather not steer,
(2) The driver should make an emergency braking, or rather should not accelerate,
(3) Combination of (1) and (2).

The following selection of applications were explored in the HMI strategy "Warnings and interventions" within the UR:BAN project:

- Collision avoidance by autonomous evasive manoeuver and braking,
- Protection of vulnerable road users by turning and crossing assistance,
- Emergency vehicle warnings and traffic jam end warnings.

In Fig. 4.5 the scheme of HMI concepts for the HMI strategy "Warnings and interventions" is shown. The scheme is divided into three modalities: 1) visual, 2) auditory, and 3) tactile. It also shows a chronology of desired actions from the driver in order to avoid a potential collision in a safety-critical situation. The stages present the criticalness of events as a warning cascade. With each stage a higher driver's action is pursued. On the basis of research studies and intensive discussions of the HMI partners, information and warnings of the different HMI components are related to each stage. The aim is to use the appropriate HMI components to achieve the desired driver's action. For example, in an early stage the main aim is to inform the driver well in advance, e. g. with a screen in the instrument cluster display, that a potential critical situation is approaching. If the driver does not react, in the next stage the aim is to warn the driver so that he/she adapts his/her behaviour to the critical situation, e. g. using a warning screen in the instrument cluster display with an additional warning tone. If a safety-critical situation is so unexpected, e. g. a pedestrian is suddenly entering the road, then an intervention of an assistance system is necessary to avoid the potential collision or at least mitigate the consequences of the collision. However, it should be noted that the next level of escalation can be avoided by the correct driver's action. Fig. 4.5 shows the organization of the relevant HMI components in the HMI strategy "Warnings and interventions". The structure of the scheme is also used for the HMI strategy "Lateral and longitudinal control" and "Recommended action" with adaptive driver's actions.

The HMI strategy “Warnings and interventions” comprises one system stage and five stages of a warning cascade. In the “system status”, the driver can inform himself/herself about the system availability. The 1st stage of the warning cascade contains the “early warning”. The aim is that the driver should become aware of the driving task and might perceive the danger well in advance. This can be realised by different HMI components, e. g. with a display in the instrument cluster/free programmable instrument cluster or head-up display (HUD). With regard to the time horizon, early warnings are desired by the driver 2.5 s and longer in advance. Nevertheless, it can be assumed that such early warnings are very limited or not yet possible especially in urban areas.

In the 2nd stage “warning”, the driver should react and make a conscious decision for a reaction (e. g. braking, steering, or braking and steering). The warning should be given between a time to collision (TTC) approximately 2.5 s and 4.5 s before a potential collision could occur. In the next stage, the “urgent warning”, the driver must immediately react, which happens mainly reflexive as the driver has no time to weigh different alternatives of actions. Here, the warning should be given between a TTC of 4.5 s and 0.9 s in advance to the driver.

The emergency intervention is the 4th stage of the warning cascade and includes the short-term takeover of the driving task by the vehicle, both in lateral and/or longitudinal control. In such cases, the aim is that the driver gets information about the intervention already in the “urgent warning” stage. The last stage then applies the “de-escalation” stage with the aim that the driver must resume the driving task.

For the visual communication of information and warnings, displays near the driver are recommended, such as the display in the instrument cluster, free programmable instrument cluster, HUD, LED-bar, and LED-outside mirror. The free programmable instrument cluster can be seen as an alternative to the traditional display in the instrument cluster. As shown in Fig. 4.5, the instrument cluster display is highly valued on the visual level in order to achieve the different driver’s action. In the HUD today redundant information can be displayed. The LED-bar should be used primarily as a display element so the driver reacts immediately. This can be supported by a warning tone in the “warning” and “urgent warning” stage. However, taking the challenges of urban area with acoustic variety into account, warning tones should only be used in these stages and not escalate. A warning displayed in the centre console display is not recommended. The voice command for early warnings, warnings, and urgent warnings is framed with dashed lines as this HMI component can be a helpful output media in safety-critical situations. However, as research in this field is still in the beginning this cannot be clearly recommended. The HMI components such as sudden braking and steering wheel motion as well as emergency brake and turn are rather recommended in the later stages (“urgent warning” and “emergency intervention”).

4.2.3.2 HMI Strategy – Lateral and Longitudinal Control

The HMI strategy “Lateral and longitudinal control” contains action-oriented HMI concepts in which the driver is continuously and safely supported in lateral and longitudinal vehicle control, e. g. within narrow roads and when changing lanes. With regard to the HMI concepts in this strategy, the following driver's actions are differentiated in the UR:BAN project:

(1) The driver should be supported in lateral control,
(2) The driver should be supported in longitudinal control,
(3) Combination of (1) and (2).

The following selection of applications were explored in the HMI strategy "Lateral and longitudinal control" within the UR:BAN project:

- Constriction assistant,
- Lane change assistant,
- Green wave assistant,
- Entrance and start assistant at intersections.

Fig. 4.6 shows the scheme of HMI concepts for the HMI strategy "Lateral and longitudinal control". Similar to the "Warnings and interventions" strategy (Fig. 4.5), the scheme divides the HMI components in three modalities and different stages of appropriate driver's action. In contrast to the "Warnings and interventions" strategy, the main aim here is that the driver has a comprehensive awareness and understanding of the continuous operation of the system. On the one hand, the driver should be informed about the current system activity. On the other hand the driver should anticipate future actions of the system in order to be prepared. In contrast to the HMI strategy "Warnings and interventions", the two system activity stages are not based on each other. Here, the time horizon is less important, rather the question: What information does the driver need to trust the system and assess it as comfortable?

After the system activity stages, the "transfer back to the driver" is mentioned. The main aim is that the driver must resume driving in the near future. Here, two takeover situations should be distinguished: the driver must resume 1) within a relaxed timeframe and 2) without a timeframe. In the first situation, the driver should be back in the driving loop within an uncritical timeframe. For example, with a false ACC without a vehicle ahead, the driver can resume driving within an uncritical timeframe. In the second situation, the driver must resume driving quickly because of a sudden system launch (e. g. due to occlusion). In the last case, the time of driver's reaction is decreasing as a potential collision might occur. As a result, the HMI strategy "Lateral and longitudinal control" is shifting into the HMI strategy "Warnings and interventions", so a potential collision can be avoided (Fig. 4.5). In this case, the HMI should illustrate the changing situation clearly to the driver.

As Fig. 4.6 shows, the communication of information about system activity is mainly recommended via visual HMI components, such as display in the instrument cluster, free programmable instrument cluster, and HUD. Here, the free programmable instrument cluster can be seen as an alternative to the traditional display in the instrument cluster. Additionally, the communication of system activity is possible with a steering wheel feedback. The presentation of such continuous information in the centre console display is not recommended. An information tone and voice commands can be appropriate in the resume stage, when the driver must resume driving in the near future. Similar to the HMI strategy "Warnings and interventions", the "system status" is included in the scheme. Here, the driver can inform himself/herself about the availability of the longitudinal and lateral control systems in the vehicle.

4.2.3.3 HMI Strategy – Recommended Action

The HMI strategy "Recommended action" contains HMI concepts of assistance systems, which support the driver in his/her route selection regarding optimal traffic flow and energy-efficient driving. As such assistance systems support the driver in longitudinal guidance without active system intervention, the information of the assistance system is only given as recommendation, e. g. speed recommendations. With regard to the user-oriented HMI concepts, the following driver's actions are differentiated in the UR:BAN project:

(1) The driver should select the optimal route.
(2) The driver should use the optimal flow with the traffic.
(3) Combination of (1) and (2).

The following selection of applications are explored in the HMI strategy "Recommended action" within the UR:BAN project:

- Energy-efficient navigation,
- Intersection area view,
- Speed recommendation.

In Fig. 4.7, the scheme of HMI concepts for the HMI strategy "Recommended action" is shown. Similar to the other two HMI strategies (Figs. 4.5 and 4.6), the scheme is divided into the different modalities (visual, auditory, tactile) and different stages of driver's action. Here, the aim is to provide the driver detailed and advanced route information in order to optimize the longitudinal guidance without any active system intervention. Therefore, two driver's actions are distinguished: (1) advanced navigation information and (2) concrete recommended action regarding traffic- and energy-efficient driving. In the first case, the driver *can* adapt his/her behaviour based on the information and no negative consequences occur. In the second case, the driver *should* adapt his/her behaviour. Additionally, the driver gets feedback concerning his/her driving behaviour. This navigation feedback is mainly given via visual HMI components, e. g. centre console display and display in the instrument cluster. Here, the driver can evaluate his/her behaviour.

With regard to the prioritized HMI components, the centre console display, the display in the instrument cluster, and HUD are seen as the best solutions to present recommended actions. The mobile device can be seen as an alternative for the display in the centre console. Feedback from the gas pedal complements the visual HMI components and enables the driver to keep an optimal speed corridor. Similar to the HMI strategy "Warnings and interventions" and "Lateral and longitudinal control" (Figs. 4.5 and 4.6), the "system status" is also included in the scheme so the driver can inform himself/herself about the system availability. Furthermore, in the "Recommended action" HMI strategy a transfer to the strategy "Warnings and interventions" is also provided.

4.2.4 Design Guidelines

The third pillar of the HMI tool kit (Fig. 4.3) includes the design requirements of urban HMI concepts for the three HMI strategies (Sect. 4.2.3). These requirements define generic design recommendations of HMI concepts for safe, comfortable, and energy-efficient driving in urban areas and clarify how information and warnings should be displayed and positioned to the driver.

In the project, three challenges for the design of the different HMI concepts of the UR:BAN applications were defined:

(1) The design recommendations should be used cross-functional and for all UR:BAN partners. This is done to increase recognition of the different HMI concepts within the UR:BAN project.
(2) The design recommendations contain HMI guidelines based on valid findings and statements for action-oriented HMI concepts specifically for the urban area.
(3) The design recommendations contain HMI guidelines according the HMI components available in the vehicle.

The qualification of the HMI components for the three HMI strategies (Fig. 4.5, 4.6 and 4.7) and the design guidelines were defined by different SWOT analyses and intensive discussions of the HMI partners. In Fig. 4.8, the design guidelines and generic challenges of urban HMI concepts are shown. A high learn value of the different HMI concepts is essential (1). Thus, the HMI concepts should indicate a clear driver's action (e. g. the driver should become aware, the driver should react), be simply designed, and follow a logical organization of the information (1a). This also implies that the information should be clearly organized to the HMI components and connected with the recommended driver's actions. Furthermore, the information should be presented with the same quality at the same display position. For example, warnings should not be presented in the centre console display.

In addition to the organization of information, a high consistency of the information can increase the learn value (1b). Clear warning cascades, unification of system status,

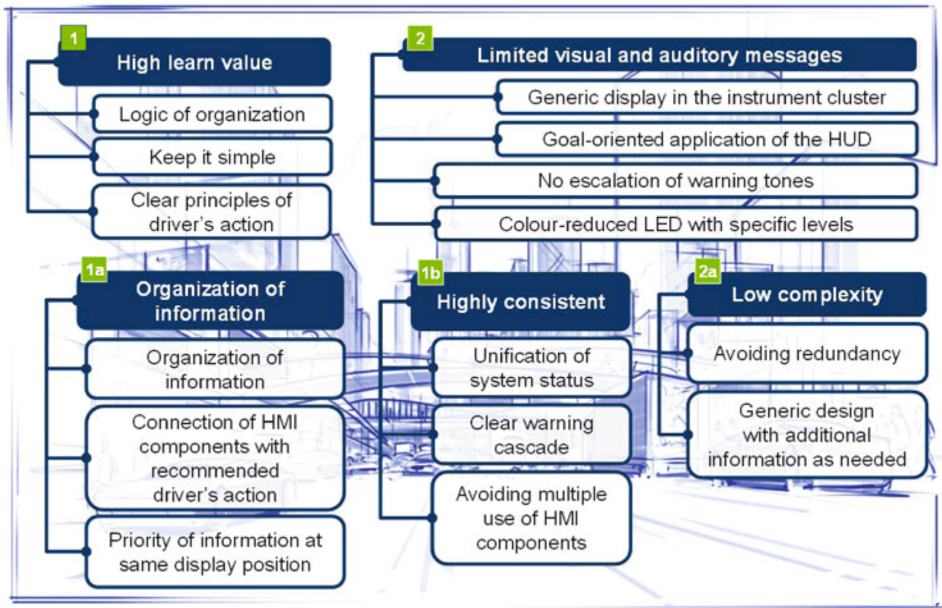

Fig. 4.8 Overview of design guidelines for urban HMI concepts

and avoiding the multiple use of HMI components (e. g. using the LED-bar for presenting both warnings and lateral and longitudinal guidance control) can contribute to a higher learn value.

Especially for the design of urban HMI concepts, it is also important to keep visual and auditory messages as limited as possible (2). This can be achieved through using generic HMI concepts with reduced information content and information mainly presented in the driver's field of view (e. g. in HUD). Furthermore, in safety-critical situations the warning cascade should be designed in discrete levels with reduced colour selection (mainly red and yellow). This also means that warning tones should not escalate. In combination of the limitation of messages, HMI concepts should also be designed simply and less complex (2a). Thus, redundancy of information should be avoided and a generic design of the HMI concepts with additional information as needed should be utilised.

These urban design guidelines are also supplemented by specific features of the HMI concepts. The features of information content and organization inside the vehicle cockpit are derived from different SWOT analyses. They contain detailed aspects regarding the organization of potential hazards, display of information status, control object, continual information of longitudinal and lateral control, and the application-related use of the different HMI components. Fig. 4.9 shows the results of the SWOT analyses regarding the organization of the information and warnings inside the vehicle.

In addition to Fig. 4.9, each HMI component is documented in detail regarding generic design recommendations. Numerous literature reviews, research studies conducted in the

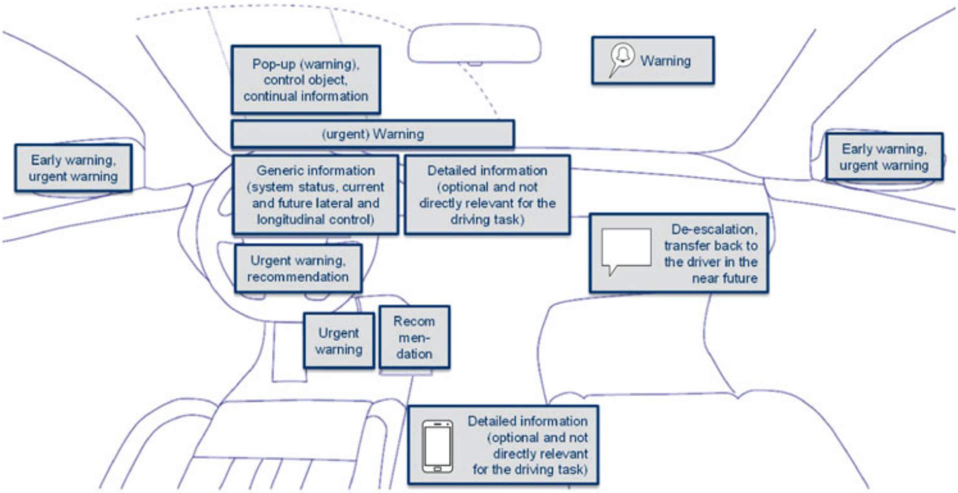

Fig. 4.9 Concept-specific design guidelines in the vehicle cockpit

UR:BAN project, and intensive discussions between the HMI partners are the basis for this input. Figs. 4.10 and 4.11 show an example of the design recommendations for the display in the instrument cluster for the HMI strategy "Warnings and interventions". The design recommendations are also described for (1) HUD, (2) LED-bar, (3) LED outside mirror, (4) centre console display, (5) mobile device, (6) warning tone, (7) voice command, (8) gas pedal feedback, (9) steering wheel feedback, and (10) sudden braking. Here, each

Display des Kombiinstruments		Warnung & Eingriff
Warnung & Eingriff	**Zielsetzung der MMI Komponente**	**Inhalt der MMI Komponente**
	• Übermittlung von aktuellen Systemzuständen, von Handlungsaufforderungen sowie Übernahmeaufgaben der MMI Strategie "Warnung & Eingriff" (alle 6 Stufen). • Liegt eine akute Kollisionsgefahr vor, sollte der Fahrer aufmerksam werden und reagieren können. Das Kombidisplay kann dabei die Richtung der Gefährdung visualisieren. • Neben der Kollisionsgefahr erfolgt eine Aktivierung der Früh- bzw. Akutwarnung auch bei Funktionen der Geschwindigkeitsanpassung, z.B. bei zu schneller Annäherung an eine Kreuzung. • Das Kombidisplay ist Teil der Eskalationsstrategie. • Als Ergänzung zu den Status-Icons kann sich der Fahrer jederzeit über die Verfügbarkeit des Systems im Kombidisplay informieren.	• Eine generische FAS-Anzeige im Kombidisplay mit EGO-Fahrzeug und einem Ring um das EGO-Fahrzeug herum; wodurch die Verortung der Gefahr dargestellt wird. • Anzeige von Warnungen (von Frühwarnung über Warnung bis zur Akutwarnung und Noteingriff); Anzeige der Deeskalationsmeldungen, Anzeige des Systemstatus (System an/aus/Verfügbarkeit). • Bei Frühwarnung, wie z.B. Annäherung eines Sondereinsatzfahrzeuges in einer Kreuzungssituation, erfolgt eine Anzeige, damit der Fahrer aufmerksam ist; Generelle Anzeige des Systemzustandes von aktiv bzw. nicht aktiv. • Bei Warnung erfolgt eine Warnanzeige, damit der Fahrer handelt; hier erfolgt keine Vermittlung des Systemzustandes. • Bei Akutwarnung erfolgt eine Warnanzeige, damit der Fahrer sofort handelt; hier erfolgt keine Vermittlung des Systemzustandes. • Bei Noteingriffen informiert eine Anzeige im Kombidisplay über die Durchführung des Noteingriffs. • Bei Deeskalationsmeldungen vermittelt eine Anzeige im Kombidisplay, dass der Fahrer wieder übernehmen muss.

Fig. 4.10 Overview of the aim and contents for the display in the instrument cluster for the HMI strategy "Warnings and interventions" (in German)

Display des Kombiinstruments		Warnung & Eingriff
Warnung & Eingriff	**Allgemeine Gestaltungsempfehlungen**	**Referenzen**
	• Das Kombidisplay als Anzeigemedium dient zur Darstellung komplexer fahrrelevanter Inhalte (z.B. Frühwarnungen und Warnungen). Die Komplexität im Vergleich zur Mittelkonsole ist jedoch geringer.	Winner, H., Hakuli, S. & Wolf, G. (2012)
	• Das Kombidisplay ist eine notwendige Anzeige der Warnung, auch mit dem Wissen, dass diese in der urbanen, akuten Warnsituation nicht wahrgenommen wird, daher ist eine Vernetzung mit weiteren MMI-Komponenten (z.B. Warnton) zu empfehlen.	Adell, E., Varhelyi, A., Fontana, M. D. et al. (2008)
	• Der Fahrer kann sich bei Bedarf im Kombidisplay informieren. Informationen können im Kombidisplay im Vergleich zum HUD leichter ignoriert werden.	Expertenrunde, AUDI-Studie im Rahmen von UR:BAN
	• Die generische FAS-Anzeige sollte sich in zentraler Position im Kombidisplay befinden.	Expertenrunde; Muigg, A. (2009)
	• Das Ego-Fahrzeug in der generischen FAS-Anzeige sollte sich mittig in der Anzeige befinden. Bei Bedarf kann in die Anzeige gezoomt werden.	Burghardt, S. (2009)
	• Die Darstellung der FAS-Anzeige sollte so generisch wie möglich erfolgen, d.h. Reduzierung des Informationsgehaltes von visuellen Warnungen.	Belotti, F., De Gloria, A., Poggi, A., Adreone, L. Damiani, S. u. Knoll, P. (2004); Maier, K. (2014); Burghardt, S. (2009) ; UMTR, Driver Interface Group (2012); Werneke, J., Wäller, C., Gonter, M., & Rhede, J. (2011)
	• Die Nutzung von Symbolen ist der Verwendung von Wörtern/Texten vorzuziehen.	Kebeck, G., Cieler, St. u. Pohlmann, St. (1997)
	• Die Positionierung der Regelobjekte sollte vor dem Ego-Fahrzeug erfolgen.	Burghardt, S. (2009); Reisemann, M. & Spiegel, G. (2002)
	• Textuelle Informationen sollten sich immer im oberen Bereich der Anzeige befinden. Der Informationsgehalt sollte jedoch in kritischen Situationen eher gering gehalten werden.	Maier, K. (2014); Reisemann, M. & Spiegel, G. (2002)
	• Die Bereiche links und rechts bzw. ober- und unterhalb vom Ego-Fahrzeug sind für Anzeigen von Objekten nutzbar.	Expertenrunde; Burghardt, S. (2009)
	• Der untere Bereich der FAS-Anzeige sollte genutzt werden, um den Systemzusatnd der warnenden/eingreifenden Systeme (an-aktiv, an-passiv, aus) darzustellen.	Maier, K. (2014),
	• Eine Anzeige der Statusinformationen der Systeme sollte innerhalb der Grafik (z.B. Zustände wie aus, an-aktiv, an-passiv) erfolgen.	Expertenrunde
	• Warnungensollten Kombidisplay dargestellt werden und ggf. im HUD ergänzt werden. Dies sollte jedoch funktionsspezifisch betrachtet werden.	Expertenrunde
	• Die Position des Warnelements sollte mit dem Warninhalt verknüpft werden.	Schartner, A.(2013)
	• Informationen bezüglich Ursache und Grund für eine Warnung sind für eine stärkere und effektivere Verhaltensanpassung des Fahrers nötig.	Werneke, J., Wäller, C., Gonter, M., & Rhede, J. (2011)
	• Für Warnungen im Kombiinstrument sollten Popups verwendet werden.	DIN EN ISO 15005 (2002); National Highway Traffic Safety Administration (NHTSA), (2007)
	• Die Farben rot und gelb sind für Warnungen vorbehalten. Eine Ausnahme bildet hier die HMI-Gestaltung der Ampelassistenz. Die farbliche Gestaltung der Ampelphasen sollte beibehalten werden.	Exptertenrunde; Maier, K. (2014),
	• Das Kombidisplay dient als Erklärung für die akustischen und haptischen Warnungen.	Kebeck, G., Cieler, St. u. Pohlmann, St. (1997); National Highway Traffic Safety Administration (NHTSA), (2007).
	• Der Warnton sollte mit dem Kombidisplay synchronisiert sein.	Expertenrunde; Maier, K. (2014),
	• Neben Kollisionswarnungen sollten Informationen über Geschwindigkeitsüberschreitung im Kombidisplay angezeigt werden.	Götze, M. , Ruff, F. & Bengler, K. (2015)
	• In der Deeskalationsphase ist eine Anzeige im Kombidisplay als Erklärung für den Fahrer über den durchgeführten Eingriff notwendig.	Expertenrunde
	• Die Platzierung des Kombidisplays sollte so nahe wie möglich an der normalen Sichtlinie des Fahrers erfolgen.	Belotti, F., De Gloria, A., Poggi, A., Adreone, L. Damiani, S. u. Knoll, P. (2004); European_Commission (2006); Wittman, M., Kiss, M., Gugg, P., Steffen, A., Fink., Pöppel, E. et al. (2006)

Fig. 4.11 Overview of the design recommendations and its references for the display in the instrument cluster for the HMI strategy "Warnings and interventions" (in German)

HMI component is considered in detail for the specific HMI strategy. In addition to the aim and content of the HMI component in the HMI strategy (Fig. 4.10), the design recommendations and its references are listed (Fig. 4.11). The detailed design guidelines are compiled in the fourth milestone report of the UR:BAN project [6].

4.3 Applications of Urban HMI Concepts

For the HMI design of the different assistance systems considered in the UR:BAN project, the HMI partners developed a generic and integrative HMI concept for the display in the instrument cluster (Fig. 4.12). The aim of the generic HMI concept is to aggregate relevant information and warnings of different complex systems in order to increase transparency by the driver. In addition to visual output media, the HMI concept contains auditory and tactile HMI components. Fig. 4.12 shows the generic HMI concept for the display in the instrument cluster. Here, it is displayed in the design of the Volkswagen AG.

The HMI concept shows the longitudinal and lateral control systems as well as the warning systems of a vehicle (e. g. early warnings, collision warnings, and emergency braking). As illustrated in Fig. 4.12, in the middle of the HMI concept the ego-vehicle, positioned on a road, is shown. A warning circle surrounds the vehicle. The aim of the warning circle is to visualise the direction of a potential hazard (e. g. an approaching ambulance from the back). In front of the ego-vehicle a white obelisk symbolizes the longitudinal guidance control, like ACC. Here, the driver is shown the current and the desired distance (coloured in blue). On top of the obelisk, the control object for the longitudinal guidance control is presented. At the left and right side of the ego-vehicle white arrows

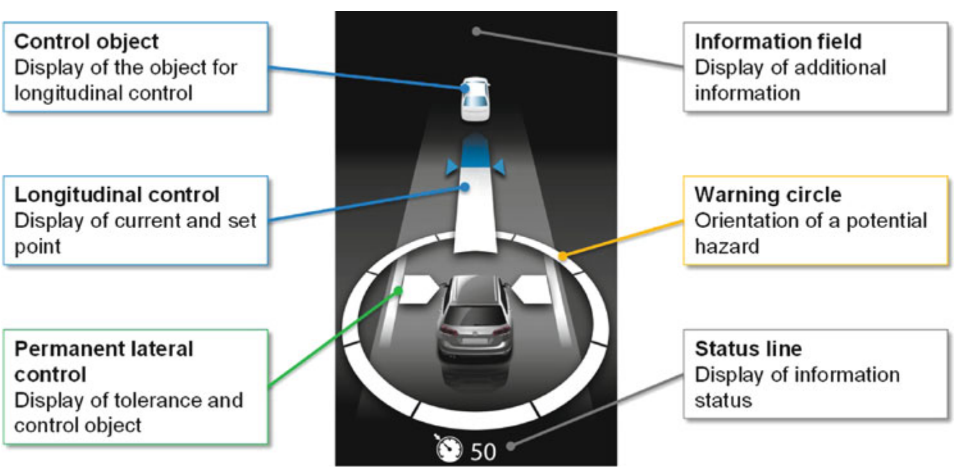

Fig. 4.12 Generic and integrative HMI concept presented in the display in the instrument cluster in the design of the Volkswagen AG

illustrate the permanent lateral guidance control. It displays the tolerance of the lateral guidance by changing the size and width of the arrows. In the upper area of the display an information field can display additional information, e. g. braking, emergency braking. The status line at the bottom of the display presents current status information, e. g. desired speed of the ACC. In the following, the HMI concepts of the constriction assistance and the collision avoidance system by autonomous evasive manoeuvres are explained.

Constriction Assistance

The aim of the constriction assistance, developed in the subproject "Safe Lateral and Longitudinal Vehicle Control in Cities" (translated "Sichere Quer- und Längsführung in der Stadt"), is to support the driver by continual system interventions when driving through construction zones, narrow roads, and passing stationary obstacles and parked vehicles in urban areas. In addition, this assistance system warns the driver for a too narrow road, which is not possible to pass (Fig. 4.13). In the UR:BAN project the HMI concepts of the constriction assistance were developed for the following scenarios: (1) constriction by one-sided parked vehicles and pedestrians, (2) constriction by parked vehicles, pedestrians, and road curb, and (3) constriction by stationary obstacles on the right and left edge of the road. Fig. 4.14 shows the chronology of the HMI screens presented in the display in the instrument cluster when it is not possible to pass the constriction because of a pedestrian crossing the road. The HMI screens are displayed in the design of the Volkswagen AG.

Fig. 4.14 shows the HMI concepts presented in the instrument cluster when the driver is supported by longitudinal and lateral guidance control while approaching and passing through a constriction. Ongoing road lanes inside and outside the warning circle symbolize the approaching and passing through a constriction (screen b–d). If it is not possible to pass the constriction, e. g. due to a crossing pedestrian, a pop-up "No pass" is presented to the driver (screen e). To drive on, the driver has to confirm by pressing "RESUME" or accelerate (screen f). As a result of different constriction widths in urban areas, in

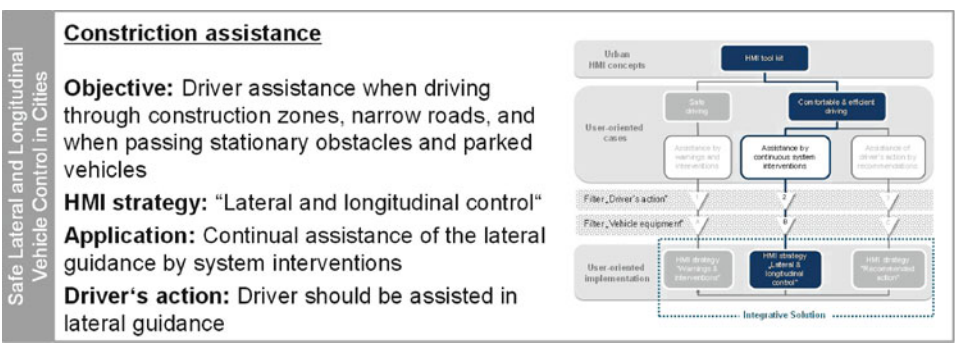

Fig. 4.13 Classification of the constriction assistance into the HMI path structure of the HMI tool kit

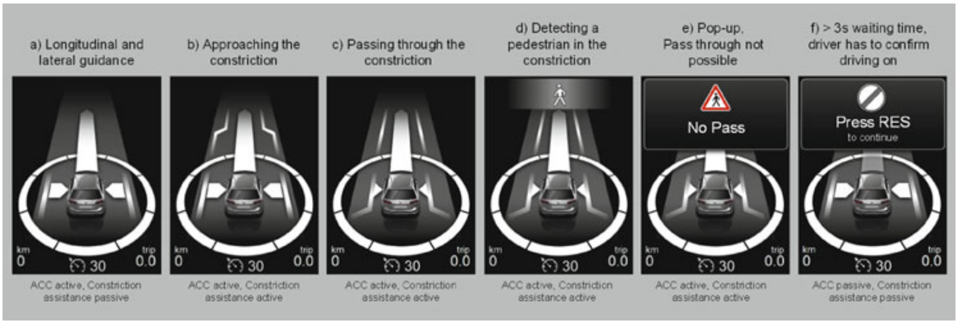

Fig. 4.14 HMI concept of the constriction assistance presented in the display in the instrument cluster in the Volkswagen AG design

addition to lateral control, the driver is also supported in his/her longitudinal guidance. For example, passing through a very narrow road can be very stressful and unpleasant for the driver. In this case, the velocity is adapted by the longitudinal control system (ACC) appropriate to the constriction width. The longitudinal guidance control is then illustrated with the white obelisk in front of the ego-vehicle and the constriction traffic sign as control object. But this is not shown in Fig. 4.14.

Collision Avoidance by Autonomous Evasive Manoeuvre

In safety-critical situations, e. g. due to a sudden obstacle on the road, the aim of the collision avoidance system is to avoid a potential collision by autonomous evasive manoeuvres (Fig. 4.15). The application can help to detect road users (e. g. pedestrians, crossing vehicles) surrounding the ego-vehicle and the road infrastructure. The assistance system contains situations, which are so unexpected that an emergency braking is not sufficient to avoid the potential collision. In the HMI tool kit (Fig. 4.4), the collision avoidance assis-

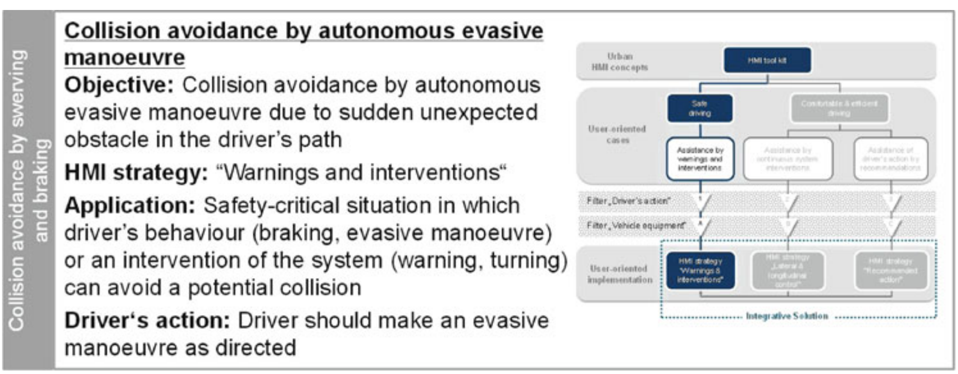

Fig. 4.15 Classification of the collision avoidance system into the HMI path structure of the HMI tool kit

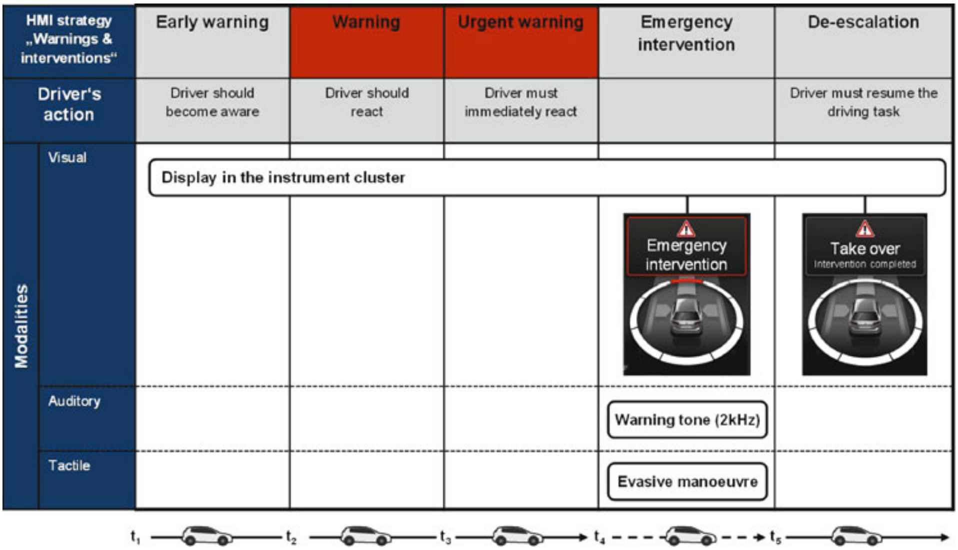

Fig. 4.16 HMI concept of the collision avoidance system by autonomous evasive manoeuvre presented in the display in the instrument cluster in the Volkswagen AG design

tance belongs to the HMI strategy “Warnings and interventions” and was developed in the subproject “Collision Avoidance by Swerving and Braking” (translated “Kollisionsvermeidung durch Ausweichen und Bremsen”). Fig. 4.16 shows the chronology of the HMI screens presented in the display in the instrument cluster in the design of the Volkswagen AG.

As shown in Fig. 4.16, a warning tone is paired with a pop-up, which signalizes the “emergency intervention” stage when the system intervention begins. In contrast to an emergency braking system, no red bright LED-bar is used. As the system is doing an autonomous evasive manoeuvre, the aim is to involve the driver as little as possible during the intervention. After the intervention, the driver resumes the driving task. In this de-escalation stage another pop-up appears, which signalizes the takeover request to the driver (“Take over – Intervention completed”). Detailed information about a research study with the aim to examine the effectiveness and driver acceptance of different collision avoidance systems in a safety-critical situation are described in Chap. 5.

4.4 Conclusion

The objective of the UR:BAN project was to develop and implement intelligent driver assistance and traffic management systems, which contribute to improving safety, comfort, and efficiency driving in urban areas. With the challenges of urban driving and potential driver’s overload with the increasing number of assistance systems, one aim of the project was to design user-oriented, integrative display and operating concepts of current and future assistance systems. Consequently, the novel and cross-functional "HMI tool kit" was developed.

The HMI tool kit enables the systematic derivation of action-oriented HMI concepts for the variety of assistance systems in urban areas. According to the urban traffic situations, the HMI tool kit provides input to how system information should be filtered and prioritized to the driver and how the preferred driver's action can be achieved by the selection of suitable HMI components (e. g. display in the instrument cluster, warnings or sounds). Furthermore, strategies for timing combinatorics and phased escalation of sensory input modes to the driver (e. g. visual, auditory, and tactile) are also included in the tool kit. Thus, by means of the HMI tool kit it is possible that the driver is warned adequate in safety-critical situations and develops also a sufficient understanding for continuous system interventions or advanced navigation recommendations. For example, hazards not visible to the driver can be indicated by the use of tactile feedback on the gas pedal and/or steering wheel. This feedback not only reduces risks, but leads to an anticipatory driving style that potentially reduces stress. In particular for trucks, it also contributes to significant decreases in fuel consumption and emissions. However, it is important to mention that through technical future trends in the next years and decades, the prioritization of suitable HMI components presented here might be shifted. For example, for the HMI strategy "Warnings and interventions" augmentation of information in the front and side mirrors might get more and more important in the following years. Overall, the assistance systems developed in the UR:BAN project and its HMI concepts deviated from the HMI tool kit contribute to an anticipatory driving style, mitigate safety-critical situations, and shows the potential to improve stress-free and low-emission driving in urban traffic.

Acknowledgement
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HMI Strategy – Warnings and Interventions

5

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5.1 Background

Within the HMI tool kit (see Fig. 4.4), the path "Safe driving" addresses assistance in safety-critical situations regarding warnings and interventions. These may have different aims, the most important being to reduce speed, to brake strongly or to perform an evasive manoeuvre. The vehicle's equipment has to be taken into account when designing warnings and interventions for these aims. With this in mind, the resulting HMI strategy "Warnings and interventions" (see Fig. 4.5) is meant for situations which will become critical or even lead to an accident if the driver does not react. Whenever possible, "*early warnings*" are given at a time-point which enables the driver to pay more attention to the driving task and to prevent the situation from becoming critical. To this aim, a reduction of speed may suffice. These kinds of "*early warnings*" are well understood and accepted,

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as the studies of [1] and [2] have shown. For such "*early warnings*", these two studies have also provided information about the best timing of these warnings with regard to the distance of the critical object. In urban situations like intersections these "*early warnings*" may be very efficient to prevent collisions, as the study of [3] has shown. In this study, an "*early warning*" when approaching an intersection was even more efficient than "*warnings*" or "*urgent warnings*".

The work within the UR:BAN project focuses on the later warning stages of the HMI strategy "Warnings and interventions" (see Fig. 4.5). A "*warning*" is given when a critical situation arises and the drivers should react to mitigate a potential danger. However, there is still sufficient time for them to understand the situation and modify their action plans accordingly. When the situation escalates and the drivers have to react immediately, an "*urgent warning*" is given (see Fig. 4.5 HMI tool kit "Warnings and interventions" strategy). In the first part of this chapter the studies of the Technische Universität Braunschweig have explored the best way to design and present these kinds of warnings using a combination of the head-up display and acoustical signals. The main question was how to design the "*warning*" and "*urgent warning*" in such a way that drivers can easily distinguish the different meanings of the warnings and act accordingly. Additionally, the integration of this warning concept with other information, which may also be presented in the head-up display, was examined. This chapter ends with practical design recommendations for these two warning stages.

Distraction is one of the main reasons why drivers need these warnings and interventions. The second part of this chapter deals with detecting visually distracted drivers and how to adapt the warnings to these situations. The authors of the Robert Bosch GmbH provide two systems using different available components in accordance with the idea of the HMI tool kit. In three studies these concepts have been developed, refined and evaluated. The authors show that both concepts are well able to reduce distraction of the drivers and will thus increase traffic safety.

While the focus of these first two research teams was mainly on situations which the driver can manage safely by braking. However, in some situations only an evasive manoeuvre can prevent a crash. This is addressed by the filter "Driver's action" in the HMI tool kit (see Fig. 4.4). In the studies of Technische Universität Braunschweig, it was not possible to elicit a steering reaction of the drivers by "*warnings*" or "*urgent warnings*". The last part of the chapter describes the approach of the Volkswagen AG to support the driver in the evasive manoeuvre by very short autonomous steering actions of the vehicle (*emergency intervention*). The main question with this strategy is how to give feedback to the drivers in this situation and how to enable them to safely take over and keep on driving after the evasive manoeuvre.

These different approaches for the HMI strategy "Warnings and interventions" (see Fig. 4.5) are described in detail in the following sections.

5.2 Concepts for Warnings and Urgent Warnings (Technische Universität Braunschweig)

The following studies address two warning stages of the HMI strategy "Warnings and interventions", which require different actions of the driver:

1. The "*warning*" is given when a critical situation arises and the driver should react to mitigate a potential danger. However, there is still sufficient time to understand the situation and modify the action plans accordingly.
2. When the situation escalates and the driver has to react immediately, an "*urgent warning*" is given.

This warning concept has two implications:

- There really are critical traffic situations which give the driver more or less time to react. Depending on the kind of situation, the respective warning stage is given.
- The driver has to understand the difference between the two warning stages and react in the manner required by it.

Within the context of UR:BAN, the aim was to identify typical critical situations and map these to the two warning stages. The first identification step focused on accident statistics. The information about relevant situations was then used to build and evaluate critical situations in the driving simulator of the Technische Universität Braunschweig. With regard to the first implication described above, the situations suited for *urgent warnings* should result in accidents if the drivers did not react immediately. In contrast, in situations suited for *warnings*, a slower and more moderate reaction should be sufficient to prevent the situations from becoming critical. This process of selection and evaluation is described in the first part of this chapter. The results of these simulator studies are then used to derive warning concepts.

These were then tested in several further simulator studies with younger and older drivers. The second part gives an overview about the developed concepts, the conducted evaluation studies and concludes with recommendations for the design of *warnings* and *urgent warnings*.

5.2.1 Identification and Evaluation of Critical Situations in the Urban Context (Study 1 and 2)

The aim of the first study was to provide a contribution to the understanding of the accident occurrence at intersections in urban areas. Table 5.1 shows the traffic accidents in the year 2011 in German urban areas [4]. These statistics were examined in order to find out which accident types occur the most and are the fatal ones. On the left side of the table,

Table 5.1 Traffic accidents in urban areas for Germany in 2011 [4]

Accident types	All accidents		Fatal accidents	
	N	%	N	%
Accidents while crossing	*56,873*	*27*	174	16
Rear-end accidents	*42,854*	*20*	92	8
Accidents while turning or entering	34,486	16	113	10
Other accidents	27,634	13	161	15
Single vehicle accidents	23,305	11	244	22
Accident with pedestrian crossing	16,459	8	*292*	*27*
Accidents with parked vehicles	8816	4	11	1
Total	*210,427*	*100*	*1087*	*100*

the percentage of different accident types can be found, whereas on the right side, the percentages of fatal accidents are shown.

Overall, accidents while crossing (entering or crossing the intersection and turning left or right) comprise 27% of all accidents. The second most frequent type of accident is the rear-end crash (20% of all accidents). When looking at fatal accidents, 27% are accidents with pedestrians crossing the street (for further information see [5, 6]).

According to this frequency distribution, the relevant traffic situations of these three accident types were examined in more detail. In a first step a driving simulator study with younger and older drivers, was conducted in order to develop and implement situations leading to accidents. For every situation, different aspects were varied (e. g. type of vulnerable road user, oncoming traffic) to find very critical scenarios. Fig. 5.1 gives an overview of the situations which the following studies were based on and also what warning stage they were designed for. An *urgent warning* was to be given when the situation was very critical. In situations being less critical merely a *warning* was to be presented.

The second driving simulator study then used these findings to develop warning concepts for both warning stages and evaluated them with sixty drivers. Firstly, the described situations were examined for the control group without a warning in order to show that the scenarios also differed from each other in various measured parameters. As Fig. 5.2 shows, the criticality of the scenarios was indeed perceived quite differently by the drivers. The first three scenarios (S1, S2, S3) were rated as being the most critical ones, followed by the S4 through S8 scenario. The number of accidents was also the highest in the three scenarios rated as being very critical (S1, S2, S3).

The analysis of the drivers' reactions supported this subjective evaluation. The brake reaction time was very short in these very critical scenarios; especially in S2 and S3 (see Fig. 5.3). While the situation in S1 was also rated rather critical, drivers had just started to turn left, were still driving relatively slowly and thus had more time to react, also resulting in less accidents than expected. The maximum braking value was largest in S2, in which their driving speed was quite high so that the situation required a really strong braking in order to prevent the collision with the pedestrian. The second strongest brake reaction

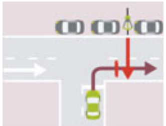
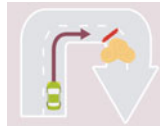
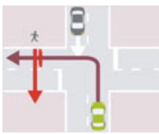
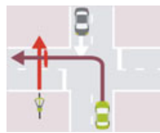
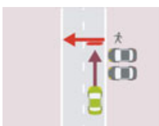
Scenarios intended for the W1) warning	S4		When turning right at a T-junction with oncoming traffic a bicyclist hidden by parking vehicles crosses the ego vehicle's path from left to right	S7		When driving straight ahead, a hay bale blocking the ego vehicle's path becomes visible after being hidden from driver's sight by a curve (evasive manoeuvre possible)
	S5		While following, a lead vehicle indicating a right turn at an intersection suddenly stops for a bicyclist crossing from left to right (evasive manoeuvre possible)	S8		When driving straight ahead, a hay bale blocking the ego vehicle's path becomes visible after being hidden from driver's sight by a hill
	S6		While following on a straight road without oncoming traffic, a lead vehicle suddenly brakes) without any warning or reason (evasive manoeuvre possible)			
Scenarios intended for the W2) urgent warning	S1		When turning left at an intersection with oncoming traffic, a pedestrian, emerging from a crowd at the farther end, crosses the ego vehicle's turning path	S3		When turning left at an intersection with oncoming traffic, a bicyclist crosses the ego vehicle's path from left to right
	S2		While driving straight ahead on a one-way road a pedestrian hidden behind parking vehicles crosses the ego vehicle's path from right to left (evasive manoeuvre possible)	S9		While driving straight ahead an oncoming traffic vehicle cuts the ego vehicle's path from left to right in order to park

Fig. 5.1 Overview of the situations implemented in the driving simulator in order to develop and evaluate warning concepts including which warning stage (*W1) warning* or *W2) urgent warning* (see Fig. 4.5) had to be presented first. Scenario S9 was added later starting with the study number 5 on older drivers

occurred in situation S5, where most of the drivers kept relatively large distances towards the leading vehicle and thus had some time to react. If they had to brake, however, strong brake reactions were needed. The less critical situations like S5 to S8 could be handled well with slower reactions and less strong braking (for further results see [7]).

To summarize, the simulator studies show that critical situations arising in urban traffic differ with regard to their criticality. Drivers adapt their reactions to these situations in order to avoid accidents. However, under certain circumstances, which were identified in the studies (e. g. not enough time to react accordingly), the spontaneous drivers' reactions were not for all drivers sufficient to avoid an accident or prevent the situation from becoming very critical. Thus, the results show a potential for warnings to improve traffic safety by supporting driver reactions. Moreover, the results support the idea of the HMI tool kit

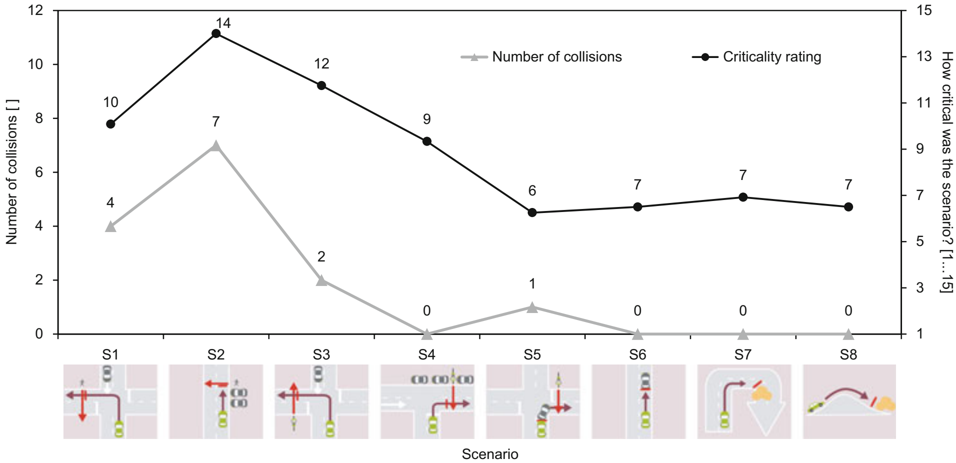


Fig. 5.2 Mean subjective ratings of the scenario criticality and number of collisions in the eight scenarios for study 2

(see Fig. 4.6) and its two different kinds of warnings since the drivers reacted differently in the various situations. In a less critical situation a *warning* (W1) should raise the attention of the drivers for a more critical situation might occur. In these situations a slight brake reaction would be sufficient to deescalate a less critical situation or even further to prevent a less critical situation from becoming a very critical one. Thus, in order to support the drivers' situation assessment a *warning* (W1) could be designed in a way, which enables the drivers to easily detect the relevant critical object. On the contrary, an *urgent warning*

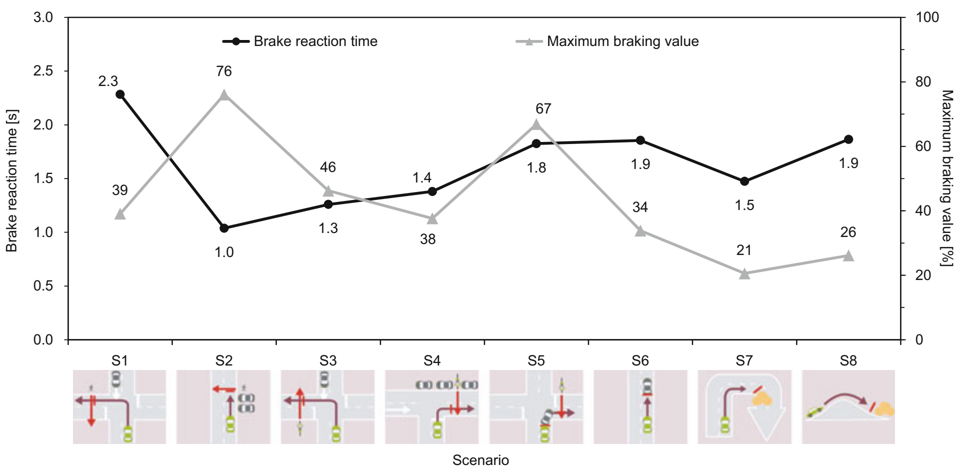


Fig. 5.3 Mean brake reaction time and mean maximum braking value in the eight scenarios for study 2

(W2) would be given in quite critical situations focussing on prompting fast and intense driver reactions. Summing up, a *warning* (W1) should elicit an evaluation of the situation and then an adequate reaction of the drivers. An *urgent warning* (W2) should trigger an emergency reaction, mostly braking but possibly also steering and avoiding critical objects. These were the basic ideas which were examined in the second part of the project and are described in the next chapter. The results and the critical scenarios from the first part described above (see Fig. 5.1) were used to test whether different warning concepts improved the reactions of the drivers and, thus, traffic safety.

5.2.2 Development and Evaluation of Concepts for Warnings and Urgent Warnings (Study 2–5)

The results described above support the idea of warning drivers in two stages as compared to a single general warning. In the first stage, a *warning* is supposed to allow drivers to evaluate the situation and give them more time to react. The driver reaction may be temperate and comfortable like releasing the gas pedal and braking moderately. The *urgent warning* should elicit either an emergency braking or an evasive manoeuvre. Drivers were to brake as fast and strong as possible. How to actually design the two warning stages so that drivers react accordingly was examined in two driving simulator studies with 60 younger (study 2) and 36 older drivers (study 3). The underlying question was how specific an attention-oriented *warning* and a reaction-oriented *urgent warning* have to be. Fig. 5.4 gives an overview about the study with the younger drivers describing the warning concepts, which were all projected into the windshield in form of a head-up display (HUD). For the *urgent warning*, a stop sign was used as a generic, well-known symbol of imminent danger (reaction generic, RG). As in some situations a steering reaction resulting in an evasive manoeuvre is more suited, a second warning type used a stop sign for braking and a cone with an arrow to evoke an evasive reaction as specific *urgent warning* (reaction specific, RS).

As can be seen in Fig. 5.4 with regard to the *warning*, a generic concept (attention generic, AG) used a caution sign (a red triangle with an exclamation mark meaning "Attention!"). A second design for the *warning* was meant to support the evaluation of the situation by providing a caution sign displaying specifically the currently relevant critical object (attention specific, AS), a pedestrian, a bicycle, a car or an obstacle (represented by a cone). These warning types were examined with five groups of drivers, comparing the different warning concepts to a control group without any warning assistance in order to evaluate the effectiveness of the different warning types. The number of collisions, the driving and gaze behaviour as well as the subjective ratings of the warning concept and the critical situations of younger and older drivers (no gaze behaviour recorded) was analysed. An extract of the data is presented in the following. For further information see [7–12].

As illustrated in Fig. 5.5, only a small amount of collisions occurred in the less critical scenarios as compared to the more critical scenarios. So again the situations differ in their

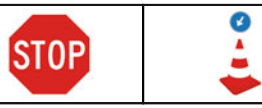
Warning type	Presentation in head-up display	Stage
1) Control (C)	No warning	
2) Attention generic (AG)		W1) warning
3) Attention specific (AS)		
4) Reaction generic (RG)		W2) urgent warning
5) Reaction specific (RS)		

Fig. 5.4 Overview about the different warning concepts assigned per group resulting in five groups of younger drivers in study 2

criticality. Yet, the number of collisions is so low in the less critical situations that they do not really allow to differentiate between the specificity of the *warning* (see Fig. 5.5a). On the contrary, a total of 49 collisions occurred in the rather critical situations. In these situations, the generic *urgent warning* was most effective with very few collisions (see Fig. 5.5b).

As Fig. 5.6a shows, the brake reaction time in the less critical scenarios was faster with both specificities of the *warning* than in the control group. However, both the generic and the specific *warning* resulted in the same average brake reaction time of about 1.3 s. In the

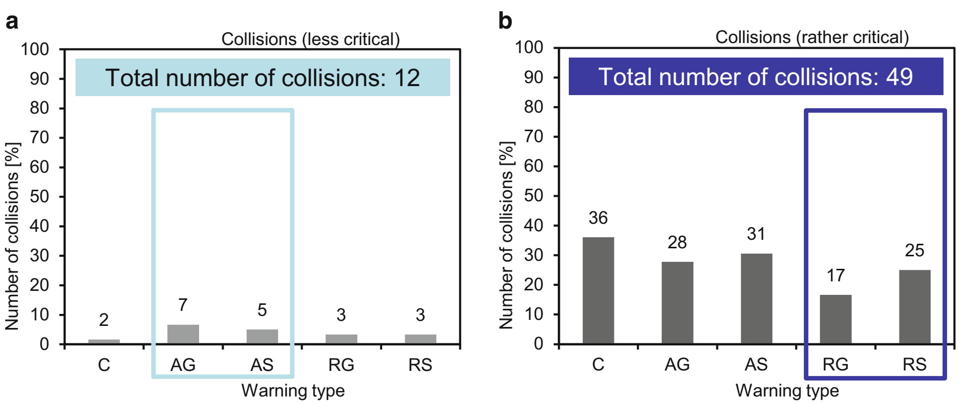


Fig. 5.5 Number of collisions for the younger drivers in the less (**a**) and rather critical (**b**) situations of study 2, framing the warning types which were should have matched the situation requirements the best

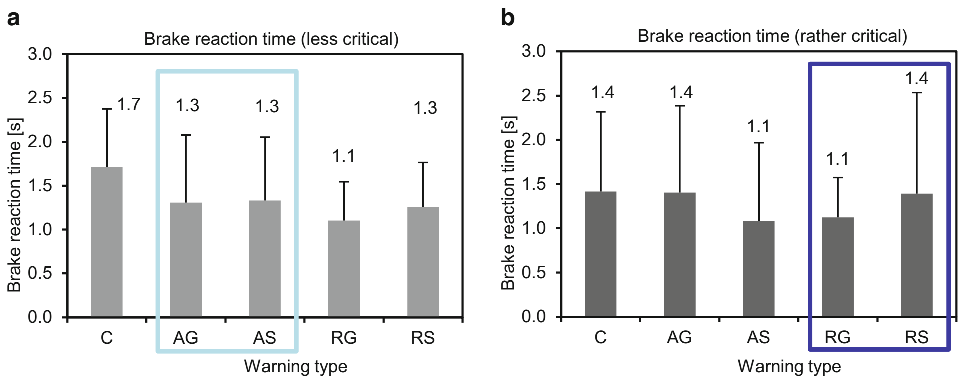


Fig. 5.6 Mean brake reaction time for younger drivers in the less (**a**) and rather critical (**b**) situations of study 2, framing the warning types which were should have matched the situation requirements the best

rather critical situation (see Fig. 5.6b) the generic *urgent warning* again was most effective with the fastest reaction times. In contrast, the specific reaction-oriented *urgent warning* did not improve the brake reaction time as compared to the control group.

The maximum braking value was also rather similar between both versions of the attention-oriented *warning* (see Fig. 5.7a). Both induced a stronger brake reaction than in the control group without a *warning*. The reaction-oriented generic *urgent warning* led to the strongest brake reactions in the rather critical situations (see Fig. 5.7b) and overall, but such a strong brake reaction would be rather inappropriate in the less critical situations like those shown in Fig. 5.7a. In these situations, this strong break reaction might lead to rear-end crashes with the following cars who do not expect such a strong, sudden braking.

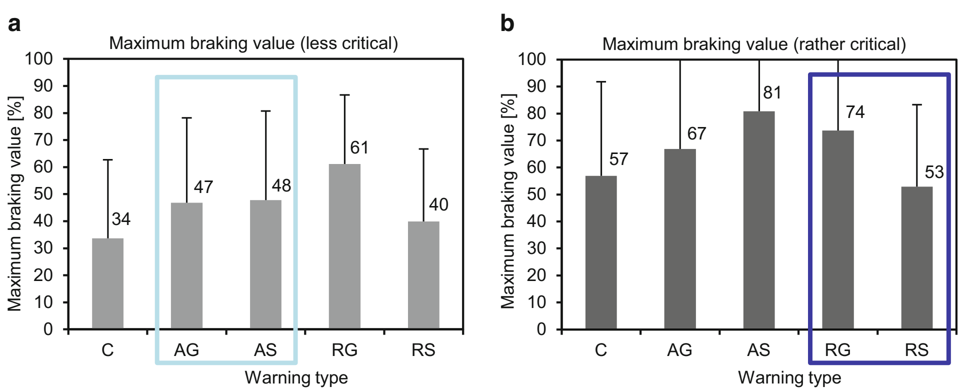


Fig. 5.7 Mean maximum braking value for younger drivers in the less and rather critical situations of study 2, framing the warning types which were should have matched the situation requirements the best

Thus, the idea to provide two different warning stages is well supported by the data. In rather critical situations the generic *urgent warning* can be used to elicit fast and strong brake reactions. In contrast, the specific *urgent warnings* did not work very well. This may in part be due to the fact that the symbol for steering is not really well known as a traffic sign. Moreover, it seems to be hard to elicit a steering reaction by drivers anyway. Almost none of the drivers showed an evasive manoeuvre upon any warning type. Thus, the stop sign seems to be an effective way to elicit a fast and strong brake reaction, which may prevent accidents or will at least diminish the consequences of possible collisions due to the reduced impact speed.

In the less critical situations, both the generic and specific *warning* led to appropriate reactions which are not as strong but sufficient to safely handle these kinds of situations. Thus, the idea that specific warning symbols would be more helpful for drivers to better detect the critical objects and evaluate the situation was not supported by the results. There were no clear advantages of the specific symbols over the generic caution sign. For the function development this may be advantageous. Even if the type of the critical object cannot be determined very well, an effective warning is still possible.

However, when interpreting these results one has to take into account that every driver group only received one type of warning concept. The results show that the *urgent warnings* are more effective in the rather critical situations, while the *warnings* may be more adequate in the less critical situations. But what happens, if drivers receive these different kinds of warnings according to the different situations and even in succession? Will drivers be able to distinguish between the *warning* and the *urgent warning*? Will they react adequately as required or do they have to learn it?

These questions and how drivers accept the warning system were examined in a third part of the project within another set of driving simulator studies, again one for younger drivers (study 4: with eight critical situations, S1–S8, $N=24$) and one for older drivers (study 5: with a reduced set of six critical situations, S1, S2, S5, S6, S8 & S9, $N=24$). Depending on the type of situation, either a *warning* or an *urgent warning* was provided in these two studies. If the drivers did not react adequately to the *warning*, the *urgent warning* followed as a second stage (see Fig. 5.8). The driving performance was examined over four learning phases (L1–4, see Fig. 5.9). The first phase L1 was driven without warning assistance. After that, three more trials commenced with *warnings* and *urgent warnings*. Additionally, the overall acceptance of the warning system was examined. Different aspects of the results are found in [13, 14] and [15].

As Fig. 5.10a shows, drivers started braking a lot earlier when receiving a *warning* (L2, L3 and L4) as compared to the first trial without warning assistance (L1). When comparing L2 to L4 there was no strong learning effect, but still some improvement became visible over time. This implies that learning of the drivers is not necessarily needed to react appropriately to the *warning*, but it can help to have experience with the warning system.

Similar results were found for the *urgent warning*. As can bee seen in Fig. 5.10a, the brake reaction time was overall faster than with the *warnings*. The brake reaction was somewhat faster when drivers were supported by the *urgent warning* (L2 to L4) than when

Warning stage	Visual	Acoustic	Scenarios beginning with this warning stage
W1) Warning		-	S4, S5, S6, S7, S8
W2) Urgent warning		1 kHz ("Beep")	S1, S2, S3, S9

Fig. 5.8 Warning concept including the two warning stages *warning* (W1) and the *urgent warning* (W2) used in study 4 with younger and study 5 with older drivers, including the scenarios in which the corresponding warning stage was presented first

not (L1), though the benefit was less than with the *warning*. This might also be due to the more limited time available to react in these more critical situations that needed an *urgent warning*.

The results for the maximum braking value are displayed in Fig. 5.10b. In accordance with the intention of the warning system, the *urgent warning* led to a noticeably higher maximum braking value than the *warning* in all learning phases. It is interesting that the overall highest maximum braking value was found in L1 and was somewhat reduced in L2 to L4. However, this is probably due to the surprise in L1 which was the first critical situation that the subjects encountered in the driving simulator. Thus, one would not interpret this as a negative effect of the *urgent warning* but as a learning effect within the driving simulator study.

As the subjective ratings in Fig. 5.11a show, the situations with the *warning* were rated far less critical than the situations with an *urgent warning*. The *urgent warning* is slightly more understandable and helpful than the *warning*, but both are well understood and help drivers. Furthermore, both warning stages are rated rather low concerning their distraction

a

	Younger drivers (study 4)			
	L1	**L2**	**L3**	**L4**
A	S_1W_0, S_6W_0	S_1W_2, S_3W_2, S_4W_1, S_5W_1, S_6W_1, S_7W_1	S_1W_2, S_3W_2, S_4W_1, S_5W_1, S_6W_1, S_7W_1	S_2W_2, S_8W_1
B	S_2W_0, S_8W_0	S_2W_2, S_3W_2, S_4W_1, S_5W_1, S_7W_1, S_8W_1	S_2W_2, S_3W_2, S_4W_1, S_5W_1, S_7W_1, S_8W_1	S_1W_2, S_6W_1

b

	Older drivers (study 5)			
	L1	**L2**	**L3**	**L4**
A	S_1W_0, S_6W_0	S_1W_2, S_5W_1, S_6W_1, S_9W_2	S_1W_2, S_6W_1, S_5W_1, S_9W_2	S_2W_2, S_8W_1
B	S_2W_0, S_8W_0	S_2W_2, S_8W_1, S_5W_1, S_9W_2	S_2W_2, S_8W_1, S_5W_1, S_9W_2	S_1W_2, S_6W_1

Fig. 5.9 Experimental design for study 4 with younger drivers (**a**) and study 5 with older drivers (**b**) displaying how the scenarios were arranged over the four learning phases (L1–L4) including the three specific warning system support forms (without – W_0; *warning* – W_1; *urgent warning* – W_2) and the two groups of drivers A and B differing only in the order they experienced the scenarios

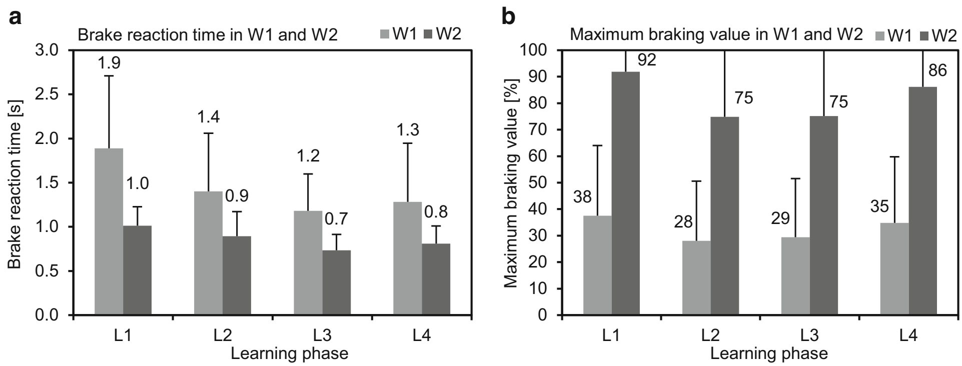


Fig. 5.10 Mean brake reaction time and mean maximum brake force in the situations beginning with warning (W1) and the urgent warning (W2) over all four learning stages (while L1 was unassisted) for younger drivers of study 4

potential. In general, the warning system is also well accepted by the drivers before and after drivers experienced it, with the usefulness of the system being rated even better than the satisfaction with it (see Fig. 5.11b).

When looking at the results of older drivers (Fig. 5.12) it also becomes clear that they distinguished between the two different warning types in L2. In very critical situations, drivers reacted faster with the *urgent warning* (W2) as compared to less critical situations with the *warning* (W1). Drivers also had a higher maximum braking value following the *urgent warning* (W2) as compared to the *warning* (W1).

The results clearly show that all drivers, independently of their age, are well able to distinguish between the two warning stages. With a *warning*, they take more time to react and brake with medium force. When an *urgent warning* is given, they react very fast and brake very strongly. Driver acceptance of the two stage warning system is also given.

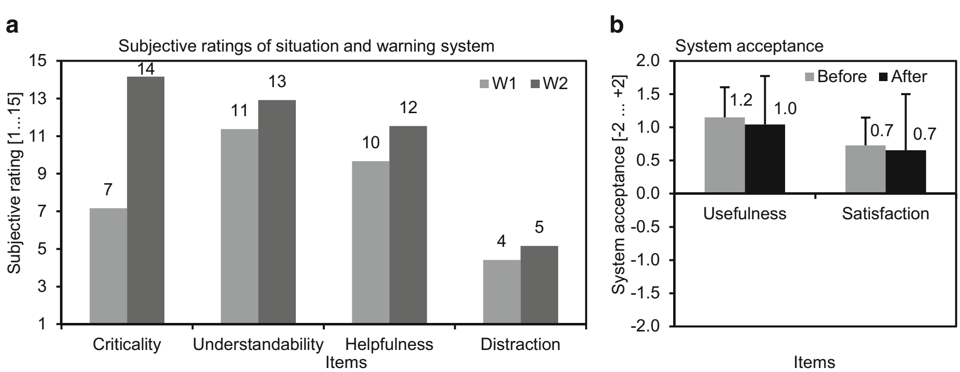


Fig. 5.11 Mean subjective ratings of the critical situations and the warning stages in the situations beginning with warning (W1) and the urgent warning (W2) for younger drivers of study 4

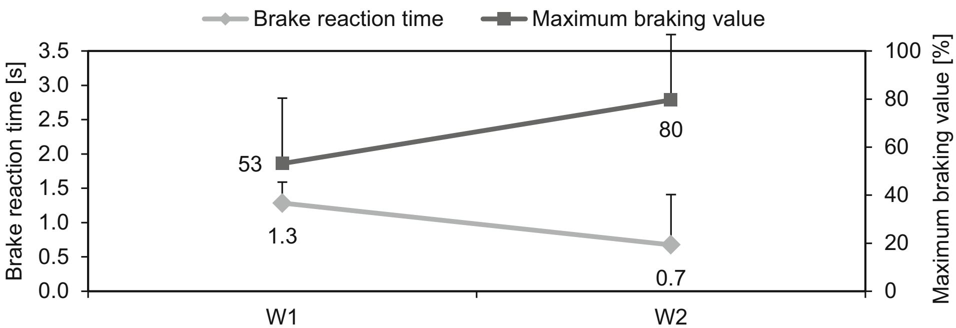


Fig. 5.12 Mean brake reaction time and mean maximum braking value in situations with the *urgent warning* (W2) and the *warning* (W1) in learning phase L2 for older drivers of study 5

Thus, these two stages of warnings using the concepts developed are very well suited to be used in different urban critical situations. As the implemented symbols are generic, they might also be useful in various other situations. Accordingly, these can be recommended for future driver warning systems in the urban context, too.

5.2.3 Recommendations for the Design of Warnings and Urgent Warnings

In urban traffic, a lot of traffic situations evolve gradually into critical situations. In many cases it is sufficient for drivers to reduce their speed or brake only slightly to avoid the situation from becoming critical. Sometimes drivers do not do that and the situation escalates. In other situations the danger arises very quickly. A pedestrian may suddenly enter a road, a cyclist may cross an intersection surprisingly or a lead vehicle may brake unexpectedly. In most of these instances emergency braking is required to avoid an accident, but drivers are often surprised by these situations and may not always be fully focused on driving. As the conducted simulator studies have shown, warnings are an effective method to prevent situations from escalating and avoid accidents. Based on the results, the following recommendations for the design of warnings in the urban context can be given:

- There should be (at least) two types of warnings – *warnings* and *urgent warnings*.
- The *warning* should be designed as a caution sign with an exclamation mark, best placed in the head-up display.
- The *urgent warning* should be designed as a stop sign, best placed in the head-up display, and be accompanied by an urgent warning sound.

The *warning* is not improved by displaying the specific critical objects which represent a current hazard. These presentations are perhaps harder to understand and more difficult to match to the real dangers. For the drivers, it seems to be sufficient to be warned and then be able to detect the imminent danger themselves. With regard to the *urgent warning*, it was not possible to elicit steering reactions and evasive manoeuvres in drivers. Thus, the effect of *urgent warnings* is at the moment limited to brake reactions. However, in most situations this will have a positive effect, either in avoiding the crash or at least in diminishing the speed of the impact and thus the severity of the crash.

In another study (not given in detail here) it could also be shown that drivers were able to understand the intentions of the two warning stages even if additional driver assistance information (e. g. navigation information, speed limit) was continuously presented in the head-up display and a *warning* was triggered when a situation was about to become critical. Thus, it is possible to show different kinds of information and warnings in the same medium. The drivers are still able to extract the relevant content and react to the two stages of the warning concept. This integration of different assistances and warnings needs further research, especially with the fast advances in research and technology nowadays.

5.3 Detecting and Warning of Visually Distracted Drivers (Robert Bosch GmbH)

5.3.1 Basic Principles

In today's traffic, the driver is exposed to a variety of distracting elements. These comprise sources of distraction from the surrounding traffic and ambience. In urban traffic, distraction is even more likely than on highways due to its increased complexity and factors like traffic lights, billboards, pedestrians and bicycles. Also, the driver is induced to perform secondary tasks not related to the driving as e. g. operating the car's infotainment system. The detection of driver distraction and the presentation of according driver warnings can be used in various scenarios:

Manual driving: Being distracted while driving manually is a major cause for accidents with an even increasing trend. It is estimated [16] that in 10 to 30% of road accidents in the European Union driver distraction is a contributing factor (the exact value being difficult to determine due to different coding schemes in the different countries). The reasons for this are that cars are equipped with complex infotainment systems as well as the increasing use of mobile devices. Reducing driver's distraction can contribute to a reduction of traffic accidents.

Assisted driving: Driver assistance systems as collision warnings or pedestrian protection warn the driver of dangerous situations. Distracted drivers have a longer reaction time compared to attentive drivers, which has to be taken into account when warning them. To warn always at an early point of time would be interpreted as a false alarm by an attentive driver and thus reduce the acceptance of such systems. If the driver's attentive level is known, the warning timing can be adapted to the driver's state.

Automated driving: Although the topic of automated driving was not covered in the project UR:BAN, driver distraction is also a relevant topic in automated driving. Current legislation requires that a driver must be able to take control over the vehicle. In partly automated driving this must be possible at any time. With higher levels of automation, it is intended to grant the driver a take-over time of several seconds [17]. Only with fully automated driving, the driver will be disengaged from the control task. Up to this time, with detecting the drivers' attentive state it can be decided if they are able to take over in time or guide their attention back to the driving scene.

In the project UR:BAN, an eye gaze tracking system was used to detect visual distraction of the driver. Video cameras monitored the eyes of the driver and calculated the gaze direction. To cover a broad horizontal field of view, four video cameras were used in the project's test car, being distributed over the width of the dashboard. In urban traffic, the driver's head is often rotated widely to the left or right, when turning or watching the surrounding traffic on crossroads.

The classification algorithm assumes that most of the relevant traffic happens in front of the car, in an imaginary window projected onto the screen called "Region of interest" (ROI). Diverting the gaze outside the ROI may be an indication of visual distraction. If the glances of the driver outside the ROI last too long or occur too frequently, the driver is classified as distracted. In this case, the driver is prompted by the warning system to pay attention to the traffic ahead.

This information is then used for the warning system, which was developed considering the guidelines of the HMI tool kit. The application – warning distracted drivers – addresses the HMI tool kit path "Safe driving – Assistance by warnings and interventions" (Figs. 4.4 and 4.5).

The HMI tool kit "Driver's action" is:

- To direct the driver's attention to the relevant traffic scene.
- To prompt the driver to take appropriate action (brake or steer).

Using the filter process "Vehicle equipment" of the HMI tool kit, the equipment that is available at the target vehicle is taken into account.

Considering these points and the recommendations that are given for each component in the HMI tool kit, three variants of the warning concepts were derived:

- An acoustic warning only.
- ICON: an acoustic warning and in addition iconic symbols that were displayed in the central information display (CID) and the head-up display (HUD).
- LED: an acoustic warning and in addition a visual warning in a LED panel. The LEDs were mounted at the A-pillars and in a bar across the cockpit.

The icons presented in the HUD and CID as well as the LED panel are shown in Fig. 5.13.

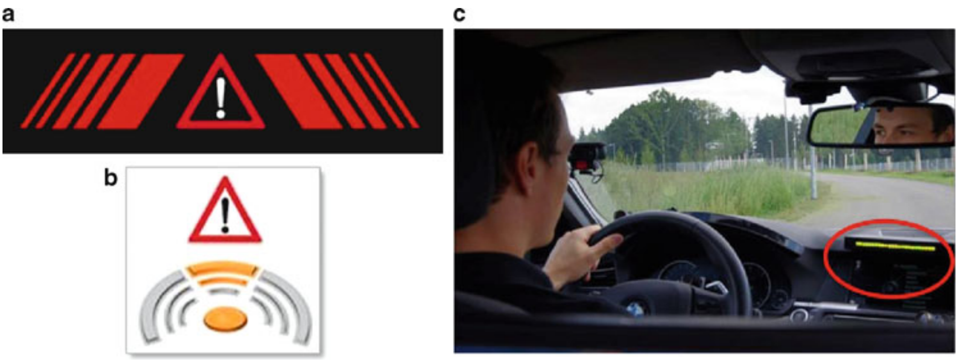


Fig. 5.13 Icons in head-up display (**a**) and central information display (**b**) as well as the LED panel (**c**)

5.3.2 Studies

Three studies were performed to evaluate the warning concepts:

- A first study was performed in the driving simulator. Its goal was to gather experience on the subjective assessment of the participants (acceptance, comprehensibility) as well as to measure the effectiveness of the warnings.
- The activation of the LEDs was evaluated in a real car study. The component "LED bar" was studied in detail to fix parameters like colour and animation speed and get a feedback to the respective recommendations of the HMI tool kit.
- The second real car study evaluated the two warning systems in their final configuration. The subjective assessment was determined, together with a detailed measurement of the effects on the driver's visual distraction.

5.3.2.1 First Study in the Driving Simulator

The components of the warning concepts (LEDs, HUD, and software) were installed in the fixed-base driving simulator at Bosch [18]. 77 subjects drove in a simulated urban scenario, where they were confronted with several distracting situations:

- Source of distraction within the car: the subjects had the task to read aloud a text that was displayed in the CID.
- Source of distraction outside the car: children playing ball at the roadside, fire engine or police car crossing.

During these situations, potential dangerous events took place (pedestrians crossing the road, sudden braking of the leading vehicle, etc., see Fig. 5.14).

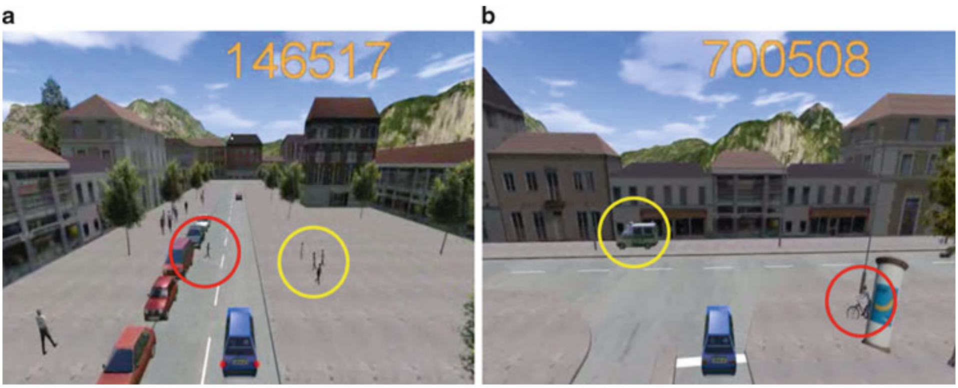


Fig. 5.14 Screenshots taken from the simulated environment. **a** children playing ball at the right (source of distraction) and a pedestrian crossing from the left (hazard). **b** police car crossing (source of distraction) and bicycle appearing behind advertising pillar (hazard). (Robert Bosch GmbH)

The driver acceptance of the systems was captured in questionnaires. The same questionnaires were used for the final real car study, which will be discussed later. The driving simulator study had the following outcomes:

- It was decided to use a LED panel that spanned the whole width of the test car, including the A-pillars. The idea was to issue the warning at the horizontal angle where the driver's gaze is located at the moment.
- It turned out that the acoustic signal alone was not specific enough to guide the driver's attention to the traffic scene. Thus, the acoustic only concept was no longer pursued in the project.

5.3.2.2 Real Car Study: Activation of the LEDs

Each LED in the panel was controlled separately and could be adjusted in colour and brightness. Several ways to activate the single LEDs were investigated. The parameters of different animations (blinking, moving band of lights, combined animation) were varied and a set of possible solutions was selected for evaluation in a real car study.

The outcome of the study was:

- A moving band of LEDs was favoured by the subjects over the blinking and combined warning.
- Setting of the parameters: the moving band starts at the horizontal angle of the driver's current horizontal gaze angle and moves to the position in front of the driver. The band starts with a width of 15 LEDs and narrows proportionally until nine LEDs. The speed is 1.25 m/s. The movement is repeated four times. The colour of the LEDs is yellow.

5.3.2.3 Real Car Study: Final Evaluation of the Two Warning Systems

The two systems – iconic warning in CID and HUD simultaneously (ICON) and LED panel (LED) – were evaluated in a real car study. The evaluation was done in two ways:

- subjective rating by the subjects,
- objective rating by analysis of the gaze adverting durations.

Three cohorts of 20 participants each were formed: one group for each of the two warning systems, respectively, and one group having no warning system, serving as a baseline to compare the gaze durations with and without warning. The test drives lasted about 30 min, and the subjects had to perform a total of seven secondary tasks to provoke visual distraction. As secondary task, digits were displayed in the CID which the subjects had to type in in a keyboard. To read the digits, the subjects had to divert their gaze from the road to the CID.

Questionnaires were used to evaluate the subjective rating (the same as in the first simulator study).

The properties “Design of the warnings”, “Attributes of the warnings system” and “Attractiveness” were assessed. For these questions, semantic differentials were used. In a semantic differential, a property is expressed in form of two adjectives having opponent meanings as “strong” vs. “weak”. The rating was done in five steps between these poles.

Fig. 5.15 shows as an example the semantic differential “Design of the warnings”. The negative pole is on the left side, the positive pole on the right side. It turns out that the warning system ICON is rated more positively in every point than system LED. This trend appears in the assessment of all surveyed properties.

The subjects were also prompted to comment freely on the implementation of the systems. It appeared that the intensity of the LED system – that was rated very positively in short-time presentations – is experienced as being obtrusive if issued frequently. However, the experimental design provoked warnings very often.

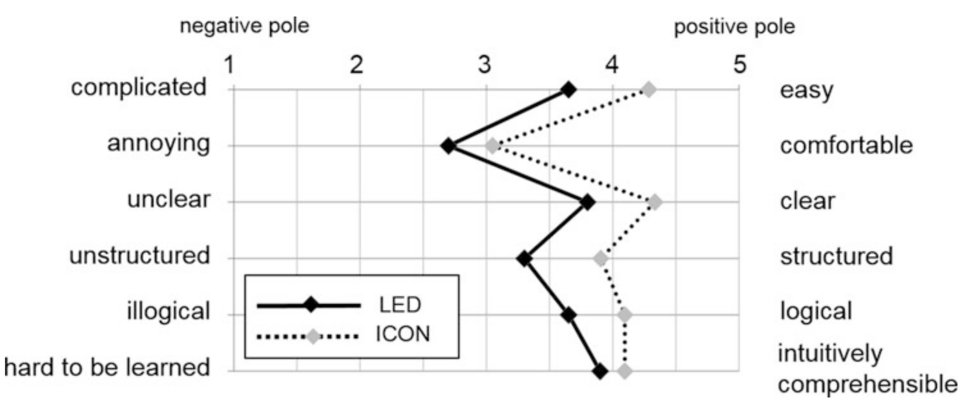


Fig. 5.15 Semantic differential “Design of the warnings”. (Robert Bosch GmbH)

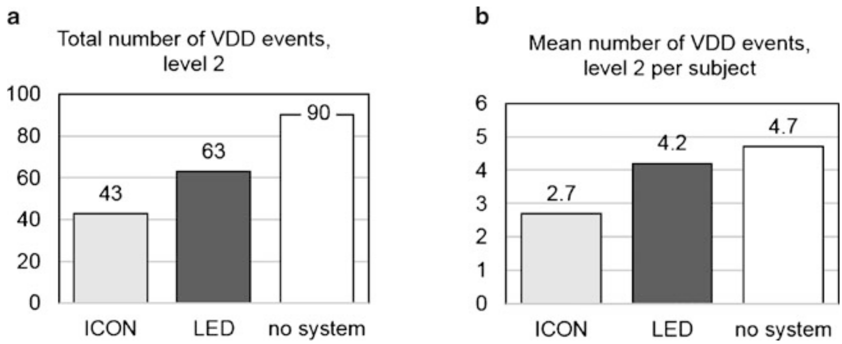


Fig. 5.16 Total number of VDD2 events (**a**) and mean number of VDD2 events per subject (**b**). (Robert Bosch GmbH)

Regarding the quantitative evaluation, a driver is classified by the algorithm as follows (VDD denoting Visual Distraction Detection):

- VDD0 (distraction level 0): not distracted.
- VDD1 (distraction level 1): This is the case if the driver's gaze is outside the ROI for a total of 3 s. If in between the gaze returns to the ROI, it must last for a minimum of 0.5 s to reset that state.
- VDD2 (distraction level 2): if within VDD1 the total duration of gazes outside the ROI exceeds 2 s (without a 0.5 s gaze to the ROI), VDD2 is reached.

In a first step, the frequency of VDD2 events was examined. As VDD1 events trigger the warnings, subsequent occurrences of VDD2 should be reduced.

Note: the per cent change p is calculated as follows (x_1, x_2: old and new value, respectively)

$$p = \frac{x_2 - x_1}{x_1} \cdot 100$$

Table 5.2 and Fig. 5.16 show the total number of VDD2 events that occurred during the study and the mean number per subject. The reduction of VDD2 events is as follows:

Table 5.2 Total number of VDD2 events and the mean number per subject

	Total number of VDD2 events		Mean number per subject	
	Absolute	Per cent change	Absolute	Per cent change
No warning system	90		4.7	
LED	63	−30%	4.2	−10%
ICON	43	−52%	2.7	−42%

Table 5.3 Mean duration of VDD1 events (left) and VDD2 events (right)

	Mean duration of VDD1 events		Mean duration of VDD2 events	
	Absolute [s]	Per cent change	Absolute [s]	Per cent change
No warning system	2.2		4.7	
LED	2.0	−9%	4.4	−6%
ICON	1.6	−27%	3.7	−21%

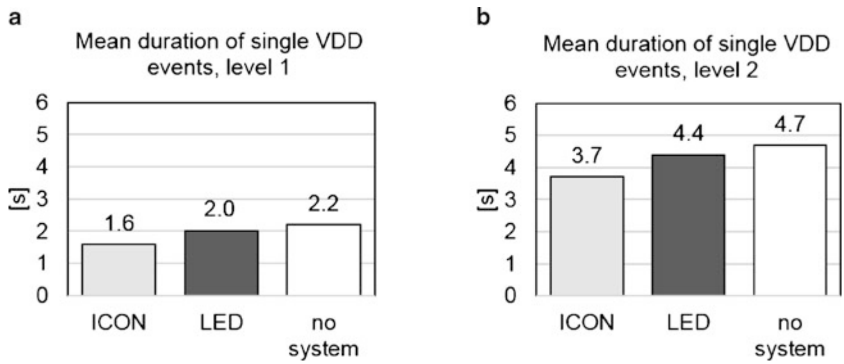


Fig. 5.17 Mean duration of VDD1 events (**a**) and mean duration of VDD2 events (**b**). (Robert Bosch GmbH)

It turned out that the warning system reduced the occurrence of distraction events (level 2). The mean number per subject was reduced by up to 42%. The warning system ICON had a greater impact than the warning system LED.

In a second step, the mean duration of VDD1 events (see, Table 5.3, left) and VDD2 events (see Table 5.3, right, Fig. 5.17) was examined. The reduction of the durations is as follows:

The duration of single distraction events can be reduced by up to 27%. Again, system ICON has a higher impact than system LED.

5.3.3 Conclusion

Using the approach of the HMI tool kit, three warning concepts have been derived. Two of them – the ICON system and the LED bar – have been evaluated in detail in a real car study. Both systems ICON and LED may reduce the impact of visual distraction by guiding the gaze back to the driving scene earlier. The ICON system was more effective than the LED bar. It was also rated more positively than the LEDs, being perceived as less obtrusive.

5.4 Collision Avoidance by Autonomous Evasive Manoeuvre (Volkswagen AG and Technische Universität Braunschweig)

The aim of the collision avoidance system presented here is to avoid a potential collision by an autonomous evasive manoeuvre in a safety-critical situation. The evasive manoeuvre is executed by the steering system of the vehicle. It is computer-based on the relative configuration of the host vehicle and the collision object which is estimated using environment sensors. The system can help to detect road users (e. g. pedestrians, crossing vehicles) around the host vehicle and the road infrastructure. The collision avoidance system contains situations which are so unexpected that an emergency braking is not sufficient to avoid the potential collision, e. g. a sudden obstacle in the driver's path.

In the HMI tool kit (Fig. 4.4), the collision avoidance system is allocated to the HMI strategy "Warnings and interventions" (Fig. 4.5) and was developed in the subproject "Collision avoidance by swerving and braking". Fig. 5.18 shows the chronology of the HMI screens of the steering system presented in the display in the instrument cluster.

As shown in Fig. 5.18, a warning tone is paired with a pop-up which signalizes the "emergency intervention" stage when the system intervention begins. In contrast to an emergency braking system, no red bright LED-bar is used. As the system is doing an autonomous evasive manoeuvre, the aim is to involve the driver as little as possible during the intervention. After the intervention, the driver resumes the driving task. In this de-

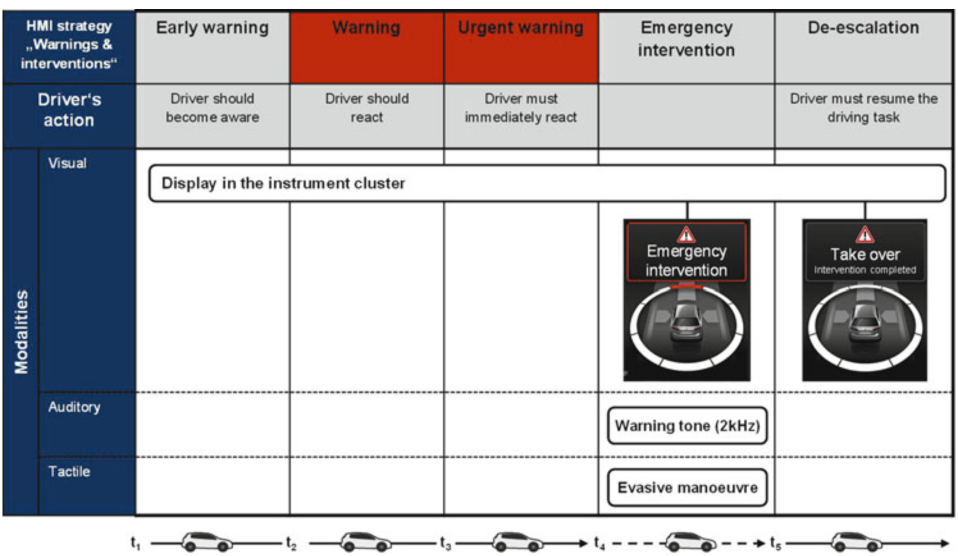


Fig. 5.18 HMI concept of the collision avoidance system by autonomous evasive manoeuvre presented in the display in the instrument cluster

escalation stage another pop-up appears which signalizes the takeover request to the driver ("Take over – Intervention completed"). In the following a test track study is described investigating the effectiveness and driver acceptance of the collision avoidance system in an unexpected situation.

5.4.1 Aim and Research Questions

In November 2015, a test track study with the collision avoidance system by autonomous evasive manoeuvre was conducted on a test track field in Ehra-Lessien, Germany. The aim of the study was to examine the effectiveness and driver acceptance of different collision avoidance systems in a safety-critical situation. The following research questions were:

1) How well can the driver manage the system intervention in an unexpected, safety-critical situation, representative for the urban area?
2) How well does the driver evaluate the collision avoidance system regarding effectiveness and acceptance in the situation?

5.4.2 Method

In the study two steering systems were compared: (1) Electric Power assisted Steering (EPS) and (2) Audi Dynamic Steering (ADS). Both systems were used to realise different kinds of steering interventions. One steering intervention uses only the EPS. Hence, the requested steering angles, steering angle velocity, and the resulting steering torque are directly sensible at the steering wheel. The other steering intervention is mainly executed by the ADS while the EPS applies the assistive torque to realise the manoeuvre. Here, ω_D corresponds to the evasive steering. Hence, the driver is not able to sense the steering angle or the steering angle velocity. The driver is, however, able to sense the torque around the superimposition gearbox which is in contrary to the actual steering intervention.

In addition, the EPS varied in the duration of the assistance: a) doing the evasive manoeuvre and driving straight to the collision object (2/3) and b) doing the evasive manoeuvre, driving straight, and turning back (3/3). Fig. 5.19 shows the three collision avoidance systems differing in duration of the assistance and steering wheel feedback.

The three collision avoidance systems were installed in an Audi A6 prototype (Fig. 5.20). The prototype was equipped with the EPS and ADS which is a superimposed steering system. Generally, the EPS assists the driver using an electric engine which applies an assistive torque to the steering gear. Thereby, the required assistive torque is estimated based on the driver's steering angle ω_D as well as the torque of the steering column. Moreover, the EPS has got an internal steering angle controller that allows for the execution of a steering manoeuvre.

The ADS system is capable to actively providing an additional steering angle ω_S to the original driver steering angle ω_D. Thereby, an additional superimposition gearbox is

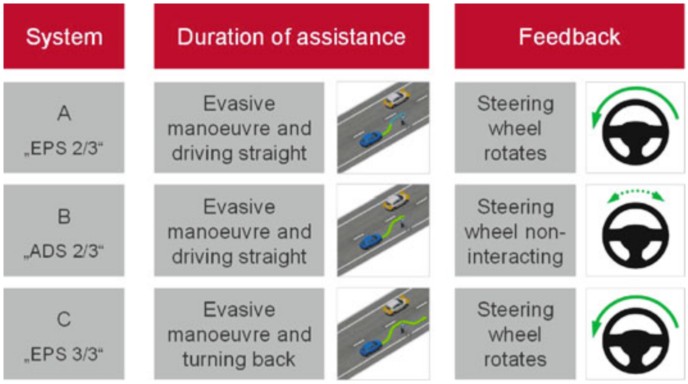


Fig. 5.19 The three collision avoidance systems of the test track study differing in duration of the assistance and steering wheel feedback (EPS = Electric Power assisted Steering, ADS = Audi Dynamic Steering)

integrated into the steering column that can actively influence the steering angle. The resulting steering angle can be written as $\omega_{D'} = \omega_D + \omega_S$.

An important property of the ADS, compared to Steer-by-Wire systems, is that even so it can influence the steering angle, the steering wheel and the front axis are mechanically coupled. Due to that, for any steering angle superimposition an equilibrium of torques is required around the superimposition gearbox. Hence, the superimposition gearbox is linked to the front axis on one side and the steering wheel on the other side, the driver has to provide the required steering torque.

Fig. 5.21a shows the driving scenario on the test track field. The scenario consisted of three sections (section A, B, C). After a big curve, the participants drove two sections of slalom driving, starting with 40 km/h (section A) and then 30 km/h (section B). At the end, the unexpected critical event occurred (section C). The critical event was a dummy, occluded by a parked vehicle which suddenly entered the road from the right (Fig. 5.21b). The test vehicle with the collision avoidance system made the evasive manoeuvre to the left. Here, the participants drove 50 km/h.

Fig. 5.20 Audi A6 prototype with the Electric Power assisted Steering (EPS) and the Audi Dynamic Steering (ADS). The vehicle is an UR:BAN prototype of the subproject “Collision avoidance by swerving and braking”

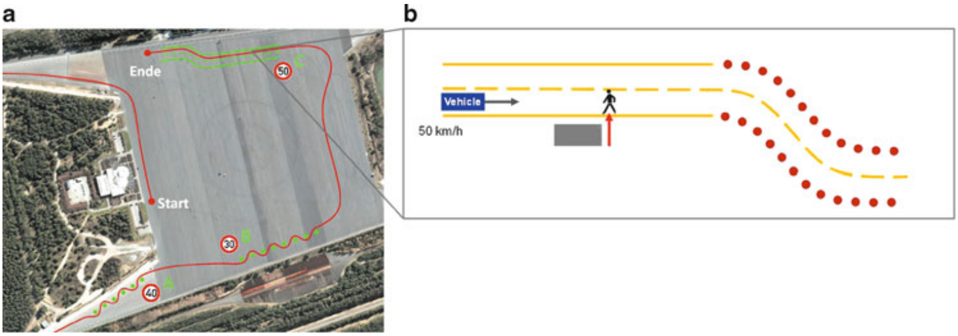


Fig. 5.21 Driving scenario on the test track field in Ehra-Lessien, Germany (**a**) and the critical event at the end of the driving scenario (**b**)

For the study, the participants were instructed that an assistance system will be active to support the driver while driving in curves, similar to an Electronic Stability Program (ESP). The participants' task was to evaluate the system based on the subjective driving feeling. In order to deflect from a potential collision avoidance system and to avoid drivers' expectation of a critical event in the driving scenario they were told to attend to the steering behaviour of the vehicle.

After the participants drove the driving scenario with one of the three collision avoidance systems (Fig. 5.19), they were informed about the real purpose of the study. Then, they drove all three systems only in section C and filled in several evaluation questionnaires including acceptance questions about, e. g. comfort, directness, usefulness, trust, understandability, and sense of security of the system intervention. In addition to the evaluation of the system intervention, questions concerning the evasive manoeuvre, the interaction between system and driver, the steering wheel behaviour, and the HMI presented in the instrument cluster display were included.

The test track study was a mixed design. The subjective evaluation of the systems was conducted in two time points. After the participants drove one collision avoidance system the first time, they filled in the evaluation questionnaires (between-subjects design). Here, one third of the participants started with EPS 2/3, another one third with ADS 2/3, and the rest with EPS 3/3. The participants were randomized to the experimental groups. After the aim of the study has been elucidated, all participants drove the three collision avoidance systems and filled in the evaluation questionnaires (within-subjects design). As a result, two data measurements for the collision avoidance system which was driven the first time were recorded. In addition to the evaluation questionnaires, driving data and driver's reaction to the critical event were recorded and analysed but will not be presented here.

A total of 23 subjects (3 female, 20 male) participated in the study. The participants ranged from 30 to 60 years of age (M = 44.6 years, SD = 8.6 years) and had a driver's license for 25.6 years (SD = 8.2 years). They were recruited via participant pool of the

Volkswagen AG. The inclusion criteria were that the participants are (1) between 25 and 60 years old, (2) have experience in driving with Adaptive Cruise Control (ACC) or lane assist, and (3) successfully completed a driving safety training.

5.4.3 Results

When driving the collision avoidance systems the first time, the results showed that all three system interventions were evaluated as "good" by the drivers and "adequate" to the unexpected situation (Fig. 5.22a). After driving the system the second time the overall evaluation increased especially for the 2/3 systems but not for the EPS 3/3.

However, when driving the system the first time the drivers rated the intervention of the ADS 2/3 as "middle understandable" compared to the EPS 2/3 and EPS 3/3 ("understandable"). This effect faded off after the second time. Here, all three system interventions were evaluated as "very understandable" by the drivers. The same evaluation trend over the time was shown regarding the "usefulness" of the system intervention. Drivers evaluated the interventions as "very useful" in the unexpected situation as a collision could be avoided.

With regard to the comfort of the system interventions (Fig. 5.22b), the drivers perceived the ADS 2/3 and EPS 3/3 as "middle comfortable", the EPS 2/3 as even "uncomfortable" when driving the system the first time. With the second driving, the rating increased to "middle comfortable" (EPS 2/3 and EPS 3/3) and "comfortable" (ADS 2/3).

When comparing the three collision avoidance systems, the best evaluations were given for the EPS 2/3 and ADS 2/3 (Fig. 5.23a). They were evaluated as "good" by the drivers

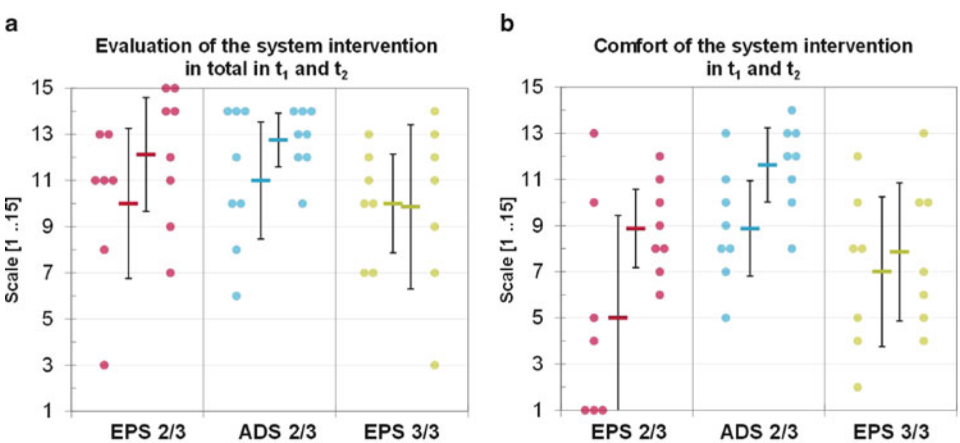


Fig. 5.22 Mean and 95%-CI of the overall evaluation of the system interventions in t1 and t2 (**a** 1 = very bad to 15 = very good) and the comfort of the system interventions in t1 and t2 (**b** 1 = very uncomfortable to 15 = very comfortable)

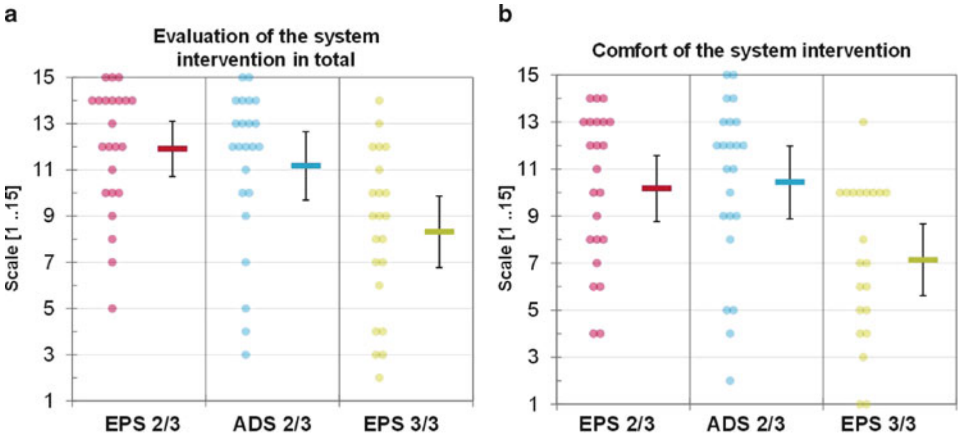


Fig. 5.23 Mean and 95%-CI of the overall evaluation of the system interventions (**a** 1 = very bad to 15 = very good) and the comfort of the system interventions (**b** 1 = very uncomfortable to 15 = very comfortable)

compared to the EPS 3/3 with "middle good". One reason for this can be seen in the evaluated comfort of the system interventions (Fig. 5.23b). Overall, the drivers perceived the EPS 2/3 and ADS 2/3 as "comfortable", the EPS 3/3 only as "middle comfortable". All three systems were perceived as "very useful" (EPS 2/3 and ADS 2/3) and "useful" (EPS 3/3) respectively (Fig. 5.24a). Finally, the understandability of the system intervention was rated highest for the EPS 2/3. The intervention for the EPS 2/3 and ADS 2/3 was evaluated as "very adequate" to the unexpected situation (Fig. 5.24b).

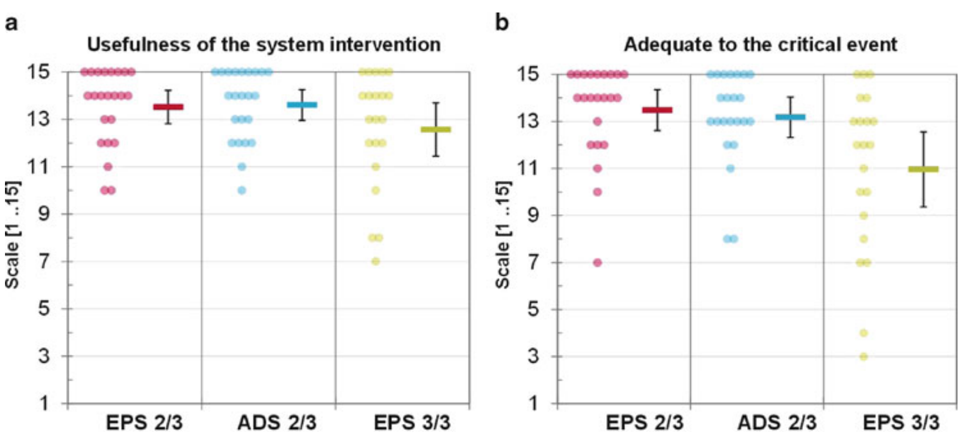


Fig. 5.24 Mean 95%-CI of the usefulness of the system interventions (**a** 1 = very little useful to 15 = very useful) and how adequate to the critical event (**b** 1 = very little adequate to 15 = very adequate)

5.4.4 Conclusion

Considering all results found in the study, it can be concluded that the accident prevention with all three collision avoidance systems was good to very good in this unexpected safety-critical situation. All systems were useful to avoid a potential collision. However, differences between the drivers' acceptance of the systems were found.

First, the EPS 2/3 and ADS 2/3 were evaluated as best by the drivers. Especially, the EPS 2/3 was rated as very understandable, even if the system intervention was experienced as rough. In contrast, the ADS 2/3 was perceived as comfortable, but less comprehensible. It is important to mention that in general all system interventions have the character of an "emergency intervention" in such unexpected situation, which makes it difficult to evaluate the comfort of such intervention. Clearly lower accepted by the drivers was the EPS 3/3. This system intervention seems to be less comfortable, rather rough, less useful, and inadequate for the unexpected situation.

Second, the results indicate that the 2/3 systems are more accepted by the drivers. They perceived the EPS 3/3 system as rather inadequate. This is mainly due to the reason of a missing threat in the driving scenario like e. g. oncoming traffic or a static obstacle that would justify an immediate return to the original lane. Nonetheless, the drivers recommend a "turning back" of the collision avoidance system, but in a more comfortable or assisting setting.

Finally, a time effect between the first and second evaluation of the collision avoidance systems was found. While the acceptance of the EPS 2/3 and ADS 2/3 clearly increased after the second drive, the acceptance of the EPS 3/3 was nearly the same. One reason for this was that nearly all drivers overrode the EPS 3/3 when driving the system the first time, which essentially rendered the 3/3 manoeuvre into a 2/3 manoeuvre. Further research studies are necessary to validate the data and to investigate if combinations of system features are necessary to increase the driving feeling of the steering behaviour and thus the driver's acceptance for a collision avoidance system.

5.5 Conclusion

Overall, the three approaches presented in this chapter have addressed the different stages of the HMI strategy "Warnings and interventions", taking driver distraction into account. The approach of the Technische Universität Braunschweig has provided recommendations for the design of *warnings* and *urgent warnings* with a special focus on the head-up display. The approach of the Robert Bosch GmbH has addressed the issue of driver distraction by providing a video-based algorithm to classify the distraction of the driver and to give according feedback. They were thus able to reduce distraction in order to support the effect of warnings and interventions. Finally, the approach of the Volkswagen AG has shown that very short autonomous interventions by the vehicle are very well suited to support evasive manoeuvres in time-critical situations in which braking only is not sufficient anymore. Integrating these results provides recommendations for the design of the different warnings and interventions based on empirical studies and reactions of the drivers. Thus, the introduction of these systems in the real traffic will hopefully be promoted as a contribution to make driving in urban areas safer and more comfortable.

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HMI Strategy – Lateral and Longitudinal Control 6

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6.1 Introduction

Advanced driver assistance systems (ADAS) which continuously intervene in the lateral or longitudinal control of the vehicle can increase the efficiency and comfort while driving. The HMI strategy presented in this section can be considered part of the developed HMI tool kit (Fig. 6.1, see also Chap. 10).

According to the Federal German Highway Research Institute's (BASt) nomenclature [1] for the degree of automation, the ADAS considered here can be classified as "assisted" as well as "partially automated" driving. This classification states that tasks are allocated to both the driver and the assistance system. During assisted driving, the driver takes over either the lateral or the longitudinal control manually, while the other part is controlled by the ADAS. During partially automated driving, both the lateral and the longitudinal vehicle control are temporarily regulated by the ADAS. In both cases, the driver must continually monitor the ADAS. As a result, the role of the driver changes. Activities that were once of a controlling nature shift in the direction of monitoring tasks [2].

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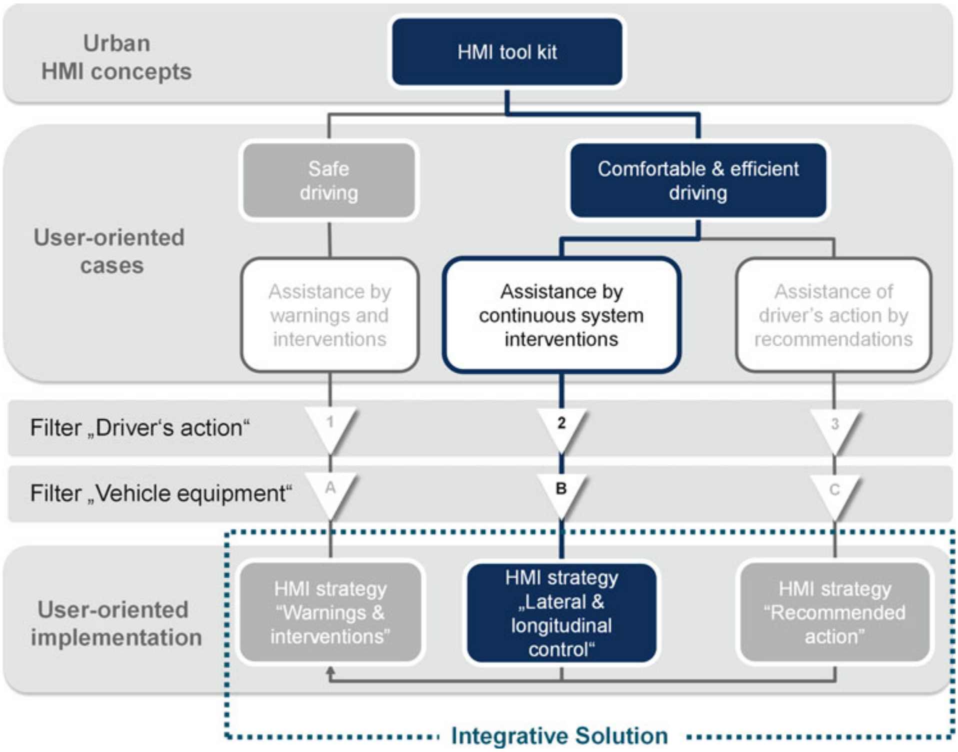

Fig. 6.1 HMI strategy for lateral and longitudinal control within the HMI tool kit

6.2 Theoretical Background

In order to ensure the effectivity and safety of the entire system of "driver-vehicle-environment", it is important that the ADAS is designed in accordance with drivers' requirements. Here, the design of the HMI concept plays a decisive role, which helps drivers structure their mental models. Mental models describe the mental picture that the driver has of the ADAS. [3] define mental models as: "(...) a rich and elaborate structure, reflecting the user's understanding of what the system contains, how it works, and why it works that way". Using the underlying mental model, the driver is able to understand and anticipate the system's behaviour. Mental models are subjective, individual, vary in their complexity and precision, and have a dynamic character [4]. They promote system transparency and the driver's understanding of the system. The construct of transparency, which originates from traditional software ergonomics, can be considered a system characteristic. The objective is to achieve an optimal match between the mental model and actual system behaviour [5]. A transparent system design can increase effectivity by preventing undesired system interventions by the driver during normal operation. At the same time, the

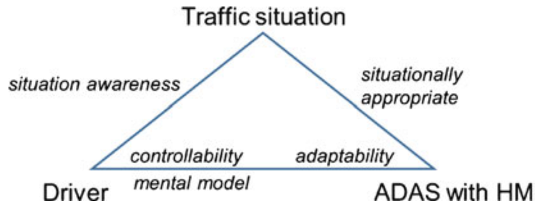

Fig. 6.2 Relationship between driver, ADAS (advanced driver assistance system) with HMI, and the specific traffic situation

safety of the entire system at its limits can be increased by a higher transparency and predictability of the system's behaviour. Here, the driver and the ADAS with HMI are related to each other in every specific traffic situation: The driver is required to have an appropriate situation awareness in every traffic situation so that he/she can stay in control of the ADAS using his/her mental model. The ADAS, in turn, should be adapted to the driver's capabilities. It should be designed to promote system transparency and should react appropriately to the specific traffic situation. This correlation is depicted in Fig. 6.2.

HMI concepts for continuously intervening ADAS should be designed so that they counteract potential negative automation effects. As the ADAS takes over more of the driver's tasks, it can lead to an insufficient awareness of the situation by the driver. Another problem is the driver's trust in the ADAS. Mistrust decreases the driver's acceptance leading to disuse of the ADAS [6, 7]. In contrast, over-reliance or complacency with regard to the system functionality can lead to insufficient monitoring, an increased willingness to take risks and to a decreased feeling of responsibility [6].

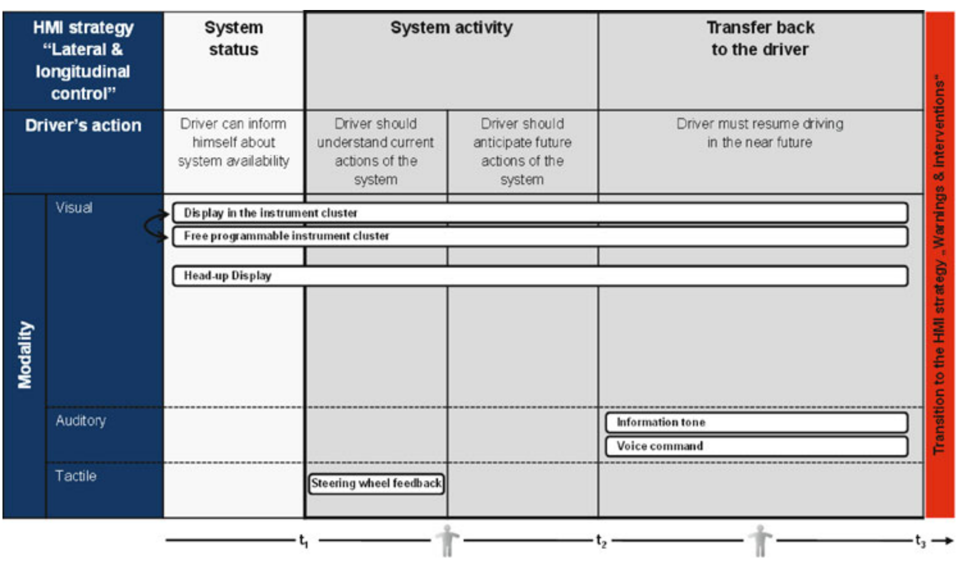

Fig. 6.3 Scheme of HMI concepts for the HMI strategy "Lateral and longitudinal control"

To counteract negative automation effects as much as possible, the following question should be considered: What could a system-transparent design of HMI concepts for a continuously intervening ADAS look like? A basic model for the HMI design focusing on heavy trucks and cars shown in (Fig. 6.3) was developed with project partners from the subproject "Human-Machine Interaction for urban environments". In principle, a basic distinction is made between the levels "system status", "system activity", and "transfer back to the driver". At the system status level, the driver is able to obtain information. At the system activity level, the driver comes to understand the current system actions and to anticipate future system actions. At the "transfer back to the driver" level, the driver must completely take over the driving task before long. Depending on the level, different modalities and components are recommended for designing the HMI (see Sect. 6.3.2).

6.3 Implementing the HMI Strategy

Sect. 6.3.1 describes the development of the HMI strategy for an automated longitudinal control in trucks. Furthermore, truck-specific aspects while driving are illustrated. Sect. 6.3.2 expands on the HMI strategy in cars for a lateral control system on narrow roads – the constriction assistant.

6.3.1 HMI Concept Development for an Automated, Fuel-efficient Longitudinal Vehicle Control for Heavy Trucks (MAN Truck & Bus AG)

At 26% of the total operating costs, fuel expenses represent a major cost factor for heavy trucks [8]. Since the driver's driving style has a significant influence on fuel consumption [9, 10], an automated longitudinal vehicle control may implement a continuous fuel-efficient driving and operating strategy. Such a strategy might regulate vehicle speed based on the vehicle's distance to another vehicle ahead, the topography as well as static and dynamic infrastructure elements. Examples for static infrastructure elements are speed limits and bends, while traffic light systems are categorised as dynamic infrastructure elements.

While vehicle speed is regulated by the system, the driver's task consists of manually executing lateral control and continuously monitoring the longitudinal control. Consequently, according to the BASt nomenclature [1] the ADAS described here is to be classified as assisted driving.

Compared to driving a car, specific, truck-related characteristics must be taken into account for the HMI concept development for truck drivers. A significantly higher mass compared to cars leads to longer coasting distances due to a higher kinetic energy. For an upcoming event with a lower target speed, the coasting point for a fuel-efficient velocity trajectory is significantly earlier. Therefore, the system might change vehicle speed and the driver will not know why, as the reason for this change in speed (e. g. a speed limit

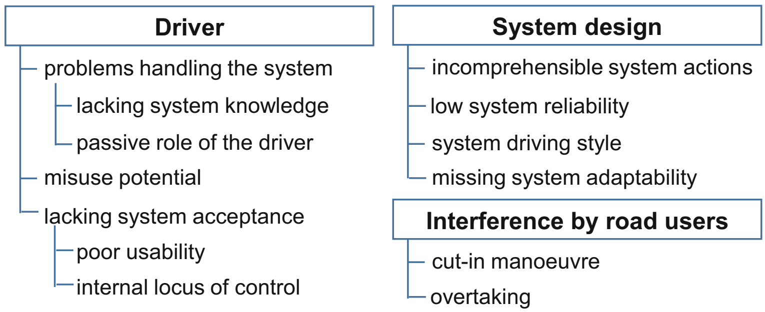

Fig. 6.4 Overview of potential problems from the truck driver's perspective

sign) is not yet visible to the driver. Due to this information disparity between ADAS and the driver, it is necessary to communicate a reason for the perceivable change in speed to the driver.

To integrate user's requirements in the early concept development phase, qualitative and quantitative methods for a user-centred HMI development were applied. While accompanying truck drivers in distribution transport, contextual interviews were conducted immediately after the experienced situations to determine the driver's assessment on the need for ADAS support. In a second focus group study with truck drivers, attitudes, opin-

Fig. 6.5 Dynamic truck driving simulator at the Institute of Automotive Technology, TU Munich, Germany

ions, and potential problems from the user's perspective were collected [11]. Fig. 6.4 gives an overview of the potential problems from the truck driver's point of view.

A driving simulator study with truck drivers determined the necessary information units. The implemented ADAS prototype was integrated in a dynamic truck driving simulator (Fig. 6.5). Thus, the participants could experience the automated longitudinal control in different driving situations. In addition to defining the information units, the objective of the study was to determine the suitable output location in the truck cockpit as well as the time at which the information should be provided. Thirty-two professional drivers (31 males, 1 female) between the ages of 21 and 66 years (M = 40.4 years) participated in the study. Ninety-four percent of the drivers had prior experience in operating a cruise control in a truck. In contrast, only 28% of the participants had an adaptive cruise control (ACC) in their most-used vehicles.

The aggregated results with regard to the necessary information units are depicted in Fig. 6.6. For promoting traceability and trust, the majority of the truck drivers surveyed requested information about the reason for the speed change and its distance to the vehicle. In order to know whether the system works correctly, information about the system status and reason for changing speed were essential for the truck drivers.

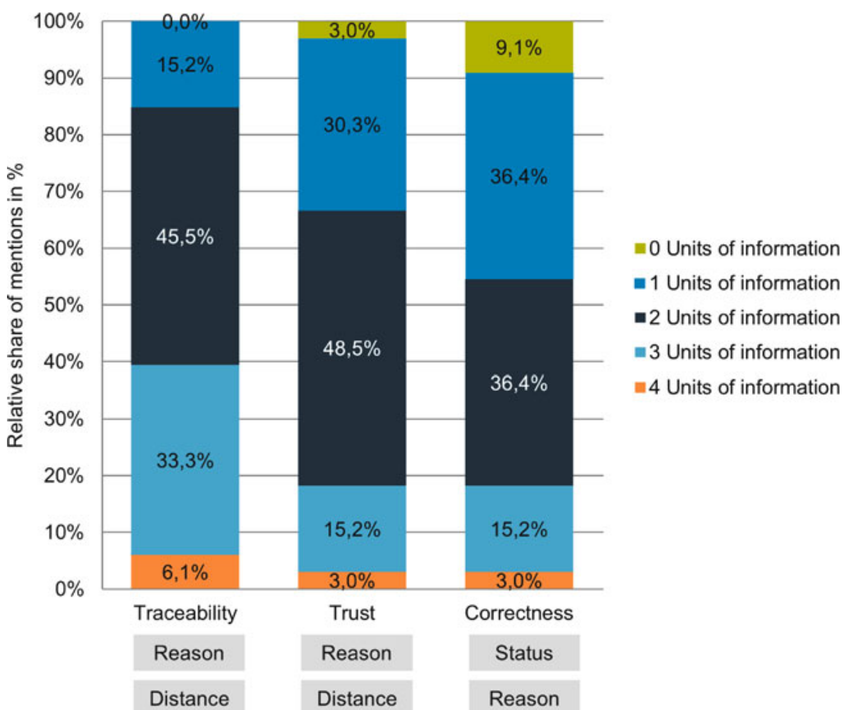

Fig. 6.6 Essentially necessary information units form the truck driver's perspective for traceability, trust, and correctness of the system

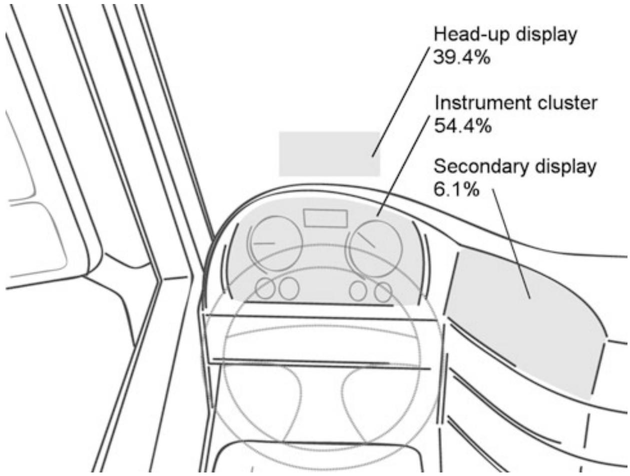

Fig. 6.7 Truck drivers' preferred output location in the truck cockpit

As an output location in the truck cockpit, 55% of the drivers preferred the display in the instrument cluster, while 39% preferred the head-up display (Fig. 6.7). It was found sufficient to provide the information at the beginning of the speed adjustment. Due to the predictable change in the velocity trajectory, providing the information at an earlier point in time was deemed unnecessary.

A scenario-based design was applied for the HMI concept development. Initial HMI concept designs were analysed using heuristical, expert evaluations. In a next step, the optimized HMI concepts were formatively evaluated in an additional driving simulator study with 36 professional truck drivers. The optimized HMI concept that was created based on these study results is shown in Fig. 6.8.

As with a conventional speed regulation system, the system status is shown in the form of a pictogram. Additional information is visualised in the ADAS area (centre) which

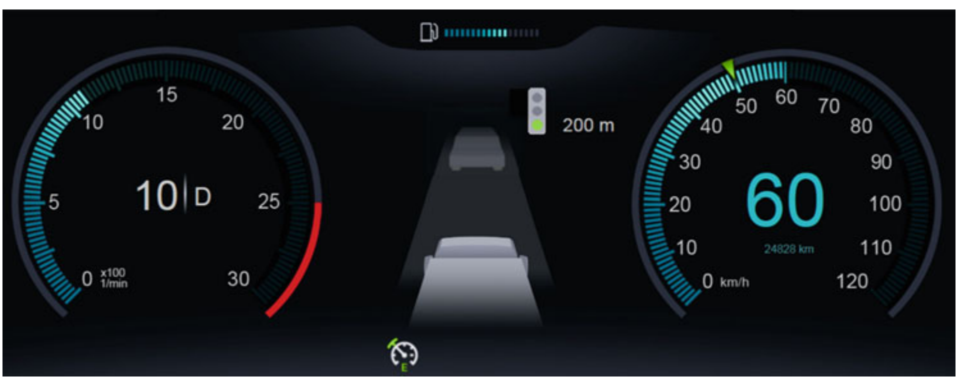

Fig. 6.8 HMI concept showing the following information units: system status, reason for speed change, distance, new target speed, and vehicle ahead

allows the driver to comprehend the speed selection of the ADAS and to anticipate the situation ahead. The reason for a long-range speed change and its distance are illustrated. Moreover, a brief adaption of speed is sometimes necessary due to a vehicle ahead. Vehicles that quickly merge and accelerate in front of a truck are a common occurrence in urban traffic. Therefore, the vehicle ahead is shown as a short-term reason in addition to the long-term reason in the ADAS graphic. Furthermore, the new target speed to which the ADAS regulates is communicated to the driver in the form of a green arrow in the speedometer. It is integrated in the display for the current speed. This allows the driver to make a quick comparison between the actual and the new target speed.

A future driving simulation study will explore to what extent drivers are capable of detecting system errors without a prior takeover request on the basis of the information units regularly displayed. Additional research could be necessary concerning whether the information units determined here can also be utilised at higher automation levels in order to inform the driver about the current system state [11].

6.3.2 Exploration of Different HMI Concepts for a Constriction Assistant (Volkswagen AG)

The development towards more and more automobiles leads to numerous conflicts in the traffic system. To counter this process, new driver assistance systems are developed to support the driver especially in urban areas and to ensure comfortable and efficient driving.

One of these assisting systems is the road constriction assistant which provides the driver with steering control while driving through a narrow street (Fig. 6.9). Bottlenecks or road constrictions are challenging driving situations, especially for novice drivers, and can impair a broad traffic area in case of an accident. To provide a comfortable driving experience, the driver needs to attain an adequate awareness and understanding of the assistance system and its continuous lateral guidance control. This understanding shall be achieved with an adequate HMI of the road constriction assistant.

The constriction assistant constantly evaluates the current traffic situation to recognise an upcoming narrow passage. Whenever an intervention is necessary, the system informs the driver in the first place and escalates to a warning and an active lateral intervention as a second step. An aimed steering torque supports the driver's steering movements to ensure a comfortable driving experience, but it does not replace the steering of the driver. The system returns to its passive monitoring state when the constriction is safely passed. While driving in the constriction lateral guidance control is performed by the system and only needs to be supervised by the driver (BaSt classification, see [1]). The question arises how an HMI concept for the constriction assistant could support understanding of the system and what kind of information should be provided to the driver. To this end, three studies were conducted: (1) a focus group, (2) a driving simulator study at Volkswagen AG, and (3) a study on a test track in Ehra-Lessien, Germany.

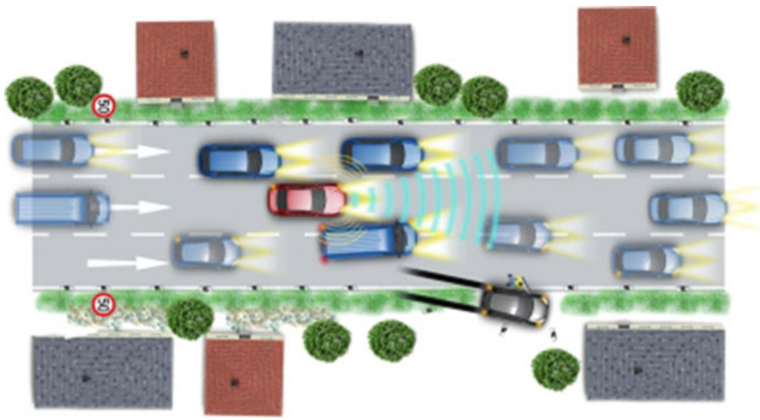

Fig. 6.9 Schematic representation of a road constriction

6.3.2.1 Focus Group and Driving Simulator Study

With the help of a qualitative analysis of the information demand on the part of the driver when passing a constriction, first HMI concepts were developed. In a focus group with nine participants, the subjective perception of 30 specifically selected narrow points on the road or constriction scenarios was analysed and the need for information was assessed. In a user-centred approach, first ideas for an HMI concept could be derived from these results.

On the basis of this input, the next step concentrated on the development of different HMI design concepts. The level of detail was varied between the concepts to achieve a presentation of different levels of information, as can be seen in Fig. 6.10. The generic HMI concept represented the basic information about an upcoming narrow passage, while the specific HMI concept included more information about objects causing the constriction

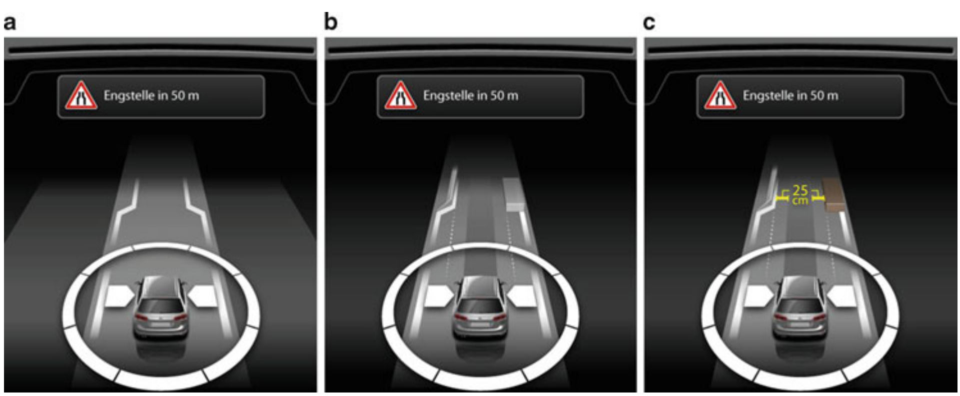

Fig. 6.10 HMI concept with varying level of information detail presented in the display of the instrument cluster: **a** generic, **b** specific, and **c** very specific HMI concept (from left)

and whether the vehicle would fit through the narrow passage. The very specific HMI concept included detailed information about how much space will be left between the obstacle and the vehicle, and if the object is a dynamic one.

The gradation of information detail was created to investigate the need for information when driving through constriction scenarios of different complexity. To this end, user studies in a simulated environment as well as on a test track were conducted with participants of the participant pool of the Volkswagen AG.

In total, 36 drivers volunteered to participate in the driving simulator study that was conducted at Volkswagen AG. Here, a static driving simulator was used (Fig. 6.11) with the simulation software VTD (Virtual Test Drive).

The three HMI concepts were compared in three urban scenarios with narrow passages that increased in complexity of the situation (Fig. 6.12). A 3×3 repeated measures study design included the factors HMI concept (generic, specific, very specific) and complexity of the situation (low, medium, high) with permuted orders, respectively (for further information, see [12]). The participants drove with a constant speed of 50 km/h, realised with cruise control functionality. The priority was given to the essential information the drivers needed to obtain situation awareness. The inherent potential of distracting the driver was considered as well. Altogether, the study aimed at identifying the assets and drawbacks of the created HMI concepts.

Major findings of the driving simulator study showed that drivers using the road constriction assistant need detailed information about both the existence of a constriction ahead and the precise distances to the vehicle while passing through the constriction. Especially information concerning an approaching constriction is of great importance. The

Fig. 6.11 Driving simulator of the Volkswagen AG

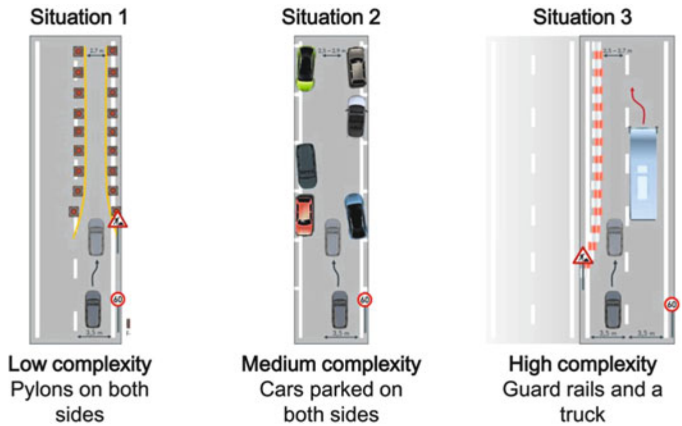

Fig. 6.12 Constriction scenarios of different complexity used in the driving simulator study

most detailed HMI concept fulfilled most of the drivers' requirements and was rated as particularly valuable. The usefulness of the very specific HMI (assessed with the System Usability Scale [SUS] and the Software Usability Measurement Inventory [SUMI] on a 15-point Likert scale) was rated significantly higher compared to the generic HMI concept, as can be seen in Fig. 6.13. Nevertheless, subjective interviews as well as objective gaze behaviour indicated that this concept might go along with a greater distraction compared to the generic HMI. Continuative research and the verification of the presented findings in an actual vehicle are advisable to examine whether these results also prove true for a real environment.

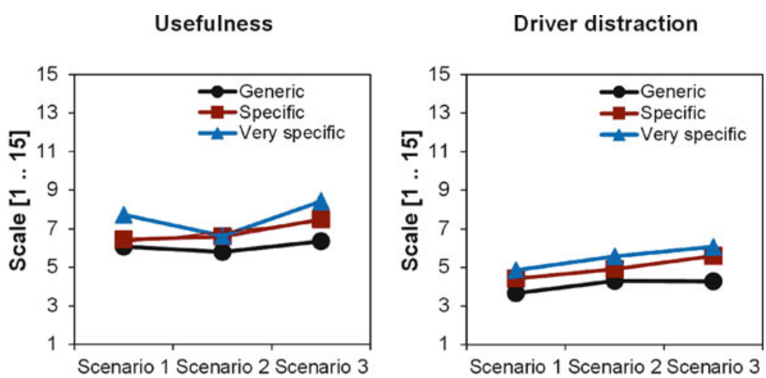

Fig. 6.13 Mean of the variables usefulness and distraction depending on the scenarios and HMI concepts (1 = very low … 15 = very high)

6.3.2.2 Test Track Study

The results of the driving simulator study mentioned above were validated by a test track study of the Volkswagen AG. In total, 19 participants took part in the study that included the experience of two static constrictions of 2.50 m und 3.00 m width that should be passed with approximately 30 km/h. The participants drove through the two narrow passages (1) manually, (2) with lateral guidance control, and (3) with lateral and longitudinal guidance control. The assistance systems were supplemented either with a generic (Fig. 6.14) or a specific HMI concept (Fig. 6.15). The 3 × 3 repeated measures design enabled the participants to compare all systems and HMI specifications.

The test track study was able to reproduce and confirm the results of the driving simulator study mentioned above to a large extend. For both approaching and passing a narrow passage, the specific HMI was evaluated as more useful (Fig. 6.16) and more understandable, compared to the generic HMI. Furthermore, drivers paid more attention to the specific HMI. The indicated distance was perceived as useful by more than half of the participants. Both HMI concepts were considered as more useful with lateral and longi-

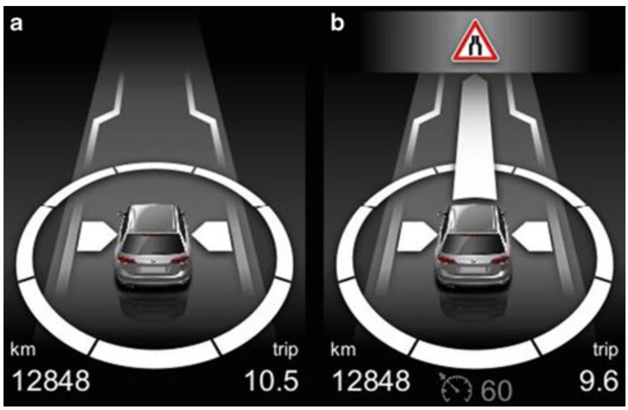

Fig. 6.14 Generic HMI concept for approaching a constriction with the lateral assistance (**a**) and lateral and longitudinal assistance (**b**)

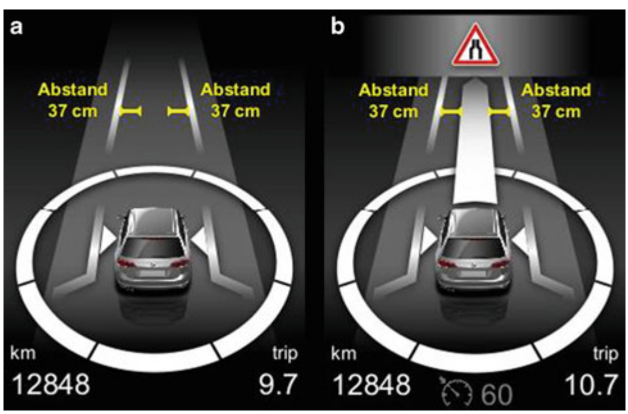

Fig. 6.15 Specific HMI concept for passing a constriction with the lateral assistance (**a**) and lateral and longitudinal assistance (**a**)

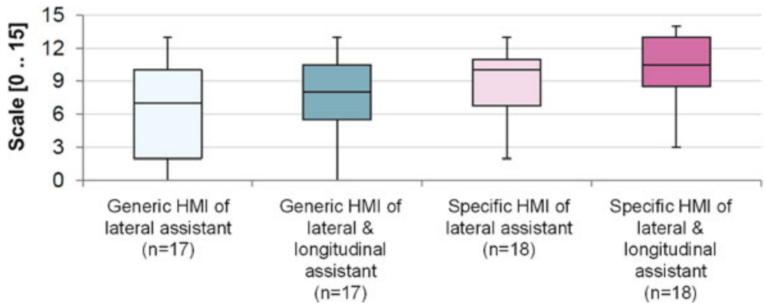

Fig. 6.16 Box plots for the variable usefulness depending on the assistance system and the HMI concept (0 = not at all … 15 = very useful)

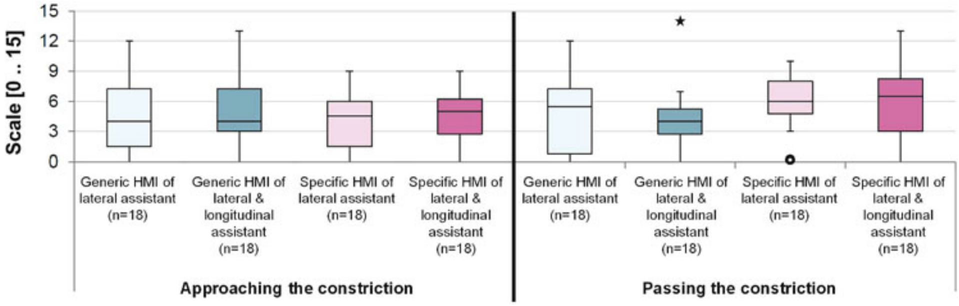

Fig. 6.17 Box plots for the variable distraction depending on the assistance system and the HMI concept (0 = not at all … 15 = very strongly distracted)

tudinal assistance. The level of distraction when approaching and passing the constriction was rated low for both concepts (Fig. 6.17). However, 74% of all participants did not pay attention to the HMI indications in the first run, and wanted the indications to be given in the head-up display.

With regard to the level of assistance while approaching and passing a constriction, the results showed that more than three quarters of all participants would like to use the lateral assistance system, and approximately 70% preferred the lateral and longitudinal control system, which was valued less because of uncomfortable driving behaviour like abrupt braking manoeuvres.

6.4 Conclusion

In conclusion, the following two HMI concepts for urban traffic were developed and refined based on the driver's demands: (1) a truck-specific HMI strategy for an automated longitudinal control and (2) an HMI strategy for a lateral control system on narrow roads – the constriction assistant.

For (1), the reason for a speed change (long-range as well as short-term), the distance to the vehicle and the target speed were identified as the essential components of the HMI. By integrating these components, an HMI was created which allows the driver to comprehend the speed selection of the ADAS and to anticipate the situation ahead.

The content of (2) depended on the context. Especially in very complex narrow passages, a need for detailed information could be evidenced. Both in the driving simulator study and on the test track, more specific information improved understanding of the situation and successfully managing the narrow passage. However, a greater potential for distraction due to the higher amount of information that has to be processed became evident as well.

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HMI Strategy – Recommended Action

7

Lena Rittger and Martin Götze

7.1 Introduction

Path three of the UR:BAN HMI tool kit (Fig. 4.4) represents HMI strategies for driver assistance systems that offer comfortable and/or efficient driving by providing recommendations and information to the drivers. The following chapters contain a definition of recommending driver assistance systems as worked out in the UR:BAN project, followed by two approaches to the development of the HMI strategy for recommending driver assistance systems.

First, relevant research questions and their experimental investigation for the development of a traffic light assistant as an example for a recommending driver assistance system are presented (Adam Opel AG). Second, the evaluation of different HMI components as generic, integrative HMI concept for the representation of multiple recommending driver assistance systems is introduced (Technical University of Munich).

7.2 Definition

Recommending driver assistance systems are based on the same sensory equipment as regulating or warning assistance systems. The sensor set (e. g. camera, radar) perceives and analyses the surrounding traffic environment. Vehicle-to-Vehicle and Vehicle-to-Infra-

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structure communication allow that information is available for the vehicle algorithms over large distances (e. g. up to 1000 m) and for future states (e. g. traffic light phasing). The in-vehicle control units and algorithms integrate the provided information from multiple sensors in order to create an interpretation of the driving situation. This process is similar for warning, regulating, and recommending driver assistance systems.

The control unit that performs the required driving behaviour differentiates regulating from recommending assistance systems. Regulating driver assistance systems interfere in vehicle dynamics by actively controlling parts of the driving task, realised as continuous system interference (Chap. 6). Recommending driver assistance systems provide the relevant information to the driver. The driver perceives and processes the information potentially through all modalities (visual, auditory and tactile) and performs the required actions. As opposed to warning assistance systems, the recommending assistance systems have no direct negative or safety critical consequences in case the driver does not follow the recommendations. Hence, escalation strategies or changes in urgency of the provided information do not apply. The beneficial effects of recommending systems depend on the driver's ability to correctly understand and interpret the provided information, the possibility to perform the required actions and, importantly, the willingness to comply with the system recommendations. Therefore, recommending driver assistance systems require HMI concepts that create good comprehension, high usability and low annoyance. In particular, when driving in urban areas, the HMI concepts need to assure low distraction.

The benefits of recommending driver assistance systems manifest themselves in cases where the sensory input gained by the systems allows the human perceptual abilities and knowledge to improve by time, space, and quality [1]. The information is available when drivers are not able to perceive it because it will change in the future (e. g. the next traffic light phasing), it is covered by the environment (e. g. speed limit behind a curve or an obstacle), or because the environment does not contain the same level of quality of the information as the sensor system (e. g. stop-and-go events of vehicles far ahead in the platoon). Additionally, the system provides information that drivers might not know based on their knowledge of the vehicle configuration and traffic situation (e. g. an efficient driving strategy). The benefits of the provided information on the human information processing, the adapted response selection, and execution lead to modifications in driving behaviour compared to unassisted driving. In summary, the main goals of recommending driver assistance systems are to enable comfortable and/or efficient driving, by presenting anticipatory information and supporting an anticipatory driving behaviour.

In terms of the primary driving task as frequently described by [2], recommending driver assistance systems influence the driver's plans, decision making and behaviour on all three levels of the driving task (Fig. 7.1). At the strategic level, the driver consciously makes a decision to increase driving comfort or efficiency and thereby makes the decision to use the system. At the manoeuvring level, the information provided by the system triggers the decision to initiate a driving manoeuver (e. g. a lane change). The control level is changed in cases where the recommending driver assistance system influences specific

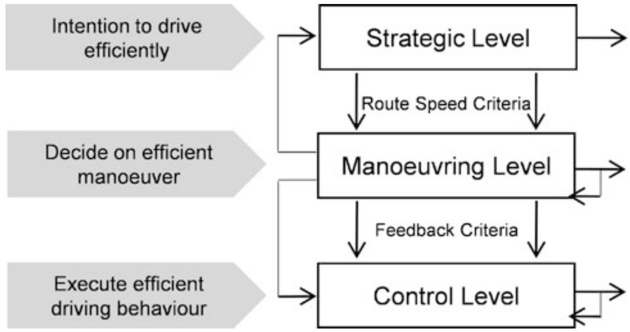

Fig. 7.1 Influence of recommending driver assistance systems on the levels of the driving task [1, 2]

action patterns (e. g. using the gas pedal to control speed). Hence, action patterns that are usually deeply engrained and performed without consciousness come to driver's attention by recommending driver assistance systems.

7.3 HMI Concept for a Traffic Light Assistant (Adam Opel AG)

The UR:BAN project supported the development of a traffic light assistance system. From a technical perspective, the traffic light assistant is based on Vehicle-to-Infrastructure communication. Wireless communication units (with IEEE standard 802.11p) allow that vehicles approaching the intersection receive information sent out by the traffic light. Available information is for example the current traffic light phase, the phase duration, the next traffic light phase and GPS traces for the driving lanes (which allow for lane matching). In cases with additional sensor technology, the traffic light can provide information on the length of the queue of vehicles waiting at the intersection. This is important to track because vehicles standing at the intersection will shift the virtual stop line.

The in-vehicle algorithm integrates the information from the traffic light with in-vehicle dynamics, in order to predict the traffic light phase at arrival at the intersection. Then the algorithm deduces a target driving speed and the current deviations from it and sends the recommended driving behaviour to the HMI units for presentation to the driver. The dynamic feedback system results into an information cycle, whereby the system influences driving behaviour and the driving behaviour influences the output of the system [3]. The two main goals of the traffic light assistant are:

- Avoiding stops by crossing the intersection at a green light phase.
- Initiating efficient stops (e. g. by early coasting), in cases of an unavoidable red light phase.

7.3.1 HMI Development

The first research question covered the development of the HMI concept for the traffic light assistant system, including the definition of the modality and HMI component, the selection of appropriate information units and the evaluation of the developed concepts in a driving simulator study.

7.3.1.1 Selection of Visual Modality

There are several arguments pointing towards the usage of visual displays for the traffic light assistant. First, the traffic light assistant provides continuous support during the traffic light approaches. Presenting the information and recommendation in a continuous form on a visual display allows drivers to re-evaluate the detailed content multiple times within an approach. As mentioned above, the recommendations are dynamic and might change due to the current driving situation. In line with this, the visual display allows drivers to re-evaluate their behaviour. Second, visual information provides detailed content by using multiple codes (e. g. colour, symbols, and texts), which enables representation of information with high levels of complexity. Third, the traffic light assistant provides information that relates to modifications in driving speed. Therefore, presenting information in close proximity to the speedometer is preferred. Finally, previous studies showed that a combination of visual and auditory information for a traffic light assistant did not change driver behaviour compared to a presentation of visual information only [4].

7.3.1.2 Definition of Presented Information Units

Traffic light assistance systems provide a large variety of information that could possibly be presented to the driver. Driver performance studies support the decision on which information content is relevant, necessary, valuable, accepted, and low distracting for the driver.

A literature analysis showed that previous recommending driver assistance systems contained at least one of the following information units:

- Current traffic light phase (e. g. [5]), which is beneficial as long as the drivers themselves are not able to see the traffic light in the road.
- Traffic light phase durations (e. g. [6]), which assume that drivers translate the phase durations into appropriate driving behaviour (e. g. adaptions of driving speed).
- Action recommendations (e. g. [7]), which allow to instruct specific driving behaviour directly (e. g. instructing to accelerate or decelerate).
- Speed recommendations (e. g. [8]), which provide target speeds that will guide the driver through a certain driving situation.

For action or speed recommendations, the systems require a higher level of automation and intelligence because more information needs to be integrated compared to the status information on the traffic light phase. With status information, the system requires that the driver interprets and performs the correct driving behaviour.

When presenting multiple information units in a visual display, two opposing theories were considered. A classic effect in divided attention research is that participants respond faster to redundant stimuli as compared to single stimuli [9–11]. The possible contents presented above contain a certain level of redundancy (e. g. the action recommendation to accelerate implies that the current driving speed is lower than expected). In case the basic research transfers to HMI design, driver performance should improve with a presentation of combined information units in the visual display compared to non-redundant information in the display. On the contrary, classic resource models (e. g. [12]). state that the extent in which two tasks use the same resource defines how well both tasks can be performed simultaneously. The driving task is mainly visual, and a visual display should be designed so that it draws on "residual capacities" that are available next to the primary driving task [12]. For the design of the visual display of the traffic light assistant, one can hypothesise that an increased number of information units in the display leads to decreases in driver performance due to increasing visual load and increased processing times.

7.3.1.3 Evaluation of Visual HMI Concepts

The study presented in the following section addresses two questions: Which information units should be presented in the visual display when approaching an intersection? Does a combination of information units lead to improved performance due to redundancy or to driver overload? The study included a systematic comparison of driver performance in relation to different display concepts.

In the experiment, drivers approached urban traffic light intersections with different traffic light phasing in a driving simulator environment. During the traffic light approaches, the traffic light assistant was active starting around 300 m in front of the intersection. The HMI concepts were presented in the instrument cluster next to the speedometer and contained the three different information units: traffic light phase information including phase duration, action recommendations and speed recommendations. The current traffic light phase was either red or green; the duration of the yellow phase was added to the red phase. Before termination of the traffic light phase, the filling of the traffic light phase started reducing like a countdown timer. A quarter of the coloured filling related to two seconds. An arrow next to the traffic light phase indicated at which traffic light phase drivers would arrive at the intersection based on their current driving behaviour. The action recommendations were either "coast", "brake", "drive" (i. e. keep speed) or "accelerate". Each recommendation was presented as a symbolic depiction of an arrow (e. g. arrow pointing downwards for deceleration). The speed recommendations were presented as numbers (e. g. 30 for 30 km/h). The combination of the presence and absence of each information unit resulted in overall eight HMI versions (Fig. 7.2). The HMI version without any information unit included the current traffic light phase without countdown timer and without information on the phase at arrival.

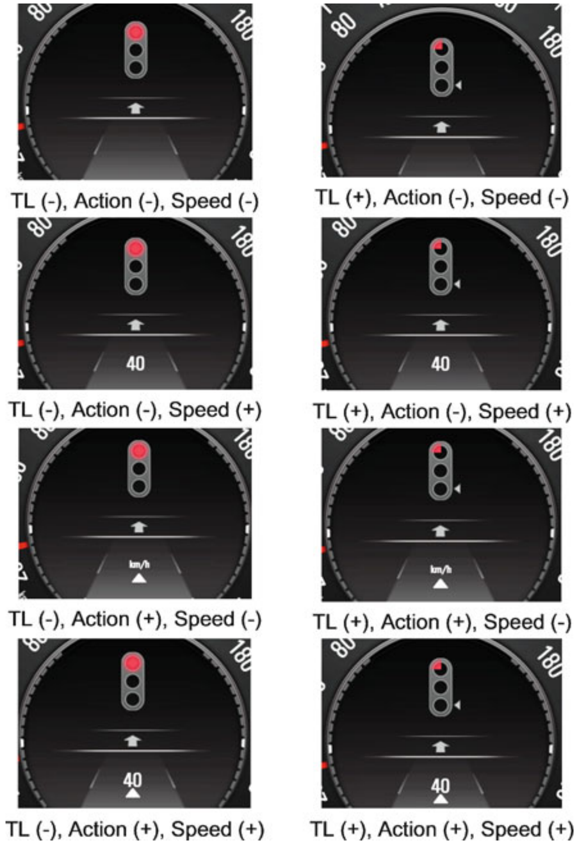

Fig. 7.2 HMI versions evaluated in the driving simulator study. The HMI versions either contained (+) or did not contain (−) each of the information units traffic light information (TL), action recommendations (action) or speed recommendations (speed)

Each participant experienced all of the eight HMI versions in eight drives through the simulated test track (containing different orders of the intersections and traffic light phases). The order of the eight drives was permuted between participants according to a Latin square. 32 participants took part in the study.

The subjective evaluation included a forced-choice question, i. e. drivers indicated which HMI they liked best, second best and third best. They also decided which HMI was worst and second worst after experiencing all HMI versions. The ratings were weighted giving three points to the best HMI version, two points to the second best HMI version, and one point to the third best HMI version. Similarly, the bad HMI versions were rated by giving two points to the worst option and one point to the second worst option. Fig. 7.3 shows the weighted number of observations. The HMI versions containing information on the traffic light phasing received the highest ratings. The HMI version containing all three information units was rated most often as the best HMI. The worst rating was given to the HMI version not containing any additional information on driving behaviour or traffic light phasing. The second worst rating was given for the option containing only action recommendations.

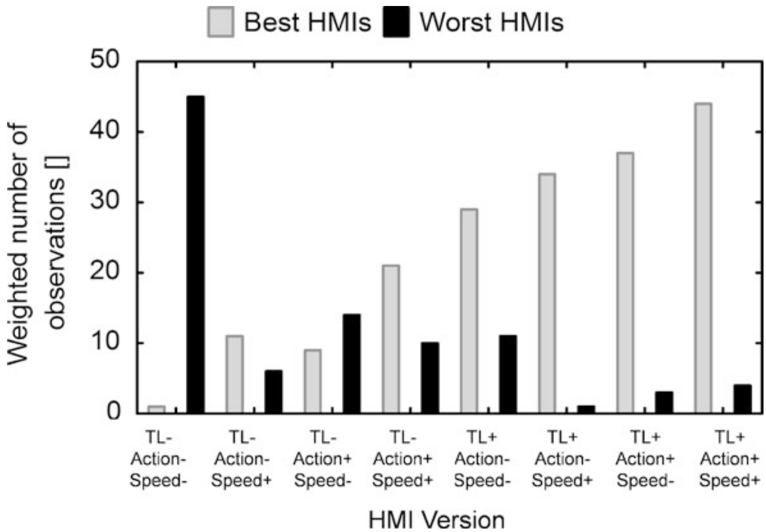

Fig. 7.3 Results from the forced choice decision to evaluate the best, second best and third best HMI version and to evaluate the worst and second worst HMI version. The HMI versions either contained (+) or did not contain (−) each of the information units traffic light information (TL), action recommendations (action) or speed recommendations (speed; [1])

Driving behaviour was evaluated in terms of speed profiles. Fig. 7.4 shows the mean driving speed averaged over all participants and repetitions, differentiated for the four different traffic light phases. The plots contain the target speed profile as calculated by the algorithm when entering the situation (dotted line) and the profiles when driving with each of the eight HMI versions. The deviations from the target speed were largest, when participants drove with the HMI version containing no information unit. The second largest deviations were observed when participants only received traffic light phase information without any speed or action recommendations. The lowest deviations from target speed were measured when the HMI contained action and speed recommendations.

There was an influence of the traffic light phase at arrival at the intersection. When approaching green traffic lights, the deviations in driving speed were generally low and additional information in the HMI display did not influence driving behaviour. In particular, drivers benefited from the recommendations, when the traffic light phase changed during the traffic light approach (e. g. changed from red to green or from green to red).

In order to evaluate the visual load that drivers experienced when driving with the different HMI versions, gaze durations were analysed. The 85% percentile was below 1.4 s gaze duration and the 95% percentile was below 1.7 s gaze duration for all HMI versions. The longest average fixation durations were measured for the HMI version showing traffic light information and action recommendations. The shortest average fixation durations occurred with the HMI version showing no information, followed by the version containing action and speed recommendations. As a conclusion, all HMI versions met the standard

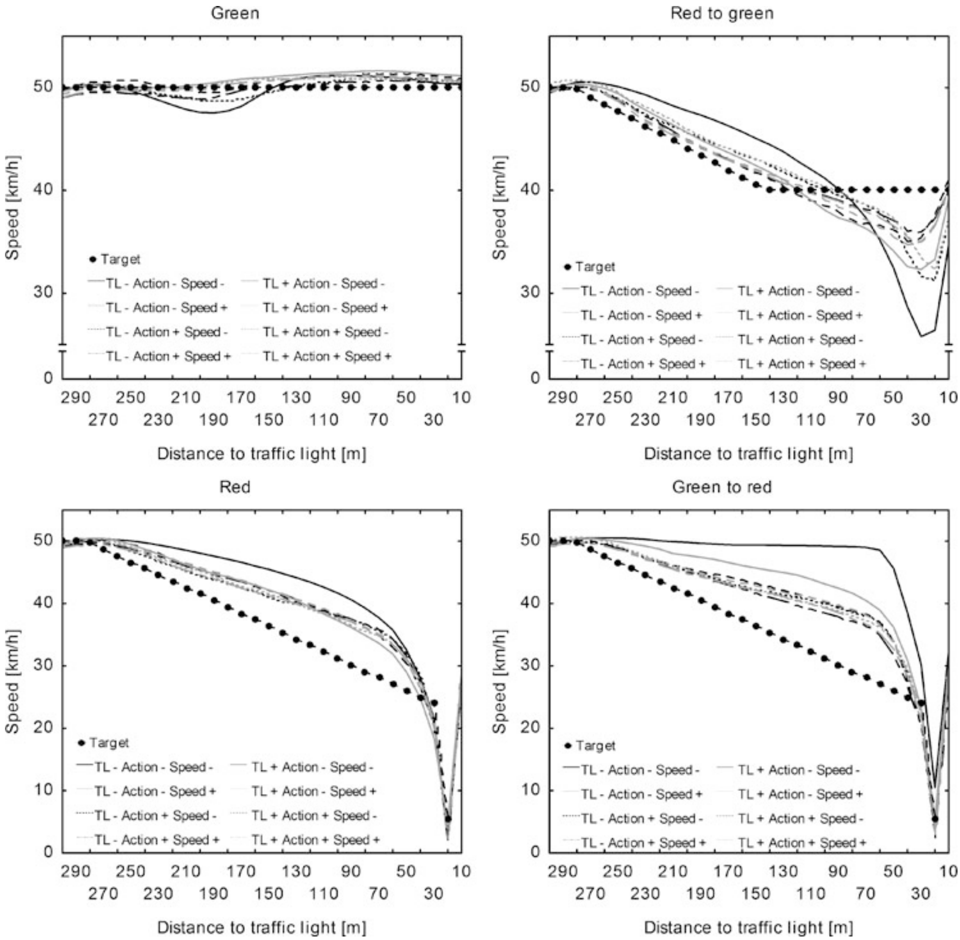

Fig. 7.4 Mean driving speed for the 30 distance sections in the 300 m traffic light approach to solid green, red to green, solid red and green to red traffic lights. The dotted line shows the target speed as calculated by the traffic light assistant. The HMI versions either contained (+) or did not contain (−) each of the information units traffic light information (TL), action recommendations (action) or speed recommendations (speed; [1])

criteria of the Alliance of Automobile Manufacturers (AAM), recommending an 85% percentile of 2 s for single gaze durations [13] and the ISO 15005:2002, which mentions maximum gaze durations of on average 1.5 s [14].

7.3.1.4 Conclusions

The study showed that drivers preferred HMI versions containing traffic light phase information. This supports previous research indicating a preference for status information in non-time critical situations [15]. From a driver perspective, the traffic light phase information best visualised the increased knowledge provided by the assistance system and might have served as an explanation for the action and speed recommendations. Driving performance was best with a combination of action and speed recommendations; by presenting these information units, drivers do not rely on their own interpretation of the traffic light status. Instead, the system provides the most efficient behaviour. Additionally, it is likely that providing speed and action recommendations allows drivers to rely on the information unit that is most relevant in each driving situation (e. g. speed recommendations when approaching a green light, action recommendations when stopping at red). In particular, the assistant was helpful in situations with a traffic light phase change. This is in line with research that demonstrated that recommending driver assistance systems support drivers in situations in which a necessary driving manoeuver (e. g. deceleration) cannot be perceived in advance [16]. There was no negative influence on gaze behaviour and drivers showed no indication for overload or stress in reaction to any HMI version. Hence, for the visual display of the traffic light assistant the combination of all three information units is recommended. The results confirm the redundancy rather than the overload hypothesis.

7.3.2 Traffic Light Assistance in Platoon Driving

Traffic is a social system and interactions between road users frequently occur in an urban road environment. For the evaluation of a recommending driver assistance system, it is valuable to evaluate the acceptance for and the effectiveness of the system in the context of driving in a platoon with other road users.

7.3.2.1 Interactions Between Road Users

When driving in a platoon of drivers, a lead vehicle driving with traffic light assistant naturally influences the driving behaviour of following vehicles. For example, [17] showed that when only the lead vehicle of a platoon of ten vehicles was equipped with a traffic light assistant, the overall fuel consumption was reduced by 30% compared to the condition without any equipped vehicle in the platoon. Others pointed out that especially in busy conditions like congested traffic, drivers attention is on safe driving rather than following the recommendations of driver assistance systems. Hence, the potential for efficient driving is reduced when drivers are not in free-flowing driving situations [18].

As mentioned above, the adaptions in driving behaviour cover basic driving behaviours like speed choice, acceleration, or deceleration. The drivers following the recommendations of the traffic light assistant have an increased awareness for their basic driving behaviour. Therefore, it was hypothesised that drivers following the recommendations of the traffic light assistant might also have an increased awareness of the influence of their own driving behaviour on other road user's perception. It is likely possible that the changes in basic driving behaviour are perceived by surrounding road users.

At the same time, the communication channels for the interactions between drivers are limited [19]. Research has shown that conflicts occur in situations when drivers in the same platoon come to different conclusions on the choice of speed, acceleration, and deceleration [20]. This is particularly of relevance when considering mixed penetration rates for recommending driver assistance systems. In traffic, there might be informed drivers with traffic light assistant as well as drivers without knowledge from such systems. The latter are not aware of the reasons for unexpected driving behaviours by the informed drivers.

7.3.2.2 Experiment in Multi-driver Simulator

In the experiment [21–23], drivers approached traffic light intersections in a platoon of four drivers. The multi-driver simulator as presented in Chap. 21 is a tool to carry out standardised experimental conditions for multiple drivers within the same virtual driving reality. The drivers were individually instructed. Half of the drivers were equipped with a traffic light assistant, while half of the drivers did not know of the presence of any assistance system. Each participant approached the intersection with varying positions in the platoon (positions 1, 2, 3 and 4; Fig. 7.5). The traffic light assistant was activated either 200 m or 400 m in front of the intersection. During the drives, the HMI screen presented the visual recommendations of the traffic light assistant.

In the analyses, the percentage of traffic light approaches with stops at the traffic light was determined for each condition. The scenarios were planned so that drivers sticking to the recommendations could either cross the intersection by adapting their driving speed or initiate a stop at a red light. Based on that, the deviation from predicted percentage of stops as planned from the structure of the scenarios and the actual percentage of stops for each condition was identified. Values lower than 0% indicate that drivers stopped more often than would have been necessary when sticking to the recommendations of the traffic light assistant. The higher the calculated values, the higher the beneficial effects of the system on driving behaviour.

On average, drivers with traffic light assistant crossed the intersection more often without a stop compared to drivers who did not receive the recommendations from the system (with assistant: m = –20.31%, without assistant: m = –30.00%). Hence, driving with the traffic light assistant has the potential to improve efficiency when approaching the traffic

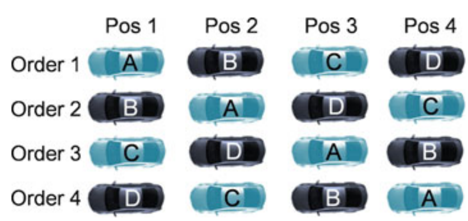

Fig. 7.5 Vehicles A–D represent the four drivers in one platoon. Drivers A and C drove with traffic light assistant. Drivers B and D did not receive recommendations. In the experiment, four orders were realised [23]

light intersections, whereby drivers without traffic light assistant benefit from drivers with system driving in front of them.

Certain conditions reduced the efficiency of the traffic light assistant (Fig. 7.6a). Drivers were less compliant to the recommendations of the system when driving in the front positions of the platoon, resulting into a higher likelihood for a stop at a red light. The influence of the position in the platoon was stronger, when the recommendations started further away from the traffic light. Beneficial effects of an early start of the recommendations at 400 m in front of the intersection were only realised when drivers were in the back positions of the platoon.

An explanation for the lower compliance in certain conditions could be seen in the drivers' emotional evaluation of the situations. Participants driving with traffic light assistant were instructed to pull a lever at the steering wheel when they felt they were bothering other road users. Fig. 7.6b shows the percentage of traffic light approaches with lever pulls of drivers with traffic light assistant in relation to the total number of traffic light approaches in each condition. The numbers were differentiated for the position in the platoon, the distance at which the HMI notification turned on, and the actual distance area in front of the intersection (i. e. if the lever pull occurred between 0–200 m in front of

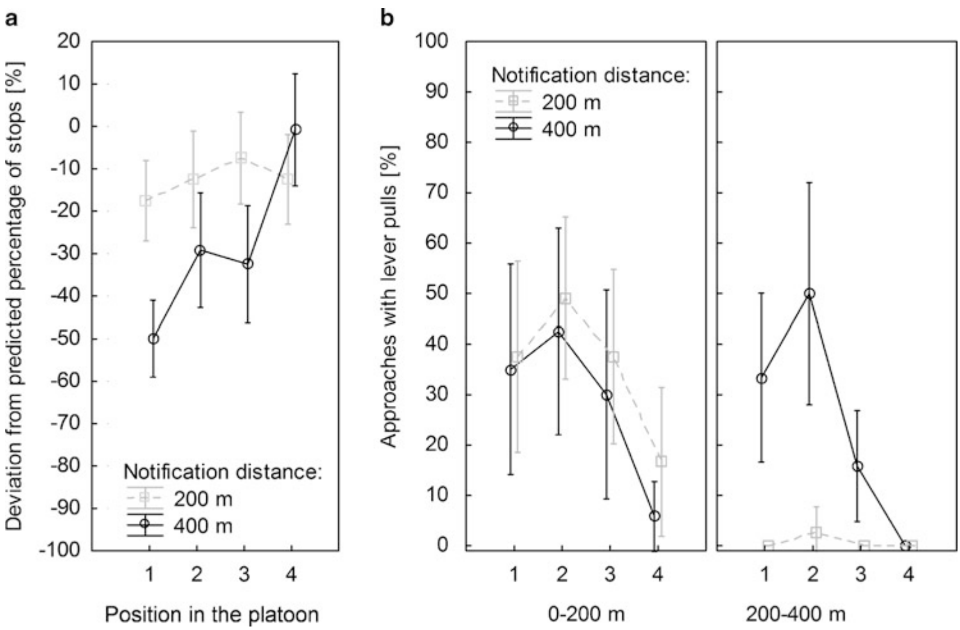

Fig. 7.6 **a** Deviation of real percentage of stops from predicted percentage of stops when considering full compliance to the traffic light assistant, differentiated for the notification distance and the positions in the platoon. **b** Percentage of traffic light approaches in which drivers pulled the lever to express that they felt they were bothering other road users, differentiated for the notification distance, the positions in the platoon and the actual distance section in front of the traffic light. The graphs show means with 95% confidence intervals

Table 7.1 Proportion of approaches in which a driver pulled the lever when the directly leading vehicle also pulled the lever [%]. The pairs are described by the position of the lead vehicle with traffic light assistant (position 1, 2 or 3) and the position of the directly following driver without traffic light assistant (position 2, 3 or 4)

Notification distance	Pair 1/2	Pair 2/3	Pair 3/4
200	31.25	53.33	0.00
400	42.11	55.88	50.00

the intersection, or between 200–400 m in front of the intersection). The graph shows that drivers more often felt they were bothering other road users when driving in the front positions of the platoon compared to the fourth position. Lever pulls were related to system activation: When the system was activated 200 m in front of the intersection, hardly any drivers felt they were bothering others between 200 and 400 m in front of the intersection. Hence, with no following vehicle, or when there was no system activated, no drivers felt that they were bothering other road users.

The results raise the question if the drivers' feeling of bothering others was justified, i. e. if the other road users were actually annoyed. During the experiment, participants driving without traffic light assistant were instructed to pull the lever at the steering wheel whenever they felt annoyed by other road users. Table 7.1 shows the relation between traffic light approaches in which a driver with traffic light assistant pulled the lever and the approaches in which the directly following driver also pulled the lever. On average, in 38.76% of the traffic light approaches in which a driver with traffic light assistant pulled the lever, the directly following driver also pulled the lever. Hence, in many situations in which drivers believed they bothered others, the following driver actually was not annoyed by the lead vehicles behaviour.

7.3.2.3 Conclusions

The compliance to the information presented by a recommending driver assistance system does not only depend on the HMI strategy in terms of display design, but also on the drivers' own perception of his current role in a platoon of vehicles. The driving simulator setting was realistic concerning the fact that no driver was aware of the presence or absence of systems in other vehicles. The results showed that in many situations in which drivers believe they bother others, they actually do not trigger anger in the following vehicle. Nevertheless, the feeling of bothering others might explain the lower compliance in certain driving situations. In future, informing other road users of the presence of a recommending system in other vehicles (e. g. by providing stickers at the trunk) could offer the possibility to communicate and explain deviations from expected or "normal" driving behaviour to other road users. In the end, this will increase the acceptance for other road users' behaviour in drivers without system and might increase comfort with sticking to the recommendations of the system in drivers equipped with the traffic light assistant. The information on the presence of the system in others could also increase the awareness of drivers who do not own the assistance system that they can benefit from following a lead vehicle with system.

Finally, the results will influence the design and parameterization of recommending assistance system. The system could avoid recommending certain driving behaviours in scenarios in which drivers feel uncomfortable by sticking to the recommendations. For example, the system should not recommend very low driving speeds at far distances to the intersection and a lower limit for given speed recommendations (e. g. 30 km/h for urban environments) should be considered. Like this, anger or frustration with the system can be avoided and drivers might be more willing to use the system in a larger number of situations, instead of turning it off for good due to low acceptance in specific situations.

7.3.3 The Influence of Complex Traffic Conditions

The two studies reported in the previous chapters were conducted in controlled driving simulator environments. The evaluation of the HMI concept in real traffic conditions represents a crucial part of the development of the system. In real traffic conditions, the number of possible influences on driving behaviour is large and both, system and driver, might show different behaviour compared to controlled environmental conditions.

7.3.3.1 Driving in Real Traffic

In the UR:BAN project, an intersection in Braunschweig, Germany was build up with research equipment and vehicle-to-infrastructure communication units. The four-way intersection shows a high level of complexity. There are multiple lanes in each of the four directions, allowing different numbers of lanes for turning left or right (Fig. 7.7). Additionally, the intersection is busy in terms of traffic density. During the testing reported in the following paragraphs, the traffic light sent information on the current traffic light phase, but did not include information on standing vehicles at the intersection.

An investigation in real traffic took place with four participants approaching the traffic light overall 28 times between 11 am and 3 pm of a weekday in May 2015. The instruction to the drivers was to approach the intersection while sticking to the recommendations of the traffic light assistant presented in the cluster display.

During the traffic light approaches, there was a major influence of the complex traffic conditions on the scenarios experienced by the participants. The likelihood for a stop at the intersection was very high, because of the missing information on the queue length of vehicles at the intersection and the high traffic density. In only 3% of the traffic light approaches, the participants were able to follow successfully the recommendations for a green light. Additionally, the chances for standardisation and reproduction of conditions within and between participants were low. Each traffic light approach took place under a different combination of traffic (e. g. length of the queue of vehicles ahead, vehicles turning, vehicles changing lanes) and traffic light phases, which resulted in subjective

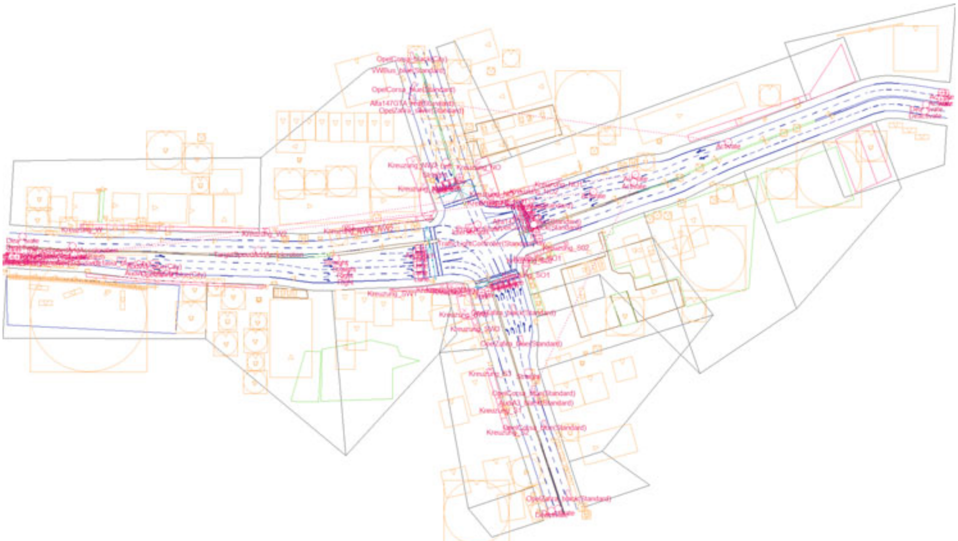

Fig. 7.7 The Braunschweig research intersection rebuild in the data base editor of the driving simulator software SILAB of WIVW GmbH with objects representing the infrastructure elements of the real intersection

evaluations of the system and driving behaviour that could not be interpreted in a meaningful way.

Following the observations in real traffic, a study design was developed that allowed to test the influence of complex traffic conditions in a standardised way [24].

7.3.3.2 Complex Traffic Conditions in the Driving Simulator

The Braunschweig intersection was re-build in the data base editor of the driving simulator software SILAB of the WIVW GmbH. The simulation contained a rebuild of the exact number of lanes, the position of buildings and trees and the position of the traffic lights. Additionally, the original vehicle application for the traffic light assistant was implemented. The system was able to process information on the queue of standing vehicles at the intersection. Hence, in cases with standing vehicles at the intersection, the increasing distance of the virtual stop line to the intersection was considered in the recommendations of the system. The system did not include information on driving vehicles around the intersection area (Fig. 7.8).

The experimental design of the driving simulator study was driven by the complexity of the road environment and the natural limitations of the function (information on standing but not on driving vehicles). There were different lead vehicle conditions, with either no lead vehicle, driving lead vehicles, or standing lead vehicles at the intersection (Fig. 7.9). The traffic light was either red or green. Additionally, the likelihood for driving through the green light was varied. From the test drives in real traffic, the expectation was that the

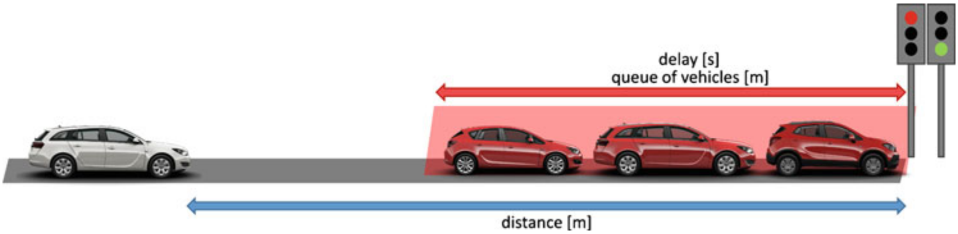

Fig. 7.8 Schematic depiction of a traffic light approach with a queue of three vehicles. A line up of vehicles leads to a virtual shift of the stop line. The algorithm considers assumptions on the duration for the reduction of the queue

likelihood for an arrival at red would influence the driver's perception of the traffic light assistant. Hence, a third of the participants experienced a 25% likelihood for reaching the light at red (i. e. more often caught a green light), another third of the participants experienced a 50% likelihood for stopping at a red light and a last third experienced a stop at the intersection in 75% of the traffic light approaches. Resulting from the combination of the lead vehicle and traffic light conditions and one repetition of each condition, drivers approached the intersection in the simulated environment 12 times with traffic light assistant, in addition to a baseline drive without traffic light assistant. Overall, 36 participants took part in the study that was conducted in a static driving simulator. Subjective evaluations and fuel consumption were investigated considering 12 traffic light approaches in total, which allows conclusions on the variation of the likelihood for arrival at a red light.

Fig. 7.9 Picture of the Braunschweig intersection with a standing lead vehicle in the SILAB driving simulator at WIVW GmbH

The analysis of individual traffic light approaches allowed investigating the influence of the traffic light phase at arrival and the lead vehicle conditions.

After driving through the whole test track with the traffic light assistant, drivers were asked about the helpfulness of the system overall. They answered on a verbal-numeric scale from 0 (not helpful at all) to 15 (very helpful). Fig. 7.10a shows that the agreement to the question was medium to low. There was an influence of the likelihood for arrival at a red light: When drivers frequently stopped at a red light, they rated the helpfulness of the system as low. In addition to the overall evaluation after the whole test drive, the experimenter asked for an evaluation of the system after each traffic light approach ("How helpful was the system in the current situation?"; Fig. 7.10b). The presence of lead vehicles had a significant influence on drivers' evaluations of the system. Without lead vehicle, the system was most helpful. Helpfulness was lower with standing vehicles and decreased further with driving vehicles at the intersection. With no lead vehicles and standing vehicles, the system was rated as more helpful when drivers reached the intersection at a green light compared to the conditions in which they had to stop at a red light. In the condition with driving lead vehicles, there was no influence of the traffic light phase at arrival.

During the tests, the experimenter collected open comments about the reasons for the numeric helpfulness evaluation. The categorization and frequencies for comments are depicted in Fig. 7.11. In conditions with driving lead vehicles, there was a large number of comments relating to other road users (e. g. "Even though there is a lead vehicle, the system recommends a high speed"). Hence, the low evaluations of helpfulness in lead vehicle conditions was actually related to the presence of the driving lead vehicle. With red traffic lights, there was a large number of comments relating to the benefit of driving with the system. Two examples for comments from that category are "Without assistance, I would

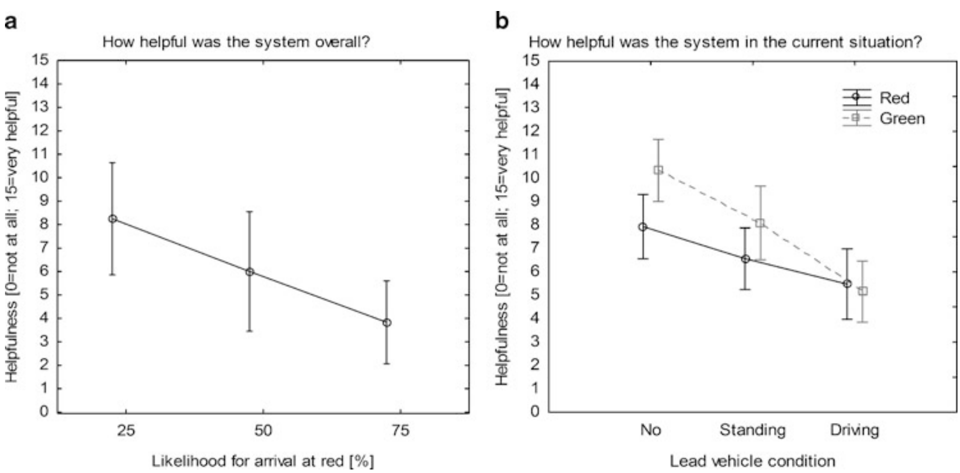

Fig. 7.10 Helpfulness evaluation differentiated for the likelihood for an arrival at red during the whole experiment (**a**) and for the lead vehicle and traffic light phase conditions averaged over individual traffic light approaches (**b**). The graphs show means with 95% confidence intervals

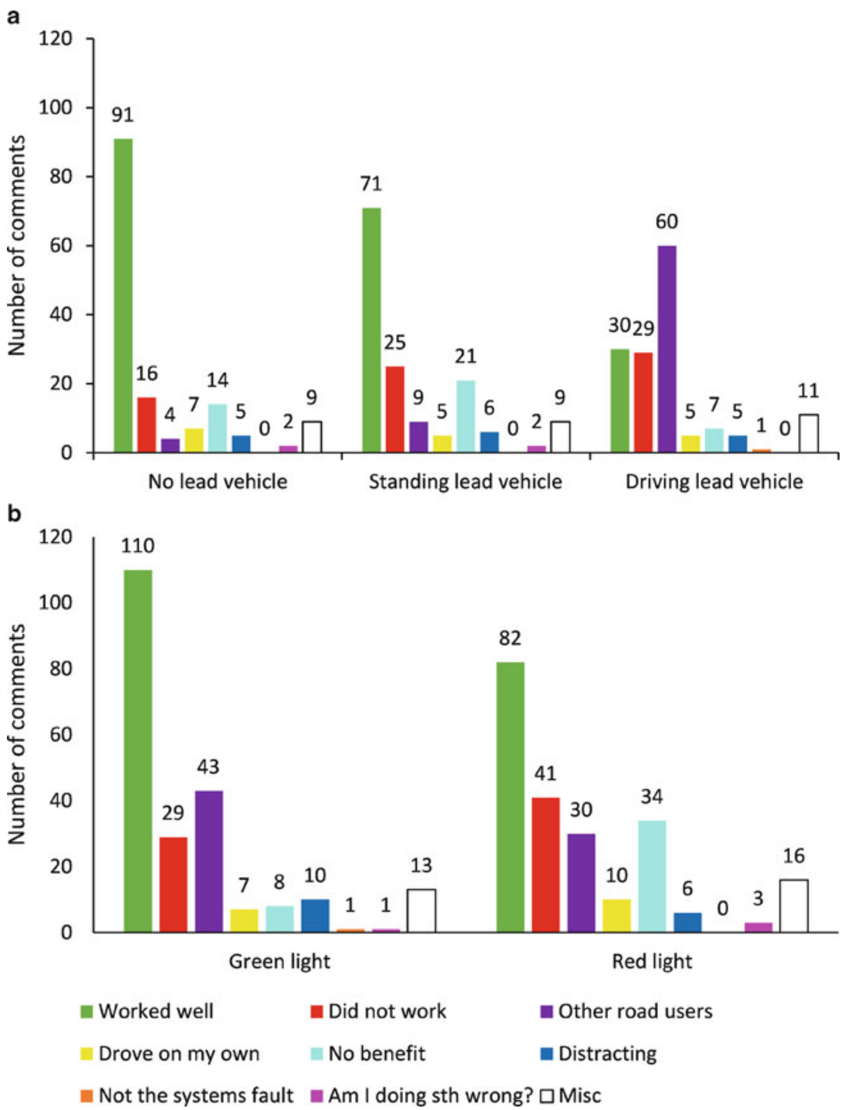

Fig. 7.11 Categorized number of comments stated by participants after each traffic light approach. Note that the same statements were categorised according to the lead vehicle conditions (**a**) and the traffic light conditions (**b**)

have driven exactly the same" and "The display did not show anything wrong, but I still had to stop at the intersection". Interestingly, only one single driver in a single situation commented that "it is not the systems fault if lead vehicles brake" (orange category). As a conclusion, even though drivers experienced that their driving behaviour was disturbed

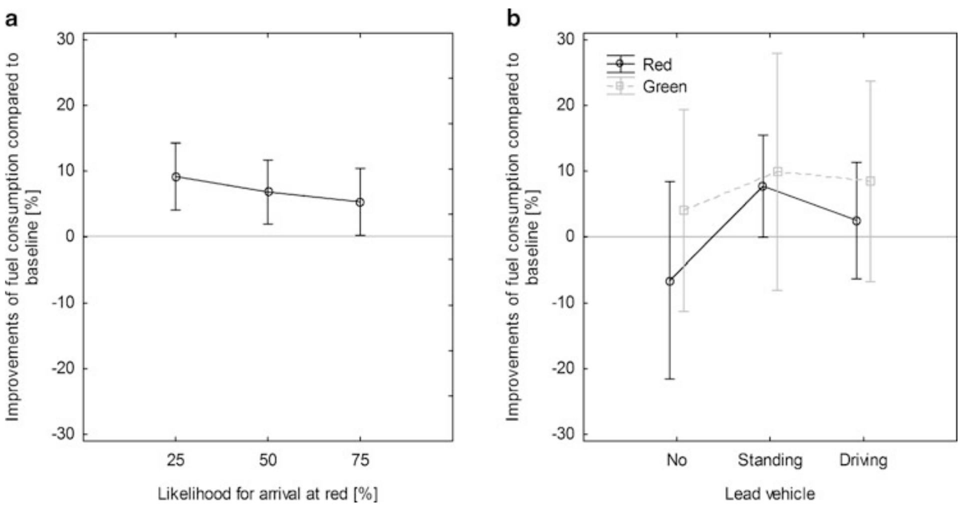

Fig. 7.12 Percentage of improvements in fuel consumption when driving with traffic light assistant compared to driving without traffic light assistant differentiated for the likelihood for an arrival at red during the whole experiment (**a**) and for the lead vehicle and traffic light conditions averaged over individual traffic light approaches (**b**). The graphs show means with 95% confidence intervals

in some situations by lead vehicles, their expectation was that the system considers the presence of lead vehicles in its recommendations.

Finally, the objective benefits of driving with the system were evaluated in terms of fuel consumption. Therefore, the SILAB driving simulator consumption model recorded fuel consumption. Fig. 7.12 shows the improvements of fuel consumption in the test runs compared to the baseline condition in percentages. Positive values indicate the percentage of improvements in fuel consumption (i. e. less fuel consumption when driving with compared to without system), negative values indicate deterioration of fuel consumption (i. e. more fuel consumption when driving with compared to without system). Again, the data were analysed based on all traffic light approaches during the whole experiment, and based on a comparison of individual traffic light approaches with different traffic conditions. In general, driving with the traffic light assistant led to improvements in fuel consumption between 5–10% during traffic light approaches. There were no significant differences between any of the conditions. Fuel savings were achieved even in conditions in which drivers evaluated the system as not very helpful.

7.3.3.3 Conclusions

First, from the investigation of the influence of complex traffic on acceptance and efficiency of a traffic light assistant, a methodological conclusion can be drawn. The complex conditions that were observed in the real traffic were successfully varied in the driving simulator setting. The original traffic light assistance system recommended instructions based on the participants driving behaviour. Therefore, the dynamics of the system were mirrored in the virtual reality, but controlled variations for lead vehicle and traffic light phasing allowed for clear interpretation of results. Second, the system led to improvements of efficiency in terms of fuel consumption. With traffic light assistant, drivers consumed less fuel compared to driving without the assistant. Third, the traffic conditions influenced how drivers experienced and evaluated the traffic light assistant. Limitations in the ability to stick to the recommendations were not attributed to the traffic conditions (e. g. a standing lead vehicle), but to the system itself. Drivers expected that in situations in which they could see the lead vehicles, the system should consider these traffic conditions. Additionally, an increasing likelihood for the arrival at red decreased the acceptance for the system. Even though the case of arrival at red is considered as a use case (and in fact leads to improvements in efficiency when following the system instructions), drivers see the traffic light assistant as a support for crossing the green light rather than as a support for an efficient approach to a red light.

Finally, the exact information on the traffic conditions in terms of surrounding vehicles and tailgating at the intersection are essential to be considered by the traffic light assistant. This could be realised by the integration of information from different sensor systems (on board sensors, sensors at the traffic light itself, Vehicle-to-X communication). Consequently, the efficiency and the acceptance for the system will improve. Emphasizing the benefits of the system to drivers (in particular for red light approaches) might improve the willingness to use the system.

7.3.4 Summary

The research presented in this section demonstrated an example for the development of an HMI concept for a recommending driver assistance system. The choice of the HMI component and the design for the presented contents was presented, along with evaluation criteria for the selection of the most appropriate concept. For the traffic light assistant, drivers subjectively desired information on the traffic light phasing, while specific recommendations of actions and driving speed improved their driving performance. The traffic light phase information was desired because it offers dynamic status information about the infrastructure that the drivers cannot perceive or deduct themselves.

The complex urban traffic conditions while using the traffic light assistant are crucial for driver's attention for the recommendations, the ability, and the willingness to follow the recommendations. Depending on the technical capabilities of the system, the system might consider other vehicles (e. g. by detection through on-board sensors), the road geometry (e. g. provided by map data), or the infrastructure elements (e. g. provided by Vehicle-to-X communication). Still, due to the complexity and dynamics of urban traffic, there are limitations to the correct representation of the real traffic conditions in the system. Even though these limitations seem obvious from a technical perspective, the studies showed that drivers experienced the provided information as incorrect because they were not able to follow or did not feel comfortable with the recommendations. The information did not match their own perception of the traffic conditions.

The advantage of recommending assistance systems in comparison to regulating systems is that the driver is the control unit who integrates all relevant information available from the system and the environment at any time. While in regulating systems, the system support ends with driver interference, recommending systems offer the opportunity for the continuous recommendation of beneficial behaviours. The system provides the dynamically changing information and the driver decides if in the current situation the recommended behaviour makes sense (e. g. in terms of limitations in traffic) and feels comfortable (e. g. in terms of bothering other road users). This might also be the reason for the subjective preference of traffic light phase information in the display, which allows the drivers an improved interpretation of the traffic situation while concluding self-paced the modification of their own driving behaviour. As a consequence, future research needs to investigate how more information on the actual benefits of using the system in various situations and on how the system actually integrates the available information, along with explanations about the influence of sticking to the recommendations on other road users could increase the acceptance and the willingness to use the system.

7.4 Generic, Integrative HMI Concept for Multiple ADAS (Technical University of Munich)

In the future, full use of advanced driving assistance systems will shift from highways and freeways to urban areas. This additional ADAS use case may require communication of additional information and warnings to the driver. Urban areas themselves are characterised by much greater complexity for different reasons such as a variety of different road users or greater information density (Chap. 1).

The solution for this might be a more generic, integrative HMI concept using a multimodal approach for recommending driver assistance systems. New technologies for in-vehicle components such as the head-up display (HUD), a programmable instrument cluster (head-down display, HDD), or a force feedback pedal will also change the way information is presented to the driver. Consequently, a new HMI concept needs to be iteratively developed and evaluated.

Defining the terms "integrative" and "generic" may help to understand the aim of this new concept. While older HMI design concepts are characterised by single solutions for every component and every single driver assistance system, an integrative approach was taken here to ensure the fewest possible information redundancies as well as action-oriented strategies featuring very little effort decoding the given information. The generic idea also combines similar ADAS with related actions in a way that the driver does not necessarily know where the information comes from but does know what to do in a specific scenario. This solution provides the expandability and flexibility to add new driver assistance systems later in the final concept.

The overall concept, developed and evaluated by the Institute of Ergonomics in the "Human-Machine-Interaction" subproject, can be found in the HMI tool kit's path "Recommended action" (see Fig. 7.13) (cf. Chap. 4). It consists of two visual and one haptic component augmented by the auditory channel for very critical warnings and navigation commands. The benefit of using different modalities derives from the multiple-resource theory [25], which states that stimuli of various modalities are processed faster than just single stimuli of the same modality. The head-up display and the instrument cluster were therefore chosen as visual components. Additionally, the force feedback pedal (FFP) represents the haptic component. These components all have several advantages (as stated earlier in the design guidelines) and disadvantages and impose qualitative and quantitative requirements [26]. For example, while information presented in the HUD allows much shorter reaction times [27], information can be much more detailed in the instrument cluster [26]. Furthermore, the FFP allows information to be presented where the driver needs to react [28] while keeping his eyes on the road.

In total, five different studies were conducted. Experiment 1 (Sect. 7.4.1) started with a literature search for the aforementioned components as well as with a specification of different information and warning strategies. In the experiment itself, the head-up and head-down display were compared in the respective categories. An initial concept was subsequently created and implemented with the information gathered for Experiment 2 (Sect. 7.4.2) in a static driving simulator. The aim of this initial study of the overall concept was to evaluate different ADAS and the way to present them to the driver in an urban setting.

The increasing number of different ADAS occasioned an additional study comparing two different ways of presenting information in a head-up display, which was conducted in Experiment 3 (Sect. 7.4.3). The results should help promote a more user-centred, action-oriented presentation of information.

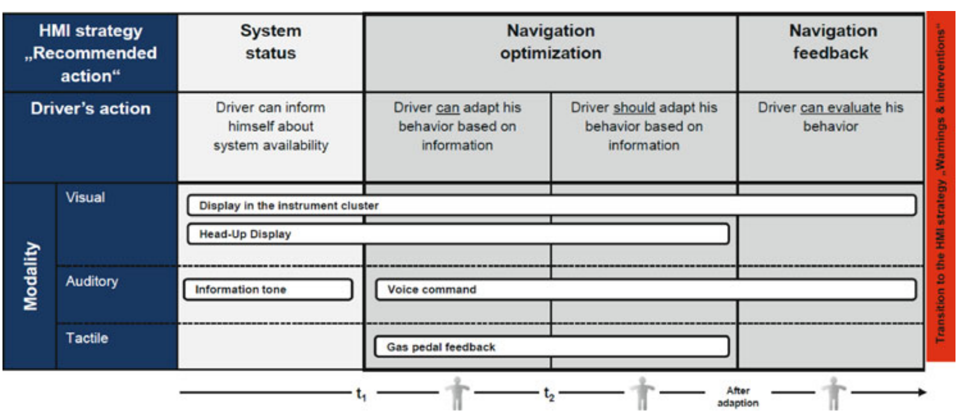

Fig. 7.13 Scheme of this specific HMI concept for the "Recommended action" HMI strategy

On the basis of those first three studies, an upgraded version of the HMI concept was implemented and evaluated in two different parts of Experiment 4 (Sect. 7.4.4) testing either longitudinal or lateral driver assistance systems alone. As a final experiment (Sect. 7.4.5), with input from all of prior studies, the final concept was tested and compared to a purely iconic approach – again in a static driving simulator. This final study included both longitudinal and lateral driving assistance systems.

7.4.1 Experiment 1: Head-up vs. Head-down Display

The information from the ADAS for the driver can be categorised into five different types. The information in each category aims to trigger different driver reactions. Fig. 7.14 presents the five categories.

The study aimed to investigate which of these five types of information is most suited for head-up or head-down displays in terms of reaction time, level of disturbance, and workload. As the first step, this should define some general guidelines for the visual components [29].

The study was conducted in a static driving simulator with 180° front view. All participants had to perform a navigated driving task in an urban environment. Each operated either the head-up display or the head-down display. Different scenarios with the aforementioned information categories were used. The driver's workload was also measured using the standardised NASA-TLX questionnaire [30]. Furthermore, objective data was recorded to compare driving performance with both conditions in terms of reaction time, lane keeping, and speed violations.

The results show no significant difference except for a tendency to favour the head-up display in terms of reaction times. Moreover, the distance to lane centre shows no significant difference either. However, the NASA-TLX reveals significantly less workload for the head-up display in the overall score (see Fig. 7.15). In detail, the physical effort,

Category	Description
Action directives/request	Concrete presentation of the required reaction e.g. demand to brake, navigation instructions
Situational information	Specific warning with indication of the type or location e.g. lane change warning
Attention control	General increase of attention or non-specific reference to risky situations e.g. warning tone
Conditional information	Representation of the vehicle state e.g. display of availability or indication
Detailed information	Numerical values or text content e.g. speedometer

Fig. 7.14 Categorisation of the content of information given with a warning/information [26]

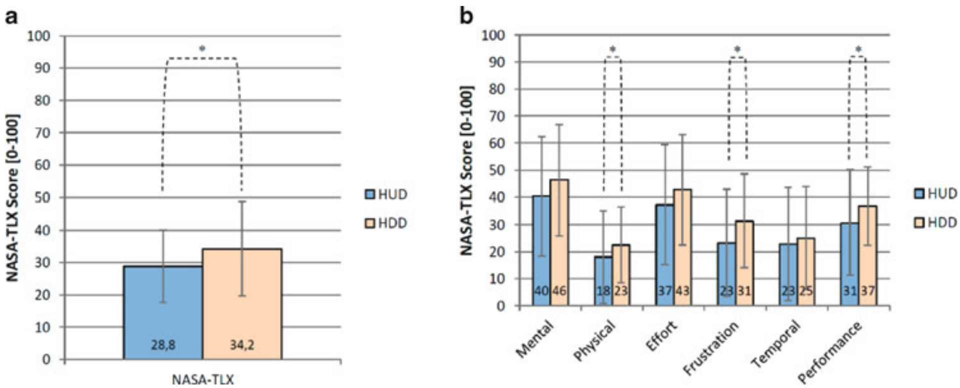

Fig. 7.15 The overall NASA-TLX score for the global task load index with the average of all six categories (**a**) and the score for each category in particular (**b**) [29]

frustration, and subjective performance are significant less. In the subjective questionnaire, participants significantly preferred the HUD to the HDD regarding the level of disturbance caused by status and indication symbols.

In conclusion, the head-up display is preferred for time critical, dynamic, and direct driving-related information while the head-down display can display non-critical, proactive, and other information in much greater detail. Götze and Bengler [29] provide all the results in detail.

7.4.2 Experiment 2: First Draft of the Overall HMI Concept

An initial draft of an overall generic, integrative HMI concept was developed after evaluating the different information and warning strategies. The force feedback pedal is henceforth included as a haptic component. A clustered HMI design concept for the head-up display was chosen (Fig. 7.16) in consequence of the literature research [26] and the first study's results [29].

Fig. 7.16 Cluster of the head-up display in the coloured version (**a**) and monochrome version (**b**) [31]

The information presented in the three clusters is divided into different categories. All of the speed-relevant information such as current speed and speed limit is presented on the left. The centre cluster is used for navigation instructions. The last category includes all of the ADAS information for the driver.

This method helps the driver to locate relevant information much more quickly. The head-down dis-play (or instrument cluster) presents non-time-critical and driving-relevant information. All of that information is displayed between the two gauges, which are left untouched. Finally, the force feedback pedal transmits an adjustable pressure threshold (speed maintenance) or a noticeable counter-pressure (speed reduction) [32]. Neither visual nor haptic information was displayed to the driver without an active ADAS.

As a first approach with the overall HMI concept, assistance systems were implemented only in the longitudinal direction. These comprised a speed assistant using the FFP's haptic feedback to help the driver maintain the legal speed limit, speed-sign icons in the HUD and HDD, and a traffic-light assistant to reduce possible downtimes when approaching a traffic light. A vehicle-distance assistant was implemented to help when following a leading vehicle.

The study's procedure was similar to that for the initial study. Participants completed two urban driving tasks: one with the HMI concept and one without any ADAS information. Objective and subjective data was recorded once again. The results showed no significant workload difference between the two concepts using the NASA-TLX score. That means displaying all that additional visual and haptic information does not create further distraction. Furthermore, significantly more speed violations exceeding 5 km/h happen without the system (cf. Fig. 7.17b).

The traffic-light assistant resulted in significantly less loss of speed when approaching a traffic light using the HMI concept (see Fig. 7.17a). Unfortunately, participants did not

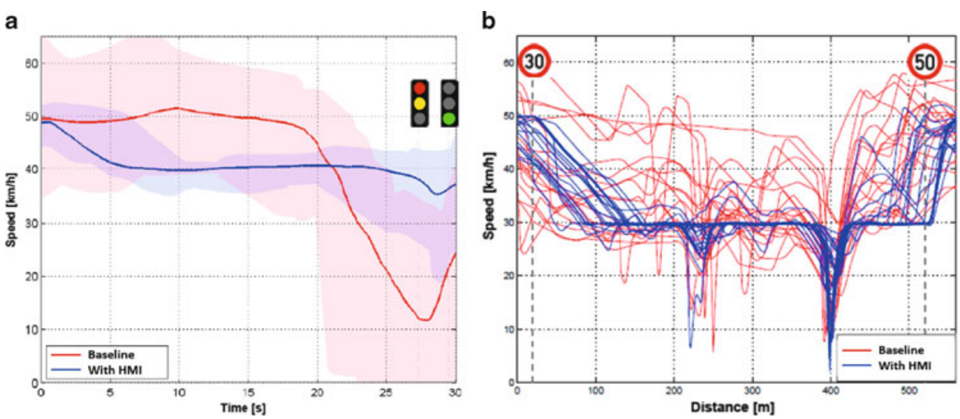

Fig. 7.17 Average speed while approaching the traffic light (with speed range of all participants) (**a**) and Velocity curve of all participants using either the speed assistant or no ADAS in an area with speed limit. The graph shows the average speed of all participants with active speed assistant (*blue*) and without (*baseline; red*) (**b**) [31]

like the vehicle-distance assistant, because some preferred larger and others smaller gaps. An adjustable version might solve this problem.

In sum, the force feedback pedal has great potential for providing speed-related information without demanding the driver's visual attention. Participants reported that the instrument cluster became unnecessary since they preferred the HUD and FFP for obtaining all of the important information and warnings. As a next step before adding more ADAS to the overall HMI design concept, a new generic way of presenting information in the HUD should be considered because of the limited space for displaying information.

7.4.3 Experiment 3: Generic Head-up Display vs. Cluster Design

The way information is presented in head-up displays needs to change due to the increasing number of ADAS available in the vehicle. While some years back most cars displayed only the current speed, traffic signs, and cruise-control information in the head-up display, there is now a lot more available such as traffic-light assistance, assistance for intersections, or narrow-space assistance. The new design concept needs to be more action-oriented, generic, and driver-focused. The idea is to present the necessary information in the centre of the head-up display with less important information at the periphery.

The new concept was compared to a well-known cluster-design concept [33] used in current vehicles. The study was conducted in a BMW X5 test vehicle with a series-type head-up display (480 × 240 px) with the colours red, yellow, and green. The vehicle was positioned in front of a protection screen (see Fig. 7.18). Participants completed a choice reaction time task (CRT) [34] and an occlusion task [35–37] using a joystick and a key pad.

During the CRT task, participants had to react to different stimuli. Reaction time and accuracy were recorded. For the occlusion task, different kinds of questions needed to be answered; only accuracy was recorded. Additionally, the Post Study System Usability

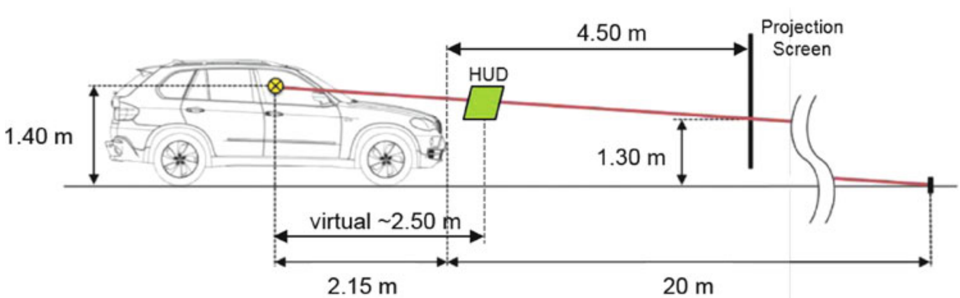

Fig. 7.18 Framework of the study showing the different (virtual) distances between the driver, the vehicle, head-up display and projection screen [38]

Questionnaire (PSSUQ) [39, 40] was used to measure the usability of the different HMI concepts and as an open questionnaire.

Thirty participants took part in the study [38]. Results showed significantly better reaction times for the new generic HMI concept (using the CRT task). No significant accuracy difference was found in either experimental part. The PSSUQ showed a tendency to significance for the clustered HMI design. Participants also commented that the cluster design felt tidier and cleaner, but the objective data contradicted them.

In summary, both concepts have advantages and disadvantages. A combined solution could offer the benefits of both design concepts for a new and better HMI for urban driving. The answer might be a clustered design with efficient classification into speed-related, navigation, and ADAS information presented in a generic, integrated way in the middle of the HUD.

7.4.4 Experiment 4: Overall HMI Concept in Longitudinal or Lateral Recommendations

With the lessons learned from studies 2 and 3, a revised version of the overall HMI concept was developed and implemented in a simulation environment. While the initial study took only ADAS in longitudinal direction into account, this experiment added an experimental part with assistance systems in the lateral direction. Participants drove either way in an independent sample.

Fig. 7.19 shows the final concept. The upper part represents the head-up display; the lower part shows the instrument cluster. The force feedback pedal was included as in the initial study. Traffic sign, traffic light, and speed assistants were implemented for the

Fig. 7.19 The final concept with the head-up design (*top*) and the instrument cluster design (*bottom*)

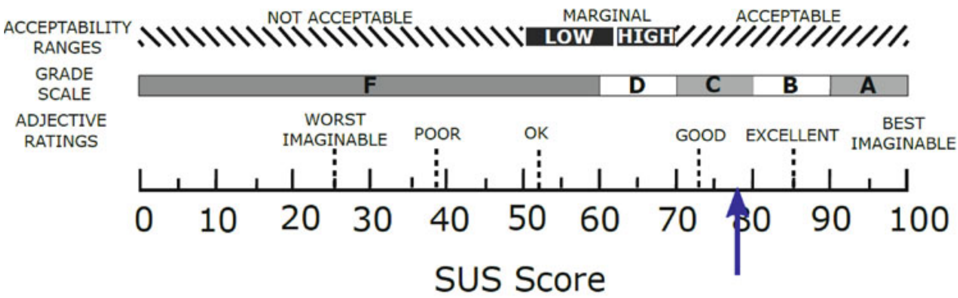

Fig. 7.20 The SUS score of 78 for both parts of the experiment with a rating between "good" and "excellent" for the overall HMI design concept

longitudinal part. The lateral experimental part included a traffic-sign assistant and a speed assistant as in the longitudinal part in addition to lane-keeping, lane-change, overtake, intersection, and narrow-space assistants.

Each of the parts was compared to a simple setup lacking HUD, force feedback pedal, and active ADAS. Objective data was again recorded to measure speed trends, time-to-collision in front of traffic lights, and reaction times. Further, the system usability scale (SUS) [41] rated the HMI concept's subjective benefits.

The results showed significantly fewer speed violations in both parts compared to no HMI concept as in the initial studies. Similar results were found for downtimes in front of traffic lights: significantly less waiting time and fewer speed fluctuations while approaching traffic lights. The lane-keeping assistant had no effect since it just informed the driver when leaving the lane and most drivers preferred driving nearer the centre of the street (not lane) when oncoming traffic was absent.

The information that the intersection assistant gave helped to avert significantly more collisions without actively assisting the driver. Furthermore, the narrow-space assistant significantly reduced entry speed. Both experimental parts show no significant workload difference compared to the part without the HMI. This indicates that the generic HMI concept's assistance for the driving task compensated for the additional visual load. Finally, the overall SUS score was 78 (Fig. 7.20) – the same for both parts, which is between excellent and good according to [42].

7.4.5 Experiment 5: The Generic, Integrated HMI Design Concept

The aim of the last study [43] was to evaluate the final HMI concept in an experiment with both lateral and longitudinal ADAS. The generic way of presenting the recommending information to the driver was not expected to cause a significantly greater workload compared to a very simple, purely visual HMI design consisting of icons (with no haptic feedback). Additionally, a prioritization strategy was developed to decide which information is more important in certain urban scenarios if several ADASs are simultaneously active.

The study was repeated in a 180° static driving simulator featuring an urban environment in which the final HMI design and the iconic HMI design were implemented. The experimental setup consisted of two very similar 15 min urban tracks with each of the aforementioned HMI designs. The head-up display, the instrument cluster, and force feedback pedal were used as in the prior studies. The speed and velocity profile, position data and distances, and TTC data were recorded for the test evaluation. Further, the NASA-TLX measured subjective workload, the SUS score rated usability, and an unrestricted questionnaire compared different subjective evaluations.

Thirty healthy volunteers with an average age of 25 years (SD = 4 years) participated in this study. Significant speed-violation differences favouring the generic design were found on both tracks (see Table 7.2). Track 1 showed about 4.1% speed violations for the iconic design compared to only 1.1% for the generic design. The difference on the second track was even higher with 9.2% excessive speed for the iconic concept and 2.3% for the generic HMI design. In addition to the significantly fewer speed violations, the variation in speed was much steadier and predictable, which yields even further advantages for efficient, proactive driving (Fig. 7.21).

This time, no significant differences were found for downtimes, TTC, or velocity variations when approaching a traffic light. There was a trend but no statistically relevant results. One of the reasons could be the identical timing of the given visual information in the head-up display and instrument cluster for both HMI concepts just with different graphics and icons. The subjective results for this ADAS implementation showed participants reporting significantly less information from the iconic design than from the generic one while yielding almost similar objective results. The narrow-space assistant produced the same results with no objective differences but subjective preference for the generic version.

The biggest difference between the two HMI designs for the intersection assistant is the localization of possible risk in the generic version while the iconic system just warns in general. The subjective results showed that this localization helped the driver to see the danger significantly earlier, with significantly less workload and significantly more awareness of other events occurring at the intersection.

Table 7.2 Speed violations for both tracks with the iconic design concept and the generic design concept. Both with significant less violations using the generic version

	Track 1		Track 2	
	Iconic	Generic	Iconic	Generic
Mean	4.13%	1.13%	9.20%	2.27%
SD	4.34%	1.55%	6.14%	2.43%
Significance	$U = -2.61$;	$p = 0.009$	$U = -3.52$;	$p < 0.001$

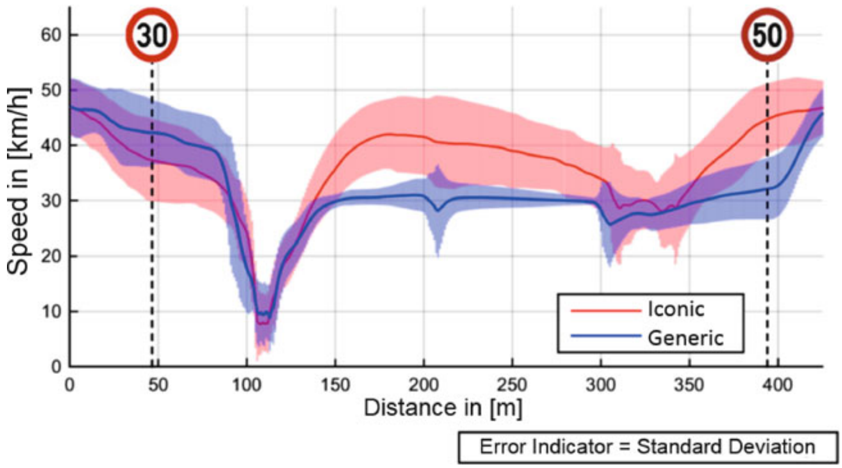

Fig. 7.21 Variation in speed passing a speed limit sign and an intersection with the iconic HMI design (*red*) and the generic design concept (*blue*)

Both concepts showed similar workload results for the NASA-TLX score. This is interesting because the generic HMI design gives a lot more specific information, which participants evaluated as significantly better. Furthermore, the overall SUS score was 72 for the iconic concept and 76 for the generic HMI design. Again, while the generic HMI falls between good and excellent and the iconic one is at the top end between OK and good, the difference is too small to show a significant advantage.

In sum, the new generic HMI concept exhibits the advantages of giving the driver detailed information without increasing workload or distraction. On the other hand, participants rated the iconic design significantly worse regarding information detail and ease of decoding. Moreover, the objective data showed significant advantages for the generic version particularly regarding speed- and velocity-related data. This can be transferred to more efficient and proactive driving. Altogether, the new concept fulfils the three main objectives of the UR:BAN project: safer, more efficient, lower stress driving in urban areas.

7.4.6 Key Messages for the Head-up Display and Force Feedback Pedal

The aforementioned studies in the project yielded a lot of interesting information and revealed the ad-vantages of different HMI in-vehicle components. This summary will help to provide an overview of the most important characteristics of the head-up display and force feedback pedal in urban scenarios. The key messages for both components regard general recommendations about "what" information should be displayed and, equally importantly, about "how" this information should be displayed to the driver. Fig. 7.22 gives a short but comprehensive overview of those findings.

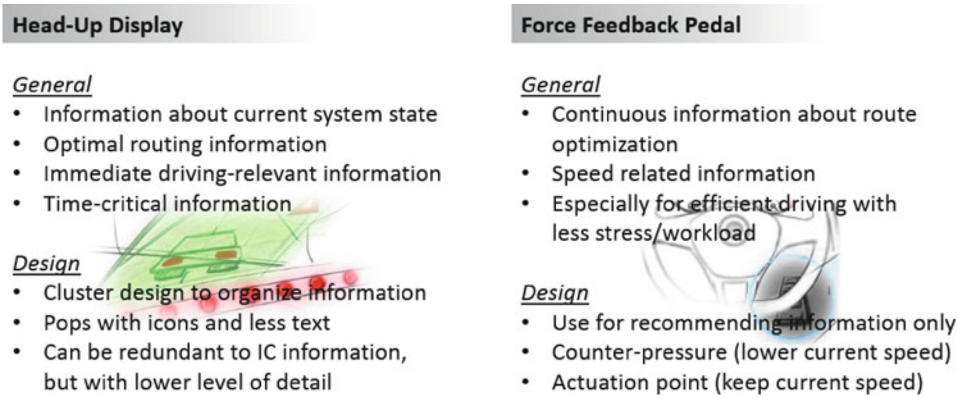

Fig. 7.22 General and design recommendations for the HMI components head-up display and the force feedback pedal

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Part IV

Behaviour Prediction and Intention Detection

Behaviour Prediction and Intention Detection in UR:BAN VIE – Overview and Introduction

8

Dietrich Manstetten

8.1 Introduction

Driver assistance and traffic systems have an enormous potential to improve road safety by targeted support of the human user (in this case the driver) in overly demanding or hazardous situations. To realise this potential and to achieve driver compliance, the systems need to act in accordance with the driver's own driving intentions and not at cross-purposes. This requirement is particularly important in urban traffic, due to its great complexity, diversity of situations and options for driver response; the limiting factor is usually the time budget for decisions, which is generally smaller than in freeway traffic and must be used as effectively as possible. If the intervention strategy of a vehicle system clashes with the intentions and actions of the driver, the resulting ambiguous situation could lead to delays, missing the window of opportunity for mitigating a traffic conflict. Hence, inferring the driver's intentions and predicting his response to a hazardous situation as early as possible are of central importance for coordinated driver assistance; intention inference and behaviour prediction should be adapted to the individual driver and the situation.

The central aims of the UR:BAN sub-project VIE (VIE is a German acronym for "**V**erhaltensprädiktion und **I**ntentions**E**rkennung", i. e. "Behaviour Prediction and Intention Detection") were:

- Systematic detection of driver intentions in urban areas on a manoeuvre and navigation level,
- prediction of his behaviour for a following manoeuvre (e. g. lane changing, turning),
- demonstration of real-time modules for driver intention inference and behaviour prediction in project test vehicles,

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- integration of the modules into the corresponding applications of the UR:BAN project "Cognitive Assistance",
- assessment of effectiveness for the overall goal of "user-friendly, safe, and anticipatory driving in urban areas".

An overview of these objectives and their consideration in the framework of the UR:BAN MV project was given in [1].

This introductory chapter on the "Behaviour Prediction and Intention Detection" part is organized as follows. It starts with a brief description of the main working steps, which were carried out in UR:BAN VIE in order to achieve the objectives. It will then summarize the main results of the project and interpret them in the context of future needs in direction of automated driving. In a final section the structure and topics of the following chapters presenting more detailed results will be addressed.

8.2 Working Steps in UR:BAN VIE

8.2.1 Literature Overview on Driver Intention

As a first working step a detailed literature review was carried out in order to capture and organize the existing research dealing with the topic of driver intention (UR:BAN VIE Report, [2]). The review was oriented according to several guiding questions, e. g.

- How to define driver intention?
- Which driving manoeuvres have been considered?
- Which measurement parameters have been used to detect driver intentions?
- How have the data been analysed, e. g. machine learning methods?
- What is the benefit of driver intention detection?
- Which models are well-suited to describe driver actions and intentions?
- Which future research need can be identified?

Some of the most relevant literature sources identified were [3–8]. It should be added that recently a good comprehensive overview to the topic appeared in [9].

8.2.2 Specification on Relevant Driving Scenarios

The requirements for the algorithms on behaviour prediction and intention detection to be developed in VIE were described in form of scenarios (UR:BAN VIE Report, [10]). As an elementary part of the scenarios the concept of driving manoeuvres was used. VIE concentrated on eight of the ten manoeuvres as defined in [11], ignoring only the 'Overtake'

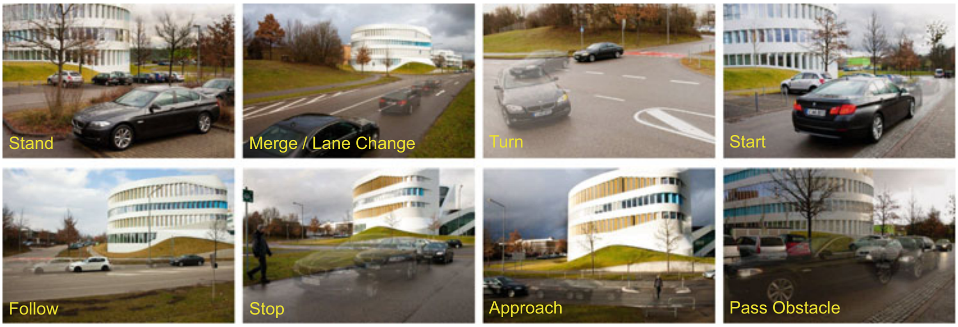

Fig. 8.1 Manoeuvres used in UR:BAN VIE. (Photographs UR:BAN VIE, Fraunhofer IAO)

manoeuvre and the ‘Slow Navigation & Parking’ manoeuvre, as those were outside the scope of UR:BAN. Fig. 8.1 shows the eight base manoeuvres used in VIE.

The description of the scenarios for VIE used the methodology of the sub-project UF, with some enhancements for the driver intentions and the phases of the driving manoeuvre. Overall, the scenarios in VIE concentrated on lane changes, intersections, approach & follow scenarios, and emergency braking & evading situations.

8.2.3 Data Collection

Data representing the specified scenarios were essential in order to develop the algorithms for diver intention detection. Most of the empirical studies performed in VIE were conducted in real traffic (see Fig. 8.2), some as well on a test track or in a driving simulator. Overall, more than 400 subjects participated in the studies, driving more than 15.000 kilometers. All studies have been documented in a joint report of the project partners (UR:BAN VIE Report, [12]), concentrating on the following aspects

Fig. 8.2 Data collection in specific scenarios with equipped vehicles. (Photographs UR:BAN VIE, TU Chemnitz/Bosch)

- Overview, including the main objective of the study,
- boundary conditions, mainly description of the environment and course, as well as temporary conditions,
- subjects, including criteria for selection and demographic overview of the participants,
- measurement equipment, e. g. vehicle parameters, eye tracking system, questionnaires,
- course of experiment, including manoeuvres to be performed, eventual secondary tasks and cover story.

8.2.4 Algorithmic Concepts

The development of algorithmic concepts was the heart of the work within the project, see Fig. 8.3 for an example. Based on the specification of scenarios, Sect. 8.2.2, and using the empirical data of the performed studies, Sect. 8.2.3, multiple methods were used to derive these concepts. Bayes' nets, Fuzzy Logic, Hidden Markov Models, and Reinforcement Learning were among these methods to learn the characteristics for the detection of

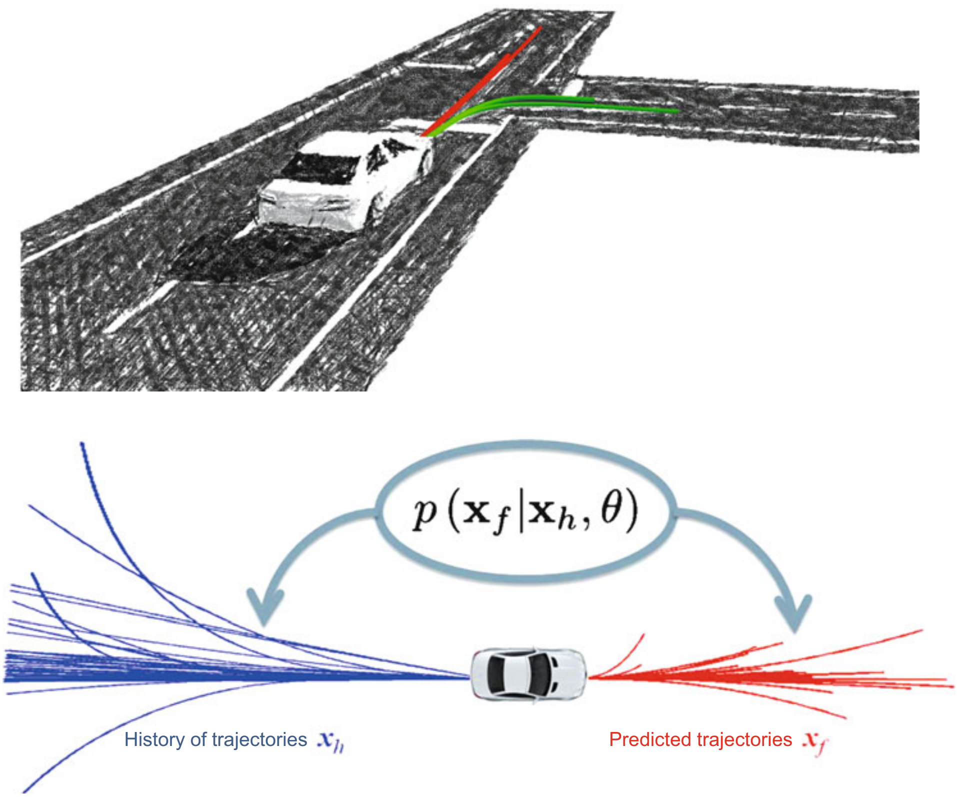

Fig. 8.3 Course prediction for intersections based on observed trajectories. (Graphics: UR:BAN VIE, Daimler)

driver's intention, as well as for his preparation and initiation of the following manoeuvre. An overview of the developed concepts was given in (UR:BAN VIE Report, [13]).

8.2.5 Test for Performance, Acceptance and Behavioural Changes

In a final step of activities, additional studies were conducted in order to test the performance of the implemented algorithms. To what extent can they realise the specification as given earlier and fulfill the expectations of detecting the intention and predicting the driver's behaviour? In some cases, additional tests were carried out testing the user acceptance and possible behavioural changes. Precondition for these additional tests is the integration of the algorithm in a functional concept reacting on the intention detection. An example for a test on user acceptance was the automatic setting of the turn indicator in case of a detected intention to change lane. The description and results of the studies were described in (UR:BAN VIE Report, [14]).

8.2.6 Demonstrators

At the final demonstration event of the UR:BAN project, held in October 2015 in Düsseldorf, six vehicles showed results of the VIE sub-project, see Fig. 8.4. These vehicles demonstrated for example

- the quality of a camera-based estimation of the viewing direction,
- a visualization of the probabilities according to the current status of manoeuvre prediction,
- a coordinated lateral assistance based on early detection of lane change behaviour,
- an automatic setting of the turn indicator according to camera-detected viewing behaviour,

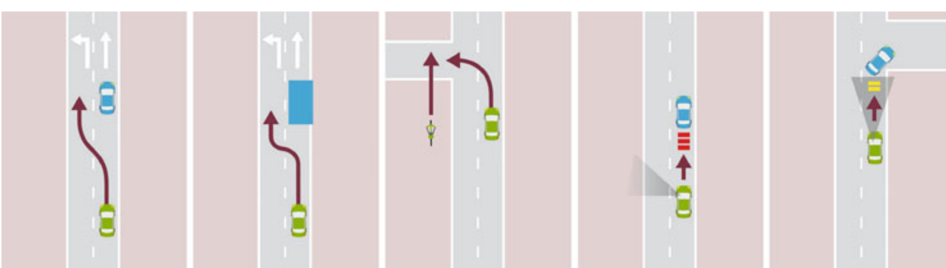

Fig. 8.4 Demonstration scenarios lane change / evading / turning / collision warning (non-attentive) / collision warning (attentive). (Graphics: UR:BAN VIE)

- an adaptation of a driver warning in following situations according to the predicted driver behaviour (warning concept in cooperation with sub-project MMI),
- the integration of detected brake intentions in a pedestrian protection system (pedestrian protection system of sub-project SVT).

8.3 Summary of Results and Outlook Towards Automated Driving

The sub-project VIE demonstrated the usage of driver intention detection for urban assistance functions as developed within the UR:BAN initiative. This section is structured in four segments: the assessment of relevance for the input signals, the restriction of the approaches, the functional benefit and an outlook to automated driving.

8.3.1 Assessment of Available Input Signals

An important contribution of VIE was the assessment of available input signals on driver, vehicle, and environment. Which signals are best suited to serve as an input parameter for driver intention detection? Different data sources show a very different potential as a predictor for driver behaviour. Interior cameras deliver data of driver's head orientation and gaze direction. A temporal and spatial analysis of these data seems to be sufficient for a basic prediction on driver behaviour. Head orientation and gaze direction allow for an earlier prediction of driving manoeuvres in comparison to vehicle data (e. g. for lane change prediction), at the price of larger inter- and intraindividual differences. Vehicle data are leading to a higher robustness, but showing a smaller predictive horizon. The potential of camera-based driver monitoring for behavioural prediction cannot be attributed equally to all types of manoeuvres, but depends on

- the relevance of environmental parameters for preparation and execution of the manoeuvre,
- the spatial assignment of the viewing areas and the resulting availability of the viewing signal (e. g. large viewing area needed for intersections compared to smaller areas during car-following scenarios),
- the dynamics of location and moment of the manoeuvre execution.

The quality of a driver intention detection can be widely increased by use of situational information. Hence, information on driver and driver behaviour should be always evaluated together with environmental information. This leads to an integration of the behavioural prediction to a situational analysis. The relevance of the signals can change during the sequence of the detection. The development of an intention manifests itself in a different way than the direct preparation or the execution. Typically, a specific point in time exists, when the decision for execution of the manoeuvre is taken and will not be canceled anymore (see the description of the rubicon model in Chap. 14). An optimal behavioural prediction needs, beside the processing of objective and robust data on driver, vehicle and environment additional information on the driver's attentional level. Finally, the potential of an individual parametrization of the driver model should be considered.

8.3.2 Restrictions

The usage of methods for behavioural prediction is determined by its quality and the temporary horizon. The temporary horizon is typically limited to about 10 s, as this correlates to the overall cycle of a manoeuvre execution. The quality of prediction is decreasing with an expansion of prediction time; an unsure information gains certainty with increasing time of observation. The temporal benefit of an intention detection depends on the driver and is larger for comfort manoeuvres as for emergency manoeuvres. The latter is a direct result of the fact that an emergency manoeuvre asks for direct action without larger planning phases.

A driver intention detection can never be perfect and error-free. In the isolated case a spontaneous, non-predicted action cannot be excluded. As a consequence, any measure based on the intentional information has to be designed in a way, that a wrong classification will not lead to catastrophic consequences. As an example, a faulty driver warning might be annoying but is forgivable. In this context, a balance between transparent system behaviour on one side and the safety potential of an adaptive warning on the other side has to be performed.

8.3.3 Usage Scenarios and Benefit

The detection of driver intentions and planned actions allows for an adaptive design of warning functions. This can provide a significant contribution to solve the warning dilemma. A warning can be delayed, if due to the prediction there is a high probability that the warning will not be needed by the driver. Examples are

- rear-end collision warnings in case of an upcoming lane change manoeuvre,
- cross-traffic warnings in case of a detected plan for a turning manoeuvre in front of the cross traffic,
- a warning for a pedestrian possibly crossing the street in case of a detected glance towards the pedestrian and a driver readiness to brake.

The optimizing of an assistance function by adapting the warning time can not only increase the safety, but also helps to gain better user acceptance, as unnecessary warnings can possibly be avoided at all. In single cases, the driver intention detection can lead to additional independent functions as well. The automatic activation of the turn indicator in case of a detected lane change intention is an example for such an added benefit.

8.3.4 Intention Detection in the Context of Automated Driving

The work within the UR:BAN sub-project VIE was performed with the background of manual and assisted driving. Future development in direction of automated driving is changing the driver's role in the vehicle. This will make some of his activities preparing a manoeuvre needless if he does not have to act. On the other hand, without acting on the stabilization level the driver may still have some tasks on tactical and navigation level. Hence, there can be a changed need for the vehicle to detect these intentions. Additionally, there is a strong need for a detection on the driver's state and his readiness to resume control in the context of automated driving. A detailed description of the research needs with a specific focus on human factors work is given in [15].

An additional focus has to be set on the intentions of other traffic participants. Whereas the VIE project studied the driver of the ego-vehicle only, the intentions of other vehicles, respectively their drivers, will remain important with automated driving. Predicting the behaviour of bicycles and pedestrians will be a further topic of relevance; [16] have already pioneered some work concerning the recognition of pedestrian intentions.

8.4 Outline of Following Chapters

This introductory chapter on the sub-project VIE gives only a very high-level overview but cannot go in the details of the work performed in the project. Therefore, the following six chapters of this part will address specific aspects and results of the project. The focus of the selection is not on completeness, but on a scientific presentation of particular topics representing the project's activities. The sequence of the chapters follows largely the working steps of VIE.

Chap. 9 addresses the challenges of collecting and handling real world driving data. This comprises strategies for data storage, data extraction, data correction and data enrichment. All these strategies are illustrated with examples from a study on driving behaviour when approaching an intersection under real environmental conditions.

An example of developing an algorithmic concept is described in Chap. 10 in the context of visual driver distraction. The driver's strategies to switch between on-road and off-road glances are modeled based on sub-optimal control. This leads to an approach for prediction of situation specific human behaviour in distracted driving.

The lane change behaviour out of an on-road study is analysed in Chap. 11 in order to derive predictors on the behavioural, strategic, manoeuvreing and control level. It is demonstrated that the familiarity with the route is the most important predictor for the number of lane changes. Mirror glance patterns for specific lane change types resulted as promising and quite stable intention predictors.

Chap. 12 is directly tied to the preceding chapter as it adds the assessment of the environmental situation to the driver's behaviour in order to predict upcoming lane changes. The two information means are fused by means of a Bayesian network. The implemented algorithms work in real-time and provide a probabilistic estimation of the intention of the driver to perform a specific manoeuvre.

Beside lane change manoeuvres the algorithms described in Chap. 13 focus on emergency braking and evading situations. The algorithm is derived by means of Fuzzy Logic and Edit Distance; the data concentrates on the driver's vehicle control and his head- and gaze behaviour. The real-time implementation calculates the manoeuvre probability and the time horizon until it will be conducted.

The final Chap. 14 of this part focusses on an algorithm to detect the driver's intention to brake when passing a pedestrian. Eye gaze data is analysed together with pedal activity to assess the driver's attention towards the pedestrian and his readiness to brake. The implementation in a research vehicle allows for early warnings, while simultaneously limiting their frequency to really relevant situations.

The work of the sub-project VIE is documented in several additional publications. Some of the English written papers to be suggested for further reading include [17–27].

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Analysing Behavioural Data from On-Road Driving Studies: Handling the Challenges of Data Processing

9

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9.1 Introduction

While driving studies on closed test-tracks or in driving simulators are characterised by a high degree of experimental control (e. g. [1]), the diverse requirements of urban driving cannot be easily simulated within these settings (e. g. concerning scenario programming). Moreover, experimental studies with a high degree of control over potentially confounding variables necessarily fail to reflect the complexity of real world scenarios. Observing driving behaviour in real-traffic environments, however, entails numerous challenges of data handling (similar to naturalistic driving studies), before data analysis, interpretation or modelling can be performed. In behavioural research, this will mostly entail calculations of statistical parameters for specific performance measures [1], e. g. mean speed when entering an intersection. When aiming to predict driving manoeuvres, this also involves the preparation of "clean" datasets, which allow for appropriate data modelling techniques and robust classification results free of interferences. The present chapter aims to outline methodological issues and provides guidelines for analysts to tackle the numerous data (and video) handling challenges that surface when confronted with similar on-road driving studies. Specifically, these data handling challenges refer to:

- data storage,
- extraction of pertinent data,
- data correction procedures,
- enrichment of data.

The challenges and possible solutions are illustrated with examples from a study that was conducted as part of the UR:BAN research initiative "Behaviour Prediction and Inten-

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tion Detection", which aimed at investigating driving behaviour when approaching intersections under real environmental conditions. Specifically, research objectives (amongst others) entailed:

a. exploration of on-road driving behaviour when approaching different kinds of intersections,
b. identification of indicators for predicting turning manoeuvres,
c. establishing a data base as basis for the algorithm implementation.

After briefly outlining the research rationale and the data collection process, the data handling challenges and possible solutions are described.

9.2 Driving at Urban Intersections

Driving in urban areas, one encounters a great variety and dynamic of traffic participants in diverse scenarios. Additionally, urban traffic scenarios vary with regard to many different environmental features which are likely to affect driving behaviour. Environmental conditions can rapidly change as the driver moves along the blocks and stretches of roads with variations in geometry or other architectural features and constraints which influence the general visibility of traffic participants and other potentially safety-relevant objects. The inner-city traffic scenario with the highest accident risk are intersections, where 24% of accidents with personal injuries occur, and 16% of accidents occur while turning [2]. While approaching intersections, the driver is confronted with a great number of tasks, which may vary throughout each intersection segment [3–5] and take predominantly part on the strategic level of the driving task [6], for example:

- planning imminent trajectories (and indicating driving direction to other participants) and safely merging into the ongoing traffic,
- while considering regulatory traffic measures (e. g. speed limits, stop signs, or traffic lights),
- and also observing and anticipating the behaviour of other traffic participants, such as pedestrians or cyclists (which may appear at crossing points or elsewhere, and may move in contradiction to actual traffic regulations).

The extent to which these tasks can be executed successfully and safely depends in part on the general visibility of these traffic features. The driver has to detect, identify and assess an increasing amount of visual stimuli correctly [7] within a brief time span, while approaching and crossing the intersection. Expectedly, drivers tend to perceive these spots as highly demanding, particularly when confronted with low visibility at intersections and when turning left [8]. Providing the driver with more support or (visual) information in these complex scenarios gives rise to the challenge of avoiding a cognitive overload ([9];

as cited in [10]). If the driver is confronted with unnecessary warnings, it may reduce driving comfort or even impact safety negatively.

Hence, not every urban scenario requires the same amount of assistance. Preferably, an ADAS should determine the general necessity for supporting the driver by considering both situational and individual aspects and adapt accordingly. This was shown (i.a.) in the UR:BAN research project "Human-Machine Interaction for Urban Environments". For example, a comprehensive situational analysis of intersections may contribute towards developing an appropriate workload management, e. g. by suppressing incoming phone calls [8, 11]. Analyzing situation-specific driver behaviour and individual driving data may also be used to detect the driver's awareness of crossing traffic and give out warnings when an appropriate driver reaction is missing [12, 13].

The UR:BAN project "Behaviour Prediction and Intention Detection" also aims to adapt ADAS strategies by predicting the intended driving manoeuvres of the driver in the near future. Focusing on intersections again – and corresponding manoeuvres of turning or just going straight – information about imminent driver intentions might be used to adjust intersection assistance systems, e. g. by re-evaluating the necessity of blind spot warning which appears when a cyclist is approaching from behind and the driver wants to turn, even if he has forgotten to activate the indicator. Regardless of crossing cyclists or pedestrians the recognition of driver's intent to turn at the next intersection, the system might just kindly remind the driver to use the indicator (up to 25% of drivers fail to comply with appropriate turn signal usage [14, 15]).

9.2.1 Effects of Driver Characteristics and Driver State on Driving Behaviour

As long as the driver remains a part of the control loop, driving and safety behaviour is more than just "the mechanical operation of a vehicle" [16], but also depends on individual's characteristics (and temporary states, e. g. stress or fatigue). In Skippon et al. [17], the correlation of observed driving data (in a driving simulator), personality traits and various subjective measures of driving style were found, such as speed choice and accelerating or braking behaviour. Similarly, the relationship of a more generic driving style measure and longitudinal and lateral accelerating behaviour in real traffic environments was shown by Deml et al. [18]. Sagberg et al. [19] outlined a conceptual framework for understanding the relationship of global driving styles and actual measures of driving data and self-report questionnaires. This relationship may be attributed to the effect of individual characteristics and personality traits e. g. locus of control, sensation seeking or risk taking [16, 20] on forming driving habits [19] and attitudes towards speed limits [21].

Combined, the previously mentioned findings suggest that drivers will behave according to their individual characteristics (e. g. driving style) as well as according to situational demands (e. g. stressful situations). For example, a driver assessed with a sporty driving style will likely accelerate more strongly from a standing position and decelerate later before turning than drivers assessed with a more relaxed driving style. In the former case, higher situational demands (e. g. time pressure) may not necessarily provoke a sportier driving style (e. g. because they already drive slightly above the speed limit). But this might not hold true for drivers with a more comfortable driving style. Here, stressful conditions may evoke a sportier driving style in order to meet the situational demands (e. g. to arrive on time at the destination). Hence, prediction algorithms, which are designed to detect the average behavioural data pattern before performing a driving manoeuvre (e. g. turning manoeuvres), might not recognise the corresponding manoeuvre intention of either sporty drivers or non-sporty drivers under high situational demands, as their driving behaviour will not match the learnt data pattern. Thus, it is assumed, that the correlation of driver characteristics and driving behaviour will also affect the classification performance of prediction algorithms which rely on driving data. The intention of the project activities was to investigate the potential and necessity of adjusting prediction algorithms to meet the requirements of individual driver characteristics (e. g. driving style or driver state) in order to provide either more precise or more timely and distinct manoeuvre predictions at urban intersections (e. g. turning or going straight).

After a brief description of the considered driving scenario, the applied strategies to gather insight into behavioural aspects when approaching intersections are presented using actual data recorded in the study.

9.2.2 Data Collection of Driving Behaviour when Approaching Urban Intersections

The on-road study entailed three identical rounds through an urban area of Munich, each with a length of about 10 km. Each round lasted about 25 min and included 17 turning manoeuvres, which varied in approaching speed (limited to 30 or 50 km/h), turning directions and structural characteristics (number of turning lanes, visibility at intersections, etc.). The sample consisted of 30 participants (15 female) with a mean age of 30.43 years (SD = 11.95 years) with an average total driving experience of more than 200,000 km. Half of the participants drove at least five times a week on a regular basis. The experimental vehicle was an instrumented Audi A6 Limousine, equipped with five cameras (front scenery, right-hand scenery, pedal view and two cameras for driver observation), CAN-bus interface and DGPS signals.

After filling in questionnaires that assessed demographic data and behavioural aspects of driving, participants familiarized themselves with the experimental vehicle. In a first round, participants experienced the route and a baseline of driving behaviour was established. The following rounds were used for manipulation of driver state (induction of stress). Participants were informed about the route prior to driving and were navigated by an instructed examiner throughout the experiment. Upon return, the driver as well as the examiner filled out a protocol to subjectively assess potential changes in driving behaviour (e. g. regarding acceleration, gap behaviour or decreasing glance behaviour into mirrors) in the stress-induced round. At the end of the session, participants were fully debriefed. Overall, the experiment took about 1.5 to 2 h.

9.3 Exploring Behavioural Data from On-Road Driving Studies: Challenges and Solutions

When observing driving behaviour in real traffic environments, the obtained data must be extensively explored and cleaned up in order to create comparable data sets which then can be used in further (statistical) analyses. Regarding behavioural aspects while approaching intersections or performing turning manoeuvres, several confounding variables must be identified and filtered, such as static intersection attributes (e. g. visibility, intersection size, or traffic regulation) as well as dynamic influences, e. g. stopping manoeuvres due to red traffic lights or interactions with other traffic participants. Moreover, to handle the great amount and variety of data from on-road studies, several data handling strategies must be conceived, which pertain to the following aspects: Data storage, data extraction, data processing, data quality, and data enrichment. In order to achieve this, a comprehensive infrastructure was developed, as shown in Fig. 9.1 [22]. The following sections describe the applied strategies to create comparable datasets, which can then be further processed in common analysis tools, e. g. SPSS, R or MATLAB, for inferential analyses or data modelling. In addition, various methods are proposed, to enrich the analyses with meta-information on intersections or by extracting additional information already inherent in the obtained data. Each step will be explained using the actual data from the study described in the previous section.

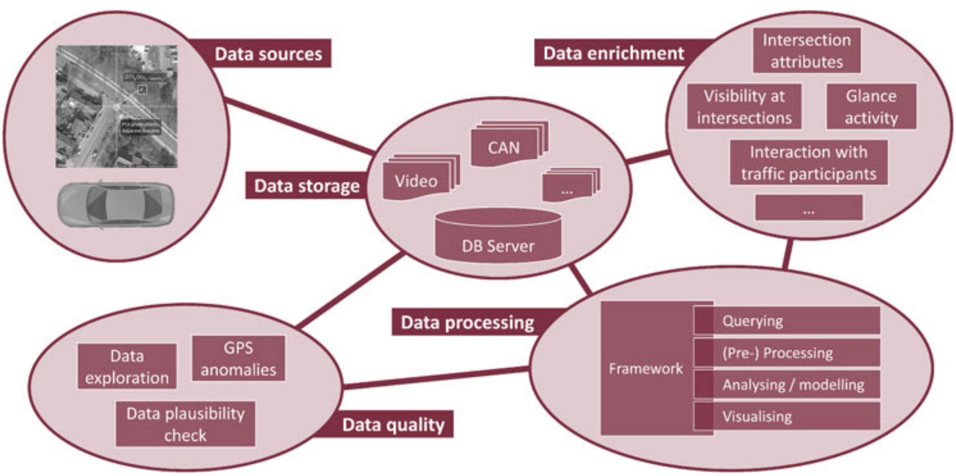

Fig. 9.1 Data handling infrastructure

9.3.1 Data Storage

For the present work, all data from the CAN-interface, GPS-signals, questionnaires and various meta-information about intersections were stored in an open-source PostgreSQL database ([1, 23]; http://www.postgresql.org). For managing DB systems the freeware version of EMS SQL Manager for PostgreSQL (http://www.sqlmanager.net) can be recommended.

The main reason for using DB were the limitations of common analysis tools with regard to handling large amounts of data, as most store the data in the computer's working memory (WM). For example, the exported data of selected CAN-signals from the present study take up about 38 Megabyte on average when saved in a text-based csv-format. Importing the data of all 30 participants into R would already take up more than one Gigabyte of the available WM. Moreover, as several steps of further data processing are necessary, there will also be additional instantiations of data objects within the used framework. Even if not all sections within these datasets are relevant at first, filtering for these sections would take up additional WM, before irrelevant sections can finally be removed to deallocate WM. In addition, this filtering of data may be preceded by computationally extensive calculations of new variables on the complete dataset for each participant that are necessary for the extraction of comparable data sections (e. g. distance to intersection; Sect. 9.3.2), and which would ultimately exceed the WM limits of common computers.

An alternative approach would be a sequential application of data filtering and processing techniques. But this procedure does not easily allow for effective data enrichments (e. g. adding data of annotated glance behaviour; Sect. 9.3.5.3) or flexible extraction of data sections with changed criteria (e. g. starting at 100 m before entering the intersection, instead of 50 m).

By design, common DB types [1] use the hard drive instead of the WM for storing and instantiation of data objects. Technically, computational seek time will be faster on WM, so final analysis would be done using common tools such as those stated above. But as the computation of the intended extraction criteria on the complete data will only be executed once, it is considerably more effective when executing the computation procedures and storing both the data and the newly computed values within a unique DB. Additionally, when using solid-state drives (SSD), computational time will significantly decrease compared to typical hard disk drives (HDD).

Aside from the advantages for data management and flexibility, an initial constraint related to DB utilization concerns the complexity of DB systems, which can lead to difficulties in user interaction without training and knowledge of a particular DB language (e. g. SQL; e. g. [24]). For more details on developing a DB for storage and analysis of behavioural data, see Pereira et al. [23].

9.3.2 Data Extraction: Identification and Computation of Filter Criteria

For the extraction of relevant data sections, it is necessary to define points-of-interest (POI) on the driven route, which can then be filtered when querying data from the DB. With regard to the research objective of developing prediction algorithms for intersection manoeuvres, the POIs were defined as the last position before entering an intersection at which any supporting ADAS may benefit from prediction results to support the driver and to avoid safety critical events (e. g. when observing rare glances into the side mirrors or glances over the shoulder to check the blind spot before performing a turning manoeuvre). This might be the middle position on the stopping line, or otherwise an imaginary line when no road markings are available, e. g. the adjacent border of the cross road, dedicated walkways or cycle lanes.

In order to operationalise a POI as a potential filtering criteria when querying data from the DB, an approximate arrival measure was computed using values of GPS, driven distance and timestamps in five steps (cf. Fig. 9.2):

1. Detecting GPS-coordinates for each POI j as reference point Ref_j using digital map data.
2. Computing the linear distances $d_{ij}(t) = d(\mathrm{Ref}_j, \mathrm{GPS}_i(t))$ between each reference point Ref_j and the actual GPS-positions $\mathrm{GPS}_i(t)$ of the driver i at each timestamp t.
3. Filtering d_{ij} for minimum values $d_{ij,\min} = \min(d_{ij})$.
4. Extracting corresponding values for driven distance $\mathrm{DD}_i(t)$ and driven time $\mathrm{DT}_i(t)$ at $d_{ij,\min}$.

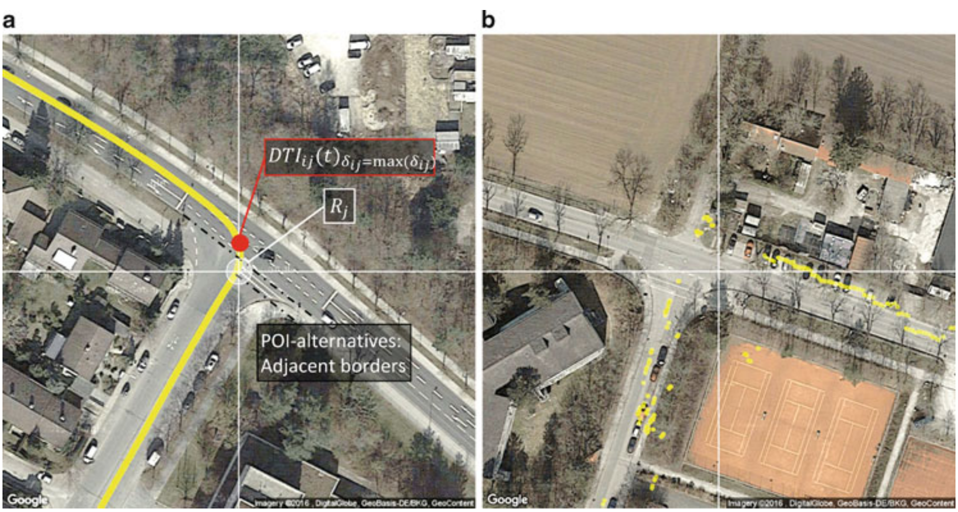

Fig. 9.2 Left: GPS-trajectory, GPS reference point and DTI of maximum steering angle (**a**) and GPS-anomalies (**b**)

5. Computing either the distance-to-intersection $\mathrm{DTI}_{ij}(t)$ and time-to-intersection $\mathrm{TTI}_{ij}(t)$ for each intersection by subtracting actual values $\mathrm{DD}_i(t)$ or $\mathrm{DT}_i(t)$ from the extracted values $\mathrm{DD}_{ij}(t)_{d_{ij,\min}}$ or $\mathrm{DT}_{ij}(t)_{d_{ij,\min}}$ found in the previous step.

Ref_j was determined by a meaningful position (here, using Google Maps) lying close to the anticipated driver's trajectory. The linear distances in step 2) were computed within the DB using PostGIS (http://postgis.net; [25]). The last step will result in an approximate measure of arriving at the POI, as Ref_j may not lie exactly on the drivers trajectory. For example, assuming a $\mathrm{DTI}_{ij} = 0$, the arrival measures will still exhibit spatial deviations from the real Ref_j ($\overline{d} = 1.07$ m and $\sigma_d = 0.65$ m), as d_{ij} only represents the smallest radius around Ref_j found in the data of each driver i. To obtain more accurate values, arrival measures can be re-computed within the analysis framework after applying extracting a small relevant data section, applying the interpolating procedures and by-re-determining Ref_j on (e. g.) the median GPS trajectories of all drivers within the extracted data section. The arrival measures can also be used for synchronizing data when comparing driving performance at different intersections.

For efficient computation of the arrival measures within the DB (as well as for reasons of clarity and comprehensibility), it is recommended to split the imported (and synchronised) vehicle data (e. g. GPS data and CAN signals) into separate datasets according to their absolute necessity for computing values of DTI or TTI. Here, this only concerns the variables of driver ID, elapsed time, driven distance, round, and GPS coordinates. Thus, no unnecessary data (e. g. values for speed) get included in each computation step, which has beneficial effects on computation time and occupied hard drive space.

9.3.3 Data Processing: Building a Framework

For querying the data from the DB and further data processing a comprehensive framework in R (http://www.r-project.org) was (iteratively) developed using RStudio (http://www.rstudio.com). The complete framework consists of numerous functions, which were continuously developed throughout the project. These functions can be assigned to five modules: Initializing, data querying, data pre-processing, data analyzing and modelling, and data visualization. The main reason for setting up this modular structure was to establish a versatile platform which facilitates a) exploring and analyzing data for all intersections from the present study and following studies, b) filtering of potentially confounding variables, adding supplemental variables or easily selecting different processing parameters (e. g. extraction criteria, or clustered groups and similarity measures), and c) high reproducibility and transparency of the applied procedures.

9.3.3.1 Initializing

The module "Initializing" was essential for all other modules, as it prepared all necessary components for further data processing when starting the framework. This was realised

Table 9.1 R packages

Function	Package	Main objective
Database	DBI	Communication between R and relational DB
	RPostgreSQL	R interface to the PostgreSQL database
Data manipulation	dplyr	Tool for working with data frame like objects
	tidyr	Tool for data tidying
Pre-processing	zoo	Infrastructure for time series
	geosphere	Functions for geographic applications
Analysis	TraMineR	Analyzing and visualizing state sequences
	kml	Clustering longitudinal data
	dtw	Computing dynamic time warping alignments for clustering
	LICORS	Cluster analysis using kmeans++
	TSclust	Time series dissimilarity measures for clustering
Visualization	ggplot2	Implementation of Grammar of Graphics
	ggmap	Spatial visualizing
	googleVis	Interface between R and the Google visualization API
	plotly	Interactive web graphics

using adjusted starting parameters of R and a single script setting up necessary data paths (e. g. for loading already processed data from the last analysis session), libraries, functions (e. g. for interpolation or correction procedures), and preliminary settings (e. g. for data analyzing, modelling and visualization). Following additional packages (which can be easily found online by searching for "R + [package name]") were used for effective data exploration and analysis (see Table 9.1).

9.3.3.2 Data Querying: Setting Data Selection and Loading Data from the Database

For efficient data retrieval from the DB a function within the R framework was built, which constructs a complete SQL query command using specified settings in a R script concerning a) data source (table name within the DB), b) selection of session-related variables (e. g. driver ID, round and intersection) and extraction criteria (e. g. DTI or TTI), and c) a selection of relevant variables of driving behaviour. The complete SQL string could then be sent to the DB using the package DBI for querying and receiving data from the DB. Additionally, DBI-functions were also used to write new data into the DB (e. g. when using R as efficient processing tool for processing questionnaire data in Excel or annotated video data from ELAN, or for saving results from diverse analyses).

9.3.3.3 Data Pre-processing

Data pre-processing involved procedures for data exclusion, data correction and data interpolation. For example, data exclusion concerned cases, in which drivers had to stop, e. g. due to red traffic lights or high traffic density. Data correction procedures concerned the adjustment of arrival measures due to some GPS-anomalies (Sect. 9.3.4.2) and the value range of some variables. Interpolation procedures were applied to harmonise datasets of different drivers in terms of DTI or TTI (e. g. equidistant steps, e. g. of 1/10 meters or seconds). This was necessary in order to correctly extract statistical key values (e. g. mean speed at a DTI of 5 m) or prepare data for cluster analyses. As the application of these procedures depends on the aim of following data analyses, they were not already included into the data querying procedure described above.

9.3.3.4 Data Analyzing, Modelling and Visualizing

The module of data analyzing and modelling consists of several standard procedures for inferring (statistical) key values (e. g. speed differences between the conditions of normal and stressed driver condition) and methods for data exploring (e. g. cluster analyses of speed profiles when approaching the intersections), which were transformed into re-usable functions for divergent research questions.

When confronted with data from real-traffic scenarios, data visualization is crucial part for gaining insights into data. Particularly interactive graphic packages (e. g. plotly and googleVis) allow for fast and valuable insights into data and case-wise identification of outliers. To create sophisticated plots, and allow for standardised designs in project reports several scripts and functions were developed for efficient re-utilization.

9.3.4 Data Quality: Exploration and Correction Procedures

Before any data exploration or analyses can be performed, many preliminary strategies for storing, cleaning, enriching and pre-processing data must be applied. Each of these strategies may be a potential source of error, particularly when applying complex processing procedures as the computation of arrival measures (Sect. 9.3.2). As a preventive measure against flawed analyses and interpretations, it is crucial to check the results of each processing step and the recorded data itself for plausibility.

9.3.4.1 Data Exploration and Plausibility Check

In order to check the data plausibility efficiently at each data processing step, it is recommended to establish a routine for creating statistical summaries or visualizations, which can be easily queried on demand. The type of these routines depends on the current computation procedure or tool (DB or data processing framework). A possible source of errors within the data can be failures in the recording procedure (which potentially cannot be changed in closed systems). For example, in the present study, this concerned the value range of GPS signals and position data of the accelerator pedal, which could easily be adjusted by linear transformation within the DB. Visual procedures were applied within the R framework, e. g. for checking variables involved for computing the arrival measures. Moreover, exploratory visualization of GPS data within extracted data sections revealed GPS signal anomalies at some intersection crossings (Fig. 9.2). Based on these data explorations appropriate correction procedures or filter methods can be developed, which can then be applied before performing final data analyses.

9.3.4.2 Correcting GPS Signal Anomalies

When applying the described procedure for computing an arrival measure to the identified intersection crossings containing GPS signal anomalies, minimum GPS distances to Ref_j and corresponding values of DTI_{ij} or TTI_{ij} would be displaced. This displacement had also been indicated by visualization of values for individual steering angle profiles while turning (Fig. 9.3), which should approximately lie on top of each other. As sample size is crucial for statistical analyses and model validation, a correction procedure was implemented using data from intersection crossings without GPS anomalies. This procedure comprises the relocation of displaced arrival measures by the difference that results from the individual drivers' position when reaching the maximum steering angle (Fig. 9.2) towards the overall median position when reaching the maximum steering angle. This can be implemented as follows:

1. Visually exploring GPS signals of each individual intersection crossing CROSS_{ij} and determining relevant cases CROSS_anom_{ij} required to be corrected.
2. Determining if signal anomalies in CROSS_anom_{ij} led to positive or negative displacement of arrival measures.
3. Filtering values of steering angles δ_{ij} for maximum values $\max(\delta_{ij})$ for each CROSS_{ij}.
4. Extracting corresponding values for $\text{DTI}_{ij}(t)$or $\text{TTI}_{ij}(t)$ within the filtered data from the previous step, where $\delta_{ij} = \max(\delta_{ij})$.

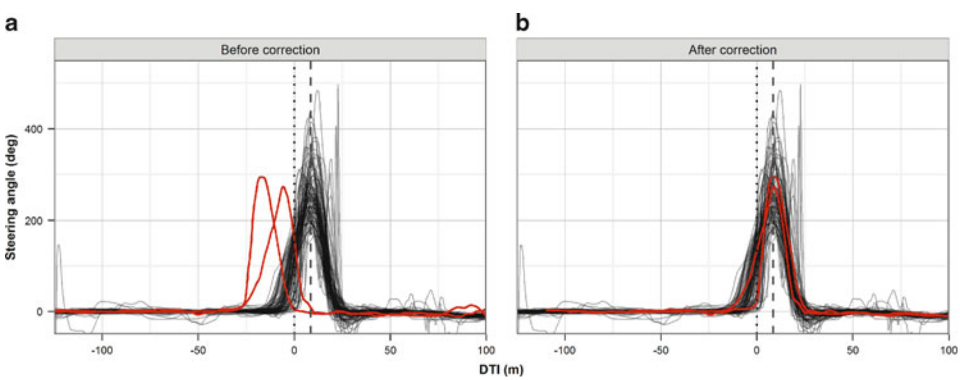

Fig. 9.3 Steering angle values before (**a**) and after correction (**b**)

5. Filtering data for ¬CROSS_anom$_{ij}$ (cases without signal anomalies) and computing the median of $\mathrm{DTI}_{ij}(t)_{\delta_{ij}=\max(\delta_{ij})}$.
6. Filtering data for CROSS_anom$_{ij}$ and compute the difference between the actual $\mathrm{DTI}_{ij}(t)_{\delta_{ij}=\max(\delta_{ij})}$ and the median $\widetilde{\mathrm{DTI}}_{ij}(t)_{\delta_{ij}=\max(\delta_{ij})}$ computed in the previous step.
7. Moving the actual values $\mathrm{DTI}_{ij}(t)_{\delta_{ij}=\max(\delta_{ij})}$ of cases CROSS_anom$_{ij}$ by adding or subtracting the computed difference from the previous step.

9.3.5 Data Enrichment

Data collections from real-traffic environments are affected by many variables. In order to analyse and interpret the data, it is therefore necessary to identify, and extract or quantify these potentially confounding variables. With regard to intersections, this particularly concerns both data related to static (e. g. obstructed visibility) and dynamic environmental aspects (e. g. preceding vehicles). Previous research also found a correlation between intersection features (e. g. geometry, turning angles and visibility at intersections) and driver perception and safety behaviour [26–28]. Moreover, the recorded data can be used to extract even more information than the actual driving performance measured by CAN signals, e. g. glance behaviour or pedal activity. Further differentiations of behavioural aspects in intersection approaches have also been made using scenario segmentations and comprehensive task analyses regarding driver's operational activities and estimated mental workload (see e. g [3, 4].).

Regarding the approaching behaviour at urban intersections, the present analysis concerned the classification of confounding or supplementing data, shown in Table 9.2.

Table 9.2 Classification of variables obtained from data enrichment

Data related to:	Variables	Data source
Static environmental aspects	Intersection type	OSM
	Speed limitations	OSM, CAN, Video
	Priority regulations	GoogleMaps (Satellite), Video
	Number of turning lanes	GoogleMaps (Satellite), Video
	Intersection angle	OSM, GoogleMaps
	Intersection size	CAN
	Path curvature	GPS
	Intersection visibility	Video
Dynamic environmental aspects	Other traffic participants	Video
	Traffic flow	Video & CAN
Driving performance	Arrival measures	GPS & CAN
	Glance activity	Video
	Pedal activity	CAN, Video
	Driving style	CAN

The first additional data related to driving performance have already been obtained by computing arrival measures using GPS signals and CAN data (Sect. 9.3.2). The followings sections describe the extraction of this additional information from the recorded vehicle or video data, and other external data sources to enrich the analyses and interpretation processes.

9.3.5.1 Intersection Characteristics Obtained from External Sources

The intersection type (three-leg T-intersection, coded as "T", or full four-leg intersection, coded as "X") and speed limitations can be easily determined by searching for relevant street names on OpenStreetMap (OSM; http://www.openstreetmap.org) and exploring the map data and the "maxspeed" parameter given in the street information panel. However, this data should also be verified by checking the actual speed profiles in corresponding data sections, and by exploring the recorded video data for street signs.

To determine priority regulations and the number of dedicated turning lanes at relevant intersections satellite images of GoogleMaps can be used. However, these data should also be verified by checking the recorded video data, which also provide information about potential temporary obstructions or construction works.

Map data (OSM or GoogleMaps) can also be used to determine the general (categorical) intersection angle (e. g. closed, perpendicular or opened angle; see [28]). Numeric values for angles can be calculated approximately by means of imaginary lines between GPS reference points on relevant crossroads, the apparent intersection center and the origin of the driver.

9.3.5.2 Supplementary Information Obtained from Recorded Data

In addition to the information on static environmental aspects obtained from external sources, more data of interest are contained within the actual recorded data, which are not readily obtainable. The following sections describe methods for extracting additional information from the data regarding further environmental aspects or driving performance.

9.3.5.2.1 Intersection Size

A measure for intersection size was derived using the distance between the Ref_j and the averaged position where drivers reach $\mathrm{DTI}_{\max(\delta)ij}$ while turning. Values range from 2.4 m (e. g. small intersections without traffic light) up to 32.9 m (e. g. multi-lane intersections with traffic lights). Table 9.3 shows a summary of categorical intersection characteristics.

9.3.5.2.2 Path Curvature

The anticipated path curvature of the driver was computed in order to implement parts of the prediction algorithm by [35], which is based on desired speed profiles when approaching intersections. To generate these profiles, they propose (i.a.) a method by extracting and converting the path curvature from digital map data into speed profiles. As no digital map information was available in the present data, path curvature was extracted using the median GPS trajectory at each intersection and an approximate computation procedure. This can be implemented as follows (cf. Fig. 9.4):

Table 9.3 Intersection characteristics

Nr.	Type[a]	Regulation	Intersection size in m (SD)		Lanes (turning)[c]	N after exclusion
1	TL	give way	2.38	(1.58)	1 (-)	54
2	XL	light	12.16	(4.41)	2 (-)	42
3	SL	give way	7.99	(2.26)	2 (1)	53
4	TL	(light)[b]	2.41	(2.68)	2 (-)	44
5	XR	light	15.02	(1.64)	1 (-)	28
6	XL	light	13.72	(2.24)	3 (1)	28
7	XR	light	12.32	(2.58)	3 (1)	36
8	TL	light	17.18	(4.79)	2 (1)	42
9	XL	light	32.94	(4.23)	3 (1)	44
10	XL	light	23.67	(4.53)	3 (1)	40
11	XR	light	9.41	(3.3)	1 (-)	25
12	XL	light	14.82	(2.58)	3 (2)	37
13	SR	light	10.52	(3.6)	2 (1)	28
14	TR	give way	8.79	(2.4)	1 (-)	55
15	XL	light	30.8	(6.31)	2 (1)	27
16	SR	light	17.1	(2.52)	1 (-)	40
17	SL	give way	7.83	(4.74)	1 (-)	58

[a] First letter represents T-intersection (T), full intersection (X) or T-intersection for either turn or going straight (S). Second letter represents direction of turning left (L) or right (R).
[b] Intersection 5 regulated by traffic lights 15 m before drivers still had to halt for giving way.
[c] Lanes represent general number of lanes before entering the intersection, independent of potential designated direction. Turning lanes correspond only to turning direction.

1. Computing the median GPS trajectory values $\widetilde{\text{GPS}}_j(s)$ for each intersection j
2. Smoothing values for $\widetilde{\text{GPS}}_j(s)$, e. g. using a moving average filter to obtain a more realistic curvature profile.
3. Calculating the radius for each data section of three points, e. g. $\widetilde{\text{GPS}}_{j_{\text{smoothed}}}(s_1; s_2; s_3)$.
4. Limiting the obtained curvature values $r_j(s)$ to a plausible value range (depending on smoothing parameters).
5. Calculating the reciprocal of the obtained values $r_j(s)$ to calculate curvature values $\kappa_j(s)$.
6. Smoothing values of $\kappa_j(s)$ to obtain the approximate path curvature model.

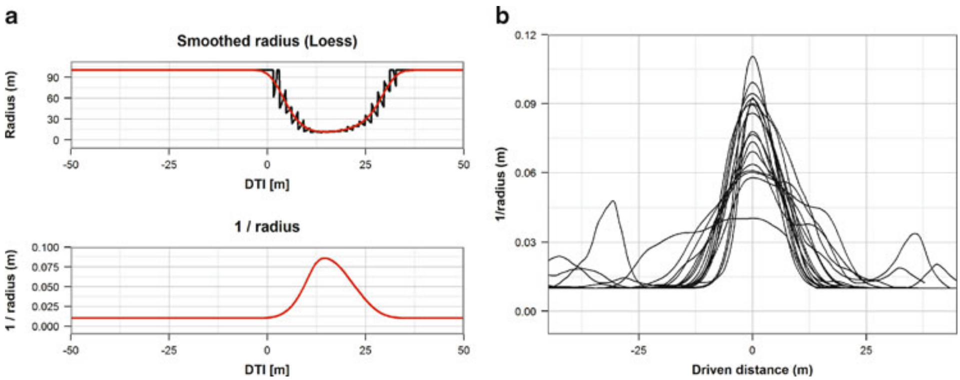

Fig. 9.4 Conversion of curvature radius into path curvature (**a**) and path curvature models of each intersection, aligned at maximum values of path curvature (**b**)

9.3.5.2.3 Visibility at Intersections

Models of visibility at intersections were estimated using scene stills from the front camera of one driver. For this purpose, images of the video were extracted at each timestamp corresponding to DTIs beginning at −50 m and ending at 0 m (Ref_j), in steps of five meters. Relevant video time stamps could easily be exported using the DB. In these images, xy-coordinates of pixels were measured (using IrfanView; http://www.irfanview.com) as markings (Fig. 9.5a) for the maximum range for potential glances to the left (red line) and right side (green line). Visibility values can be computed either as percentage of range to any side relating to the center of the camera (black line) or the middle of the intersection (blue line). For smoother projection of the data against DTI, computed visibility values were smoothed by curve fitting (see Fig. 9.5b).

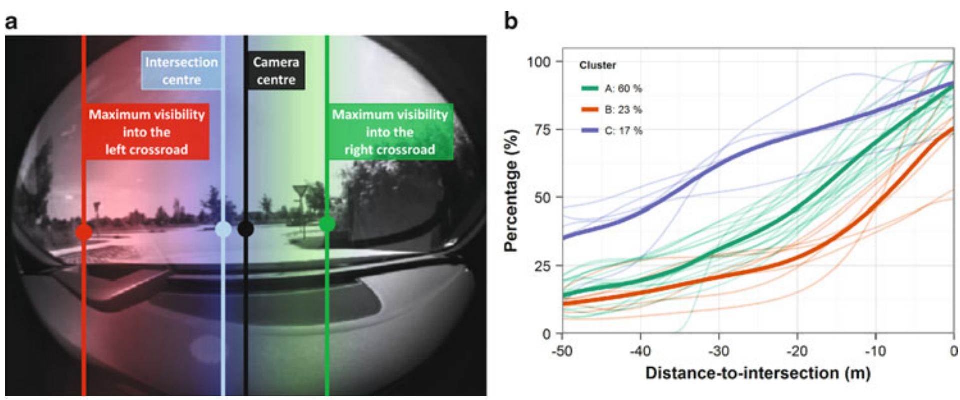

Fig. 9.5 Extraction of visibility parameters (**a**) and clustered visibility models into each crossroad (**b**)

To obtain more precise visibility models, sophisticated methods using LiDAR techniques are proposed in literature, which can also consider parameters of the vehicle model and the driver's eye-height [29, 30]. Moreover, further differentiations could be made by determining actual (e. g. poles) and potential obstructions (e. g. tree branches; see [30]), or – with regard to urban areas – temporal obstructions, as parking delivery trucks.

9.3.5.2.4 Other Traffic Participants and Traffic Flow

To avoid biased interpretations of individual driving behaviours, the presence of preceding vehicles had to be analysed using video analysis for each subject at each intersection. In combination with speed data it could be determined if the crossing involved 1) free-flowing traffic without stopping (unimpeded driving), 2) free-flowing traffic, but stopping (e. g. at stopping line, due to red traffic light), 3) following a preceding vehicle without decelerating, 4) following preceding vehicle decelerating to stop, and 5) approaching the end of a tailback (2–5 impeded driving). Here, a lower deviation of 5 km/h before entering the intersection was used as stopping criteria (Fig. 9.6). Further, video data of interactions with pedestrians or cyclists were explored, which did not occur at the relevant intersections.

With regard to the research question, these filters for stopping drivers or preceding vehicles (impeded driving vs. unimpeded driving) were used to establish a "clean" data basis for modelling driver behaviour when approaching intersections and implementing the prediction algorithm for turning manoeuvres.

9.3.5.3 Video Annotation of Glance Behaviour

The study was intentionally designed with the constraint of using only technologies, which can already be used in commercially available cars (e. g. CAN signals, GPS data or cameras for driver observation) and would not require any additional actions by the driver. Hence, no system for detecting eye- or head movements was used to avoid distraction of the driver, potential discomfort due to eye tracking glasses or time-consuming calibration

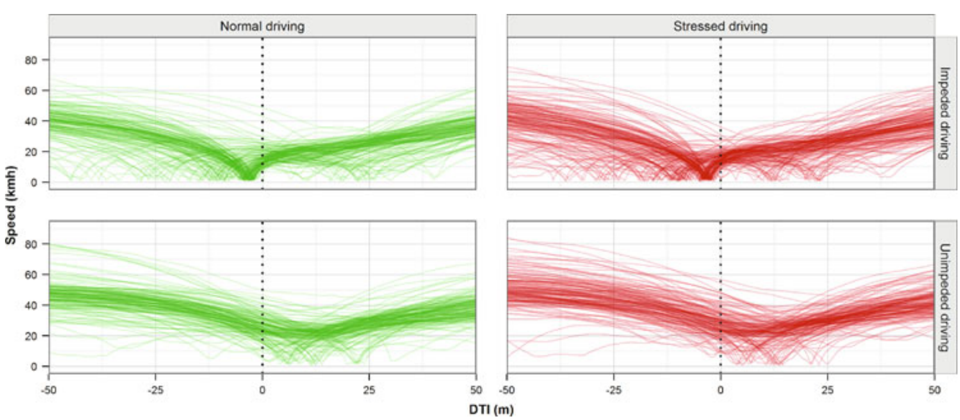

Fig. 9.6 Speed profiles for impeded and unimpeded driving before entering the intersection

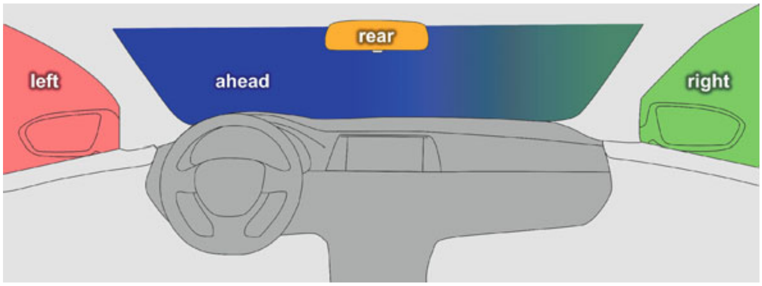

Fig. 9.7 Areas of interest. (© UR:BAN)

procedures. Past research efforts has demonstrated the possibility of extracting glance directions by means of video cameras (e. g. [31]). Although similar computational detection algorithms for deriving glance activity could have been used in offline data, a manual annotation procedure was preferred to ensure that the analysis and interpretation processes are based on a complete dataset.

Glance directions were annotated from video data of two driver observation cameras, frame-by-frame. For the annotation process the software ELAN (http://tla.mpi.nl/tools/tla-tools/elan/; [32]) was used. The analysed categories for glance directions (Fig. 9.7) were chosen based on preliminary considerations of potential areas-of-interest and literature (e. g. [33]). Glances to side mirrors could not be differentiated consistently from general glances to corresponding sides and were therefore merged into global categories of "left" and "right".

Only video data for the second and third round were annotated, and only for sections immediately preceding the intersection. Annotations started at DTIs within a range of −100 to maximum −35 m, depending on the intersection lying within the driver's field of view, and ending at corresponding video timestamps when reaching Ref_j. Relevant ranges of video time stamps could easily be exported using the DB. All data were double checked by a second annotator. Annotation data were stored and synchronised with CAN-signals in the DB (Sect. 9.3.1).

9.4 Summary and Conclusion

Compared to studies on closed test-tracks or in driving simulators, observing driving behaviour in real-traffic environments not only involves a great amount of data but also numerous potentially confounding variables. The purpose of this chapter was to outline methodological challenges that ensue when confronted with on-road driving studies or analyzing driving behaviour in complex (urban) traffic scenarios. Several strategies were proposed to meet the related challenges of data handling. The strategies were illustrated based on a study that had been conducted to analyse and predict turning manoeuvres at urban intersections based on real driving behaviour.

With the proposed infrastructure, data correction procedures and extracted filters for potentially confounding variables, it is possible to establish a "clean" data basis to implement and adjust a prediction algorithm for turning manoeuvres according to individual driver characteristics.

Urban intersections are characterised by numerous individual features. The proposed classification of environmental features can be used to build a comprehensive model of an individual urban intersections in order to better understand related driving behaviour (but is not intended to be exhaustive). This classification could also be used to supplement analyses of driver operations (or driver workload) in task analyses. Within each section, all necessary tools or packages were cited (and are freely available) to re-build the proposed infrastructure.

Applying the described strategies for data handling using DB systems and data processing framework as well as applying the procedures of data correction and data enrichment is effortful, time consuming, and requires some additional programming skills and software knowledge (which can be easily learned considering the many free online tutorials on SQL, R, MATLAB etc.). Nevertheless, experience has shown that it is worth the effort in many ways. Storing data in a unique place makes data easy accessible and allows for highly flexible analyses. Further research activities also built upon the proposed infrastructure (e. g. [34]). Moreover, the procedure of computing extraction criteria has been successfully applied to other on-road studies. With respect to large-scale research initiatives (such as UR:BAN) or similar complex research questions involving driving studies in real-traffic environments, it is highly recommended to anticipate a similar comprehensive structure for data processing and analyzing from the beginning, as it will yield many benefits throughout further research activities.

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10 Predicting Strategies of Driving in Presence of Additional Visually Demanding Tasks: Inverse Optimal Control Estimation of Steering and Glance Behaviour Models

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10.1 Introduction

Driver distraction is a psychological concept that can be defined as "diversification of attention away from activities critical for safe driving towards a competing activity" [1]. Commonly, driver distraction is categorized into three types: *Visual* distraction, is the diversification of visual attention from the scenery in front of the vehicle to other regions. For example, drivers are frequently looking at an in-vehicle display instead of the road ahead of the vehicle. Often, interaction with in-vehicle infotainment does not only require looking at a display but also removing one hand from the steering wheel to press certain buttons. Hence, this activity does impose *manual* distraction in addition to visual distraction. Finally, distraction can also result from bound cognitive resources, e. g. during intense conversations, which is *cognitive* distraction (ibid.). Safe driving requires predominately the acquisition and processing of *visual* information for lateral and longitudinal vehicle control [2]. Accordingly, several studies found distinct negative effects of visual distraction, i. e. too less glancing on the road, on driving performance. Some authors e. g. showed slower and impaired response to lead vehicle braking [3] or impaired lane-keeping [4] of visually distracted drivers. In contrast to that, the influence of cognitive distraction on driving performance is rather ambiguous: [5] found a decrease of the deviation from the lane-center, while in [6] a delayed hazard response was observed. Therefore, this chapter will focus on modelling driver behaviour under visual distraction *only*. All forms of distraction considerably contribute to accidents on streets, roads and highways. An analysis

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of the 100-Car Naturalistic Driving Study even concludes that approximately 80% of all crashes and 65% of all near crashes involve inattentive drivers as a contributing factor [7]. Hence, mitigation of the driving deficiencies caused by driver distraction promises a great impact on road safety.

10.2 Distraction and Additional Tasks in Driving

As already included in Lee's definition, distraction is normally induced by an additional activity the driver is engaging while driving. The activity, that can range from reading in-vehicle instruments, to checking the mirrors, using the vehicles infotainment, or texting on the smartphone, is considered as a *secondary* task opposing the *primary* task of safe driving. Some authors differentiate secondary tasks e. g. (ibid.) between *distraction by non-driving related secondary tasks* (e. g. texting on the smartphone) or *driving-related inattention to the forward roadway* (e. g. checking the mirrors). Instead, we follow [8] and treat glances away from the forward-road the same independently of the cause. Regarding driving safety, the most important driving tasks are keeping the vehicle in lane and keeping a safe distance to all obstacles in driving direction. As both of these tasks require the perception of visual cues in the forward scenery, all long glances off the road endanger driving safety.

10.3 Approaches to Mitigate Distraction

10.3.1 Conventional Driver Assistance Systems

Critical situations resulting from visually distracted drivers can already be partially mitigated by conventional driver assistance systems, e. g. forward collision and lane departure warning. However, these systems can be greatly improved in their risk assessment, if they take into account the driver's ability to deal with the current driving situation by his own. For example, an impending lane crossing can be the result of an intended lane change or be rooted in a driver who is distracted and does not perceive the vehicle's position in lane. Considering the vehicle's trajectory alone both cases are hardly distinguishable. However, in the first case a warning is not necessary and can even be a nuisance, whereas in the latter case even an earlier warning might be appropriate. Hence, knowledge of the driver's distraction state and a holistic risk assessment could prevent unnecessary interventions and greatly improve system effectiveness, as demonstrated in [9, 34].

10.3.2 Driver Assistance Systems for Assessment of Distraction

Because of its strong influence on crash risk, several approaches for detection and assessment of inattention have been proposed, which are reviewed in [10]. Recent progress in computer vision enabled real-time eye tracking. Therefore, many approaches that address visual distraction rely on the driver's gaze-direction (or the head-orientation as an approximation). Many authors [7, 11], first processed the raw gaze direction by detecting if it intersects a certain Region Of Interest (ROI). This region is defined as a plane, through which the driver has to look to gather necessary visual information for lane keeping and headway control in the forward road scenery. A possible ROI is depicted in Fig. 10.1.

An open question in driver distraction research is how to algorithmically decide, that drivers are too distracted in a specific situation. Yet, an assistance system would warn or even intervene on the algorithms decision. Consequently, the system would become a nuisance if the driver was falsely detected distracted too often and cause the driver to turn it off. Nevertheless, any dangerous situation has to be classified correctly.

Several authors, e. g. [11, 12], proposed algorithms for decisions on critical distraction that in fact detect the periods of engagement in a secondary task during driving. Often such additional tasks are the reason for long off-road glances, as already mentioned before. Still, this approach has an issue: Some potentially visually distracting activities, e. g. checking the speedometer or mirrors, are required for safe driving. If those instruments are placed carefully, those activities pose little risk in many situations, as they require only short glances. Additionally, drivers often apply compensatory mechanisms [13] in secondary task engagement. Therefore, drivers should not receive interventions from the system for those task *per-se* in low criticality situations. For example, a short glance on the rear mirror or *also* to the infotainment (as we don't distinguish between types of tasks) should be allowed at low speed in light traffic on a highway.

As an alternative to detecting secondary task engagement the perceived distraction can be predicted, as proposed by [14, 35]. To achieve this, subjective distraction ratings based on 10 s of video of the driver and the outside scenery were used. While ratings are very useful to judge the quality of a final mitigation system including warnings, this approach is problematic for the sole assessment of distraction. First, it does not reliably relate to objective risk. Objective risk, e. g. the probability of a lane departure, depends on several variables of the situation, like the position of the vehicle in lane or the vehicle's velocity, which can rapidly change over seconds. Although humans are able to process these variables and act accordingly, it is usually munch harder to jointly quantify these in a single

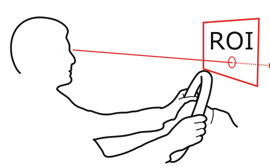

Fig. 10.1 Illustration of a typical ROI

rating. This is the case especially if a rather vague definition as the one of [1], which we cited in the introduction, is used for instruction.

Prediction of the *relative* crash risk by ROI-based algorithms was investigated by [15]. Here, the authors used data of a large naturalistic driving study [7]. Similar to the other approaches, the dependence of appropriate gaze behaviour on the specific situation was neglected. For development of a mitigation system, this methodology bears an additional problem: It would require a similar amount of crash data with the specific sensor concept of the system for algorithm evaluation. Clearly, this is not economically feasible.

10.4 Modelling Driver Strategies for Allocation of Visual Attention

A major problem of the reviewed approaches for assessment of driver distraction was a missing relation of the attentional demands of the current driving situation for safe driving. However, it is long known in the human factors and cognitive science communities that drivers are able to adequately adapt their gaze behaviour to situational demands: [16] showed already that the time drivers are willing to drive with occluded vision monotonically decreases with the vehicle's velocity. Other authors, e. g. [17], repeated the experiments and found similar results. In this chapter we present how these findings can be modelled in the context of a present secondary task. Here, we consider attentional demands of driving situations and the additional task and derive the potentially sub-optimal strategies applied by drivers.

10.4.1 Related Approaches based on Optimal Control

In driving and many other cases attention is closely linked to performance in a control task, e. g. keeping the vehicle in lane. For these scenarios [18] suggested that the behaviour of an experienced operator can be characterised by an optimal joint attention allocation and control strategy. Blaauw et al. [19] applied this model to lane keeping under temporary occlusion, where the experimental data of experiment [17] could be predicted.

As the opinion paper [20] suggested, we build on the optimal attention allocation control concept for modelling visually distracted driving. In this work, similar as [19] the scenario of lane keeping is considered. Here, we extend previous approaches by employing the principle of Maximum Causal Entropy (MCE) [21] to explicitly model to what extent drivers deviate from the optimal strategy. This is highly important for risk assessment. In contrast to previous work, where the attention allocation strategy was computed by "brute-force" search, we recently presented an efficient solution for optimal gaze-switching distracted driving by means of dynamic programming [22]. Finally, we adapt the inverse optimal control method of MCE to infer the optimization objectives and the human execution precision from real-traffic behavioural data. In previous work those values were hand-tuned.

10.4.2 Optimal Strategies in Markov Decision Processes

Markov Decision Processes (MDP)s provide a mathematical framework for characterizing sequential decision-making. An MDP consists of a state space X, a control space U, a stochastic process model $P(x_{t+1}|x_t, u_t), x_t \in X, u_t \in U$ and a reward function $r(x_t, u_t)$. The goal in a *finite-horizon* MDP is to find a policy $\pi(u_t|x_t)$ maximizing the expected reward

$$\mathbf{E}\left[\sum_{t=0}^{T} r(x_t, u_t) \middle| P(x_{t+1}|x_t, u_t), \pi(u_t|x_t), p_0(x_0)\right]$$

over a time horizon T, conditioned on the policy π, the dynamics P and an initial state distribution p_0. The optimality criterion is given by the famous Bellman equations:

$$Q_T(x_T, u_T) = r_T(x_T, u_T) \tag{10.1}$$

$$Q_t(x_t, u_t) = r_t(x_t, u_t) + \mathbf{E}[V_{t+1}(x_{t+1})|P(x_{t+1}|x_t, u_t)] \tag{10.2}$$

$$\pi'_t(u_t|x_t) = \text{argmax}_{u_t}[Q_t(x_t, u_t)] \tag{10.3}$$

$$V_t(x_t) = E[Q(x_t, u_t)|\pi'_t(u_t|x_t)] \tag{10.4}$$

Here, the function $V_t\colon X \mapsto R$ is called Value-function and $Q_t\colon X \times U \mapsto R$ is called Q-function. Note that $\mathbf{E}[V_0(x_0)|p(x_0)]$ equals expected reward

$$\mathbf{E}\left[\sum_{t=0}^{T} r(x_t, u_t) \middle| P(x_{t+1}|x_t, u_t), \pi'(u_t|x_t), p_0(x_0)\right]$$

under the optimal policy. Starting with Q_T the Bellman equations can in principle be used to optimally solve MDPs recursively, what is referred to as dynamic programming. However, in practical problems X, U are usually of large size or even continuous. This often prevents analytic computation.

The optimal policy π in Markov Decision Processes requires perfect knowledge of the state x_t. However, in visually distracted driving this is not the case: If the driver is not looking at the road he/she cannot perceive the vehicles position. Instead, he/she relies on an uncertain estimate of the states. Partial Observable Markov Decision Processes (POMDPs) offer an extension of ordinary MDPs to account for this issue. Instead of perfect state knowledge the policy relies on observations o_t that result from the "true" state by an Observation Model (OM) $p^o_t(o_t|x_t)$. These observations can be used to maintain an estimate of the state x_t in form of a belief distribution $b_t(x_t)$ that encodes the uncertainty about the true states. Given a new observation o_t the belief is updated by means of Bayes' rule

$$b_t(x_t) \propto p^o(o_t|x_t)\,\mathbf{E}\left[P(x_t|x_{t-1}, u_{t-1})\,|b_{t-1}(x_{t-1}), u_{t-1}\right], \tag{10.5}$$

using the past belief $b_{t-1}(x_{t-1})$ and the past applied control u_{t-1}. Defining new states $x'_t := b_t(x_t)$ and a new reward $r'(x'_t, u_t) := \mathbf{E}[r(x_t, u_t)|b_t(x_t)]$, every POMDP can formally be transformed into an equivalent MDP in the belief states. However, as x'_t is in any case continuous valued, solution via the Bellman equations is often intractable.

10.4.3 A Markov Decision Process Model for Lane Keeping Under Distraction

10.4.3.1 Vehicle Model

We start with modelling the vehicle's lateral dynamics by a *kinematic* single-track model that is also frequently used in lane keeping systems e. g. [23]. It is formulated by the system of ordinary differential equations

$$\begin{bmatrix} \dot{y}_t \\ \dot{\Phi}_t \\ \dot{\alpha}_t \end{bmatrix} = \begin{bmatrix} 0 & v_t & 0 \\ 0 & 0 & cv_t \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} y_t \\ \Phi_t \\ \alpha_t \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \dot{\alpha}_t + \begin{bmatrix} 0 \\ -v_t\kappa_t \\ 0 \end{bmatrix}. \tag{10.6}$$

The model can be derived from geometric relations illustrated in Fig. 10.2, using linear approximations for trigonometric relations involving the small angle Φ. We also employed a linear approximation of the steering wheel angle to $\dot{\Phi}$ relation. The variables and parameters of the vehicle are explained in Table 10.1

In this work we investigate driver behaviour based on data obtained in a rate of 25 Hz. Hence, we time-discretize the differential equation system and obtain the following dis-

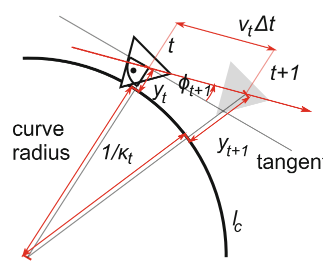

Fig. 10.2 Illustration of the geometrical relations of the variables in the kinematic vehicle model

Table 10.1 Variables and Parameters of Kinematic Vehicle Model

Symbol	Definition	Unit
y_t	Lateral position wrt. lane center l_c	m
Φ_t	Angle between tangent of lane and vehicle's longitudinal axis	rad
α_t	Steering angle	rad
v_t	Vehicle's absolute velocity	m/s
κ_t	Curvature of lane	1/m
c	Steering-wheel transmission ratio	

crete-time linear-affine system

$$x_{t+1}^p = A(v_t)x_t^p + B(v_t)u_t^p + a(v_t) + \epsilon_t \,. \tag{10.7}$$

Here, we summarize the vehicle states in a primary-task state $x_t^p = [y_t; \dot{y}_t; \Phi_t; \alpha_t]$, and define $u_t^p = \dot{\alpha}_t$. To account for unmodeled effects, our model also includes a normally distributed noise ϵ_t according to a distribution $N(0, \Sigma_s)$.

10.4.3.2 Model of the Driver's Perception

In this work, we make two simplifying assumptions about the driver's perception of the vehicle states:

1. All vehicle states are perfectly perceived when the driver's glance is on the road. Although this is not entirely physiologically plausible, as e. g. the human vestibular system cannot detect yaw rates below ~ 0.025 rad/s [24], we chose this model as it allows more efficient optimal control. We compensate model errors by allowing stochastic deviations from the optimal policy.
2. The driver can perfectly perceive the steering angle and cannot perceive all other vehicle states during distracted driving. For the secondary task we used in the experiment, this assumption is reasonable, as it requires glances with high eccentricity from the road viewing direction. Hence, effects of peripheral vision can be considered negligible.

These aspects can be formalized in the OM

$$p(o_t|x_t^p) = H(x_t^o)x_t^p := \begin{cases} o_t & \equiv & [y_t; \dot{y}_t; \Phi_t; \alpha_t] & \text{if } x_t^o = 1 \\ o_t & \equiv & [0; 0; 0; \alpha_t] & \text{if } x_t^o = 0 \end{cases} , \tag{10.8}$$

where the binary variable x_t^o indicates whether the driver looks through a ROI what allows to obtain information about the vehicle state ($= 1$) or not ($= 0$). The driver can change x_t^o by means of gaze switches u_t^o:

$$x_{t+1}^o = \begin{cases} x_t^o & \text{if } u_t^o = 0 \\ \neg x_t^o & \text{if } u_t^o = 1 \end{cases} . \tag{10.9}$$

10.4.3.3 Rewards for the Primary Task of Vehicle Control

To finalize the MDP a reward-function is required to assess policies. Regarding the vehicle states we apply the reward model

$$\theta^T \varphi(y_t, \dot{y}_t, \Phi_t, \alpha_t, \dot{\alpha}_t) = -\theta_1 y_t^2 - \theta_2 \dot{y}_t^2 - \theta_3 \alpha_t^2 - \theta_4 \dot{\alpha}_t^2, \forall_i : \theta_i \geq 0. \tag{10.10}$$

We assume that the driver seeks to keep the vehicle in the lane center, hence the squared deviation from the road center and the squared lateral velocity are minimized. Further, penalties for the square of the steering angle and its velocity are employed to account for steering of minimal effort. Note, that previous work used similar objectives in POMDP modelling of automobile driving [19, 33].

10.4.3.4 Transformation from POMDP to Belief MDP

Before we proceed with describing the reward model on the secondary task and the gaze behaviour, we first transform the discussed POMDP element into a belief MDP.

The partial observable vehicle states are subject to linear-affine dynamics and a linear observation model with Gaussian noise. Hence, as a basic result from filter theory, the belief is a Gaussian $b_t\left(x_t^p\right) = N\left(\mu_t^p, \Sigma_t^p\right)$ that is given by the a-posterior distribution resulting from the Kalman filter. Accordingly, the belief update manifests in

$$\Sigma_{t+1}^p = \Sigma_{t+1}^1 - \Sigma_{t+1}^2 \tag{10.11}$$

$$p(\mu_{t+1}^p|\mu_t^p, \Sigma_t^p) = N(\mu_{t+1}^p|\mu_{t+1}^1, \Sigma_{t+1}^2) \tag{10.12}$$

$$\Sigma_{t+1}^1 = A(v_t)\Sigma_t^p A(v_t)^T + \Sigma_s, \mu_{t+1}^1 = A_t(v_t)\mu_t^p + B(v_t)u_t^p + a(v_t) \tag{10.13}$$

$$K_{t+1} = \Sigma_{t+1}^1 H(x_{t+1}^o)^T (H(x_t^o)\Sigma_{t+1}^1 H(x_{t+1}^o)^T)^{-1} \tag{10.14}$$

$$\Sigma_{t+1}^2 = K_{t+1} H(x_t^o)\Sigma_{t+1}^1. \tag{10.15}$$

The reward model of the belief, $\mathbf{E}\left[\theta^T\varphi\left(x_t^p, u_t^p\right)|b_t\left(x_t^p\right)\right]$ can be expressed by

$$-\theta_1\left(\mathbf{E}[y]\right)^2 - \theta_2\left(\mathbf{E}[\dot{y}]\right)^2 - \theta_3\left(\mathbf{E}[\alpha]\right)^2 - \theta_4\dot{\alpha}^2 - \mathrm{tr}\left(\mathrm{diag}(\theta_1, \theta_2, 0, \theta_3)\Sigma_t^p\right). \tag{10.16}$$

Here, $\mathrm{tr}(X)$ denotes the sum of the diagonal elements of a matrix X and $\mathrm{diag}(x, y)$ denotes the diagonal matrix built from the scalars x, y. Note that as $\Sigma_t^p = 0$ if the driver is looking at the road, i. e. if $x_t^o = 1$, the number of the timesteps d_t the driver's glance is off the road can be used to substitute Σ_t^p.

10.4.3.5 Rewards for Secondary Task and Gaze Behaviour

The optimal policy with respect to the objective on the vehicle states alone, results in fully attentive driving. This is because the observation model when glancing away from the road decreases control performance and leads to lower reward. Therefore, we assume that the secondary task engagement is of some utility to the driver, i. e. also produces a certain amount of reward. Mathematically, we formulate this as a generic constant positive reward for every time step of engagement,

$$\theta_5\varphi\left(x_t^o\right) = \theta_5 x_t^o, \theta_5 \geq 0, \tag{10.17}$$

to account for a variety of tasks. As long as the reward from the secondary task outweighs the loss of reward resulting from deteriorated vehicle control a certain amount of glances will be paid to the secondary task. However, in the current reward model the optimal policy will switch between both tasks in a high frequency: Because of the gradual increase of the covariance in the belief $x_t^o = 0$ will be held for only very few time steps. However, in driving less gaze switches occur in the time scale of 25 Hz. This is because switches require interrupting the task, moving the eyes from the secondary to the outside scenery, and likely also a refocus. Hence, we add a penalty

$$\theta_6 \varphi(u_t^o) = \theta_6 u_t^o, \theta_6 \leq 0 \tag{10.18}$$

to the reward model to account for the effort of gaze switching, similar as proposed in [18].

10.4.3.6 Taking into Account Human Execution Quality

Although, optimal control provides a sound basis to characterise the driver's strategic behaviour, the optimal policy is not perfectly executed in real driving. One reason for this is, that we neglected certain human limitations in the MDP. Additionally, individual drivers differ in the specific choice of the control objective: For example, some drivers might value the secondary task higher than others. For these reasons a stochastic policy is more appropriate for predicting the range of real-world behaviour of drivers. This is important especially in lane keeping, as the steering performance additionally influences the necessary gaze policy: A driver who uses a more foresighted and low-noise steering policy can glance away from the road much longer. Already [19] mentioned, that the driver's steering noise had a strong influence in their model. We adapt the principle of Maximal Causal Entropy MCE [21] to systematically address this aspect in the optimal control model. Here, we assume that drivers act according to a distribution of policies:

$$p(\widetilde{\pi}(u|x)) \propto \exp\left(\mathbf{E}\left[\sum_{t=0}^{T} r(u_t, u_t) | P\left(x_{t+1}|x_t, u_t\right), \widetilde{\pi}\left(u_t|x_t\right), p_0(x_0)\right]\right). \tag{10.19}$$

Under this distribution, the likelihood of a specific policy is a monotonic function of its expected reward, i. e. the higher the reward, the more likely is the policy. This leverages the interpretation of MCE as a model of sub-optimal yet proficient behaviour. Note that scaling the reward controls the spread around the optimal policy – multiplying r with a factor $0 < c < 1$ results in an increase in variation.

The stochastic policy (this is equivalent to a distribution over policies) can be computed by "softened" Bellman equations:

$$\widetilde{Q}_T(x_T, u_T) = r_T(x_T, u_T) \tag{10.20}$$

$$\widetilde{Q}_t(x_t, u_t) = r_t(x_t, u_t) + \mathbf{E}\left[\widetilde{V}_{t+1}(x_{t+1}) | P\left(x_{t+1}|x_t, u_t\right)\right] \tag{10.21}$$

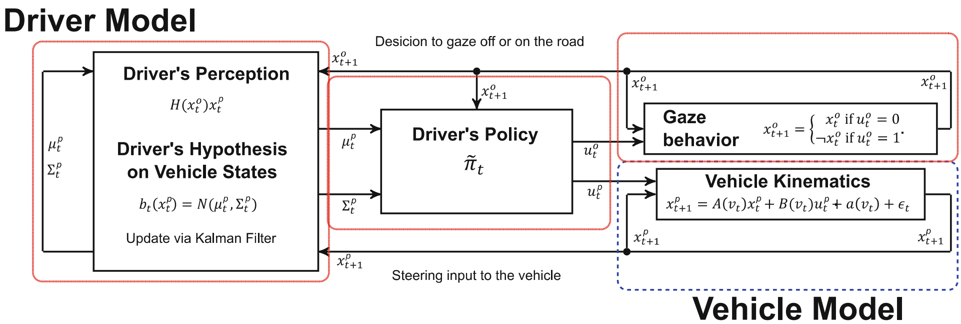

Fig. 10.3 Illustration of the final model comprising of a driver and a vehicle model that are connected by the driver's policy

$$\widetilde{V}_t(x_t) = \log\left(\int \exp\left(\widetilde{Q}_t(x_t, u_t)\right) du_t\right) \tag{10.22}$$

$$\widetilde{\pi}_t(u_t|x_t) = \exp\left(\widetilde{Q}_t(x_t, u_t) - \widetilde{V}_t(x_t)\right) \tag{10.23}$$

Similar as [25], we apply the MCE to the previously derived belief-MDP. This enables to compute the stochastic policy by a Riccati-type iteration combined with the "softened" Bellman equations [22]. The final model including the vehicle kinematics, driver perception and the policy is illustrated in Fig. 10.3.

10.4.4 Learning Driver Strategies

For numerical computation of the drivers policy and behaviour prediction, it is necessary to specify the reward parameters $\theta_i, i = 1, 2, \ldots, 6$. The correct numerical values are of high importance as they *implicitly* define both the optimal and the MCE policy.

10.4.4.1 Inverse Optimal Control

In this work we infer θ from collected driving data. We assume that the driver follows an optimal or proficient policy that generated sequences of states and controls $D = \left\{(x_t^i, u_t^i), t = 0, 1, \ldots, T\right\}, i = 1, 2, \ldots n$ in the derived stochastic process model under a reward model $\theta^T \varphi(y_t, \dot{y}_t, \Phi_t, \alpha_t, \dot{\alpha}_t, x_t^o, u_t^o)$ with unknown parameters θ. In this setting the parameters of the underlying reward can be estimated by means of Inverse Optimal Control (IOC).

In our case of a linear parametrization of the reward, the feature matching condition for reward reconstruction [26] can be applied. This criterion is stated as follows: If reward parameters $\hat{\theta}$ are found that the optimal policy $\hat{\pi}$ for reward $\hat{\theta}^T \varphi(x, u)$ fulfils the feature matching condition

$$\mathbf{E}\left[\sum_{t=0}^{T}\varphi(u_t,u_t)\middle|\, P\left(x_{t+1}|x_t,u_t\right),\hat{\pi}\left(u_t|x_t\right),p_0(x_0)\right]=1/n\sum_{i=1}^{n}\sum_{t=0}^{T}\varphi(x_t^i,u_t^i), \tag{10.24}$$

then $\hat{\theta}^T\varphi(x,u)$ is a reward the observed policy is optimal for.

10.4.4.2 Inverse Optimal Control in MCE

While the scale of θ does not matter in optimal control (without restriction θ can be assumed to have unit norm), in MCE this quantity is controlling the execution quality and must also be inferred. For this purpose, in IOC in the MCE framework the feature matching condition is combined with maximization of the conditional entropy of the policy $-\mathbf{E}\left[\pi\left(u|x\right)\log\pi\left(u|x\right)|p\left(x\right)\right]$. Here, $p(x)$ is the state distribution resulting from roll-out of $\pi(u|x)$ wrt. to the MDP process model. Effectively, this estimates the policy distribution with the highest variation that still archives the same expectation in all parts of the reward model as the data. As shown in [21], this results in a very statistically robust estimation procedure. Mathematically, this approach is formulated as the following constrained optimization problem

$$\max_{\pi}-\mathbf{E}\left[\sum_{t=0}^{T}\pi_t\left(u_t|x_t\right)\log\pi_t\left(u_t|x_t\right)\middle|\, p(x_t)\right] \tag{10.25}$$

$$\text{st. }\mathbf{E}\left[\sum_{t=0}^{T}\varphi(u_t,u_t)\middle|\, P\left(x_{t+1}|x_t,u_t\right),\pi_t\left(u_t|x_t\right),p_0(x_0)\right]=1/n\sum_{i=1}^{n}\sum_{t=0}^{T}\varphi(x_t^i,u_t^i) \tag{10.26}$$

The optimization problem can efficiently and globally be solved by solution of the equivalent [22] unconstrained convex minimization problem

$$\min_{\theta}\mathbf{E}\left[\tilde{V}_0^{\theta}\left(x_0\right)|p\left(x_0\right)\right]-1/n\sum_{i=1}^{n}\sum_{t=0}^{T}\theta^T\varphi\left(x_t^i,u_t^i\right). \tag{10.27}$$

Here $\widetilde{V}_0^{\theta}(x_0)$ is the result of Eq. 10.22 given a specific θ. The gradient of the optimization objective required for numerical solution is given by

$$\mathbf{E}\left[\sum_{t=0}^{T}\varphi(u_t,u_t)\middle|\, P\left(x_{t+1}|x_t,u_t\right),\pi_t^{\theta}\left(u_t|x_t\right),p_0(x_0)\right]-1/n\sum_{i=1}^{n}\sum_{t=0}^{T}\varphi(x_t^i,u_t^i) \tag{10.28}$$

10.5 Experiment in Real Traffic

10.5.1 Experiment

To evaluate our modelling approach, we conducted a experiment on a public highway. We decided against a experiment in a driving simulator because of possible influences on the participants' behaviour by absence of real risk. In addition to that, evaluation of prediction robustness on realistic sensor input, i. e. noisy signals, is important.

We recruited seven drivers (6 male, 1 female) that had taken part in an internal driving safety training. The experiment consisted of four fixed driving speed conditions $\{80, 90, 100, 110\}$ km/h. Vehicle speed was controlled by the vehicle's Adaptive Cruise Control (ACC) to prevent drivers from adjusting their speed as a compensatory action while being engaged in a secondary task. A conservative time gap was employed to ensure that the distance to preceding vehicles did have the least possible influence on the drivers' behaviour. When the vehicle travelled at the required speed, the measurement periods were started. Such a period was either a reference, where the participants drove fully attentive or involved a visually distracting secondary task. At each speed level three secondary tasks and three reference periods per participant were triggered by the investigator.

The task we used in this experiment consisted of reading and typing a series of 3×10 random numbers. The individual numbers that could either be a "1" or a "2" were displayed at the position of the vehicle's central information display. Fig. 10.4 shows both the position of the display and the task presentation. Once the participant had pressed the correct number on a number pad, the next number was generated and displayed. To induce realistic behaviour, the participants were instructed to "perform the secondary task as quickly and correctly as possible while not endangering driving safety". This artificial task was chosen, as it resembles the principle of a variety of real visual-manual tasks performed while driving, and possesses several advantages. First, the task state is fully

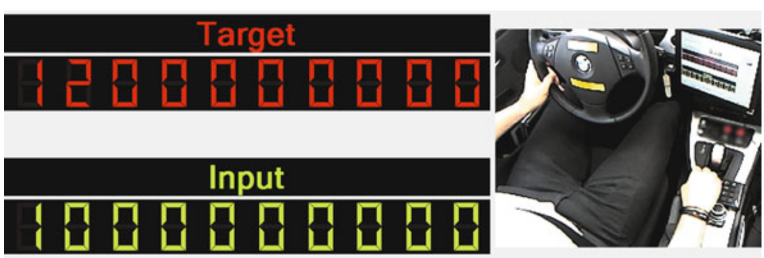

Fig. 10.4 Illustration of the used secondary task. Left picture shows the task representation on the display where the participant is requested to type the first digit "1" and second digit "2". The remaining digits are not shown yet, instead their fields are initialized with "0". Right picture shows a participant conducting the secondary task while driving

measurable and can be modelled easily, in contrast to the tasks on the vehicle's interaction system. Second, the participants needed only little practice to reach maximum execution performance, resulting in no significant learning effects during the experiment.

10.5.2 Sensors and Measured Signals

10.5.2.1 Measurement Equipment

The demonstrated behaviour in the experiment was recorded with a variety of sensors: The position of the vehicle in lane y_t, the angle between the tangent of the lane boundary and the vehicle's longitudinal axis Φ_t and the curvature κ_t were measured by tracking the lane boundaries using the Multi-Purpose Camera (MPC2) system (Robert Bosch GmbH, Stuttgart, Germany). The remaining vehicle signals were recorded from the vehicle's Controller Area Network (CAN). The driver's gaze direction and head orientation were estimated using the infra-red eye tracking system with active illumination SmartEye Pro (SmartEye AB, Gothenburg, Sweden). The test-vehicle was equipped with three-cameras in the left A-pillar, in front of the instrument cluster and on the dashboard above display. The output of the eye-tracking system was fused by an in-house algorithm and reduced to the binary eye-on-road or eyes-off-road signal x_t^o based on a ROI-algorithm similar to other authors [1].

10.5.2.2 Pre-processing

In order to ensure sufficient quality for numerical evaluation and computation of statistics, the following pre-processing and filtering steps were performed on the collected raw data:

1. We first selected the valid trials according to a fixed protocol. Here, we automatically excluded lane changes and their preparation phases: As a different driving manoeuvre than lane keeping it requires a different driving and gaze policy. Also situations where the ACC controller reduced the vehicle speed by more than 5% were left out: We found that approaching a preceding vehicle increases the amount of glance time in the ROI. Additionally, distinct speeds are required to separate the driving conditions. The final dataset consisted of 136 valid segments comprising of 53 reference and 83 secondary task periods with an average duration of 20 and 45 s.
2. As the used sensors operate at different frequencies, e. g. the eye-tracking at 60 Hz but the lane-tracking at 25 Hz, we subsampled all signals to 25 Hz. Thereafter, the Kalman-smoother was employed for filtering of the partially low resolution signals $y, \Phi, \alpha, \dot{\alpha}, \kappa$ using the previously presented kinematic vehicle model. The system parameters c, Σ_s as well as the sensor noise-covariance Σ_μ were estimated by expectation-maximization as proposed for vehicle models by [27]. Here, we used the data of both reference and secondary task periods.

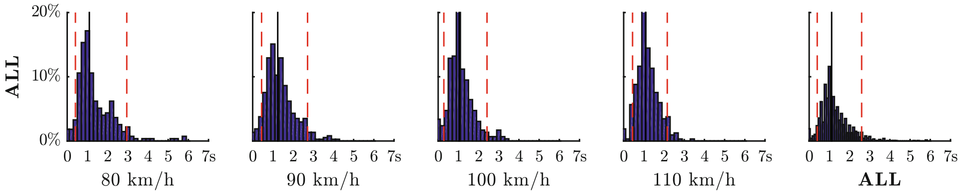

Fig. 10.5 Illustration of the distribution of off-road glance duration. Dashed lines in red indicate the 5 and 95% percentiles, the median is indicated with a black continuous line

10.5.3 Behavioural Statistics

In the experiment similar glance behaviour as described in previous work in real traffic [5] was observed. As can be seen in Fig. 10.5, the artificial secondary task resulted in a pronounced mode at the median of the distribution of the off-road-gaze duration at approximately 1.2 s. This mode appeared to be consistent across the four speed conditions. In contrast, the higher percentiles decreased with increasing speed. This could statistically be verified for the groups 80, (90, 100), 110 km/h and the 75 precentile.

Another important metric used for quantification of the effects of distraction is the standard deviation of the lane position. We computed this statistic for each period of reference driving and driving with a secondary task.

As can be seen from Fig. 10.6, this metric was significantly lower in driving without a secondary task $p = 3{\times}10^{-4}$. This shows that the used secondary task induced significant distraction resulting in decreased driving performance.

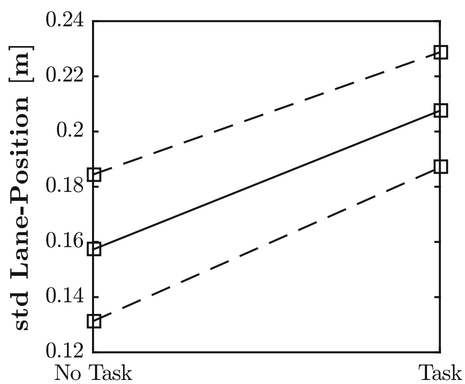

Fig. 10.6 Illustration of the standard deviation (std) of the lane position. Continuous line indicates the median, while the dashed lines indicate the 95 and 5% confidence bounds

10.6 Numerical Evaluation

To demonstrate the effectiveness of our IOC-based approach we conducted two numerical evaluations which will be presented in the following section. Here, we compared against a baseline comprising of established behaviour models for human attention allocation and foresighted steering.

10.6.1 Baseline Model

Johnson et al. [28] presented a model for gaze-switching in visual dual tasking, where the probability of a glance to a task is a logistic function of the uncertainty in its states. In our case, uncertainty is only present in the vehicle states – the random number on the display is either known if the driver has seen it already or unknown otherwise. Hence, we adapted the original approach to our scenario and applied a model given by the switching policy $\pi^{\lambda}(u_t^o | x_t^o, \Sigma_t^p)$

$$p(u_t^o | x_t^o = 1) = \frac{\exp(\lambda_1) + u_t^o}{\exp(\lambda_1) + 1} \tag{10.29}$$

$$p\left(u_t^o | \; x_t^o = 0, \Sigma_t^p\right) = \frac{\exp\left(\lambda_2 + \mathrm{tr}(\Lambda \Sigma_t^p)\right) + u_t^o}{\exp\left(\lambda_2 + \mathrm{tr}(\Lambda \Sigma_t^p)\right) + 1} \tag{10.30}$$

with parameters $\lambda_1, \lambda_2, \Lambda$.

Furthermore we used the two-point-steering model of [29] to model human foresighted steering, including curve negotiation. In that model it is assumed that the driver's steering policy builds on a visual near-angle β_1 and a visual far-angle β_2. Given a line with width w, the visual near-angle is defined as the angle between a line from the vehicle center to a point on the road center typically 2 m ahead and the vehicle's longitudinal axis. The far-angle β_2 is defined as the angle of minimal magnitude of the angles between the tangents from the vehicle's center to both boundaries and the vehicle's longitudinal axis. Both angles are illustrated in Fig. 10.7 using an arc approximation of the track.

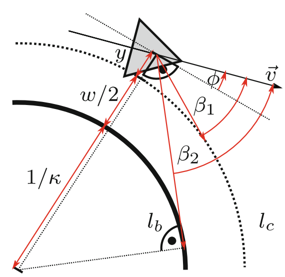

Fig. 10.7 Illustrations of the geometric relations in the two-point steering model, give an arc track-model

Correspondingly, we computed both angles using the equations:

$$\beta_1 = -\arctan\frac{y}{2m} - \Phi \tag{10.31}$$

$$\beta_2 = \begin{cases} -\arccos\left(\frac{1}{1-\kappa\left(\frac{w}{2}+y\right)}\right) - \Phi & \text{if } \kappa < 0 \\ +\arccos\left(\frac{1}{1+\kappa\left(\frac{w}{2}+y\right)}\right) - \Phi & \text{if } \kappa \geq 0 \end{cases}. \tag{10.32}$$

The resulting angles were fed into a stochastic policy

$$\dot{\alpha} = \lambda_3\beta_1 + \lambda_4\beta_2 + \lambda_5\alpha + \epsilon_6. \tag{10.33}$$

This differs from the approach of (ibid.), were a proportional-differential (PD) controller was applied. However, using the arc-approximation of curves the PD turned out to be unstable on real data. The reason is, that the curvature measured by lane tracking oscillated around 0 leading to frequent jumps in angle β_2.

Both approaches for attention allocation and foresighted steering were combined by replacing y, Φ in Eq. 10.32, by their expectation under the Kalman filter, if $x_t^o = 0$, i. e. if the gaze of the driver is off the road. Note, that this principle was also adopted in [28], however the authors used a proportional-integral-differential controller acting directly on the vehicle states.

10.6.2 Evaluation Protocol

In the numerical evaluation of our MCE-IOC based approach against the baseline, we subdivided the reference and secondary task periods Sect. 10.5.1 into smaller snippets of $5s$. Which is the maximum realistic prediction horizon of an assistance system relying on behaviour prediction.

A common issue in statistical parameter estimation is the problem of overfitting. This occurs when parameters are inferred that are too specific for a subset of the data not generalizing on the rest of the data. For this reason often the parameters of models are regularized in the estimation procedure. In MCE-IOC we relax perfect feature matching Eq. 10.26 to a tolerance of one percent of the norm of the empirical feature expectation

$$\frac{\left|\frac{1}{n}\Sigma_{i=1}^{n}\Sigma_{t=0}^{T}\varphi\left(x_t^i, u_t^i\right) - \mathbf{E}\left[\Sigma_{t=0}^{T}\varphi\left(u_t, u_t\right)|P\left(x_{t+1}|x_t, u_t\right), \pi_t^\theta\left(u_t|x_t\right), p_0\left(x_0\right)\right]\right|}{\left|\frac{1}{n}\Sigma_{i=1}^{n}\Sigma_{t=0}^{T}\varphi\left(x_t^i, u_t^i\right)\right|} < 0.01 \tag{10.34}$$

what effectively adds a regularization of $\rho|\theta|$ to the MCE-IOC objective. The baseline parameters λ_i were inferred by rewriting both models as generalized linear models. MATLAB's implementation of parameter estimation including auto-optimization of a regularization of $\rho|\lambda|$ was used in the numerical experiment [30].

To assess the prediction quality of both approaches in the evaluation snippets, the first states x_0^s, x_0^o were used as the initial state distributions p_0. Following, we sampled 100 state sequences of each model by policy roll-out, i. e. given a state new controls were sampled from the policy and together a new state was sampled by means of the process model. Here, the pre-estimated steering angle transmission ratio c and system model noise covariance Σ_s Sect. 10.5.2.2 were used. Two numerical experiments were conducted:

1. We evaluated the overall prediction performance. Therefore, we randomly divided the entire data into two subsets of equal size *independently of participant, condition and track topology.* One set was used for parameter estimation (train) while the other set was used for evaluation on unseen data (test). Afterwards the roles of both sets were changed. To increase robustness in the performance statistics, we repeated the procedure 10 times.
2. We evaluated the transfer performance, i. e. the generalization of the approaches on unseen driving speeds. If employed in any assistance system, a prediction model has to be of low error in *all* relevant scenarios. However, it is impossible that all these scenarios are contained in a training dataset. For this reason, it is important to also asses if and to what extent the prediction quality is affected when testing on unseen speeds. For this purpose, we first trained on half of the data of a single speed. Thereafter, we evaluated on the other half of the same speed (same) and the all the data of other speeds (trans). Similar as in evaluation (1.) the procedure was repeated 5 times.

On the obtained data in both evaluations the prediction quality was assessed by two metrics:

We computed the expected squared error in prediction of the trajectory, i. e. the sequence of lane positions:

$$\mathrm{SE}^i(y) = \mathbf{E}\left[\frac{1}{T}\sum_{i=0}^{T}\left(y_t - y_t^i\right)^2 \middle|\, \pi, P, p_0^i\right]. \tag{10.35}$$

This metric assess if the effects of distraction on driving behaviour can be predicted. Note that both the steering policy and the gaze-switching policy contribute to this metric.

In addition to that, we also separately assessed the prediction of the gaze behaviour. Here, we investigated the difference in distribution of the time passed since the last glance on the road, i. e. the eyes-off-road duration d_t, in the collected data $p^i(d)$ and the prediction $p(d)$. This difference can be quantified in the Kullback-Leibler divergence, defined by

$$\mathrm{KL}\left(p^i\,(d)\,||\,p\,(d)\right) = \sum_d p^i\,(d)\,(\log p^i\,(d) - \log p\,(d)). \tag{10.36}$$

Note, that both metrics are strictly positive resulting in skewed distributions. For this reason, we will report nonparametric statistics in the following results section.

10.6.3 Results

The results of the first evaluation comparing the baseline model (base) and our approach (ours) are presented in Table 10.2, while Table 10.3 summarizes the results of the second evaluation.

The results are further illustrated by box-plots in Fig. 10.8. Here, the strongly skewed shape of the error distributions, mentioned earlier, are apparent.

Table 10.2 Results of Evaluation 1 – Overall Prediction Performance

Metric	Base train	Test	Ours train	Test
Median SE	0.0482	0.0484	0.0154	0.0157
Median KL	0.0998	0.1006	0.0731	0.0727

Table 10.3 Results of Evaluation 2 – Transfer Prediction Performance

Train	Metric	Test			
		80 km/h	90 km/h	100 km/h	110 km/h
80 km/h	*SE* ours	0.0154	0.0143	0.0164	0.0154
	Base	0.0293	0.0572	0.0725	0.0836
	KL ours	0.0851	0.0744	0.0738	0.0701
	Base	0.1280	0.1180	0.1025	0.1216
90 km/h	*SE* ours	0.0152	0.0148	0.0159	0.0163
	Base	0.0310	0.0365	0.0477	0.0627
	KL ours	0.0833	0.0748	0.0730	0.0721
	Base	0.1307	0.1146	0.1018	0.1200
100 km/h	*SE* ours	0.0147	0.0160	0.0155	0.0161
	Base	0.0311	0.0390	0.0450	0.0584
	KL ours	0.0838	0.0763	0.0731	0.0693
	Base	0.1374	0.1124	0.1100	0.1173
110 km/h	*SE* ours	0.0157	0.0152	0.0179	0.0177
	Base	0.0401	0.0408	0.0479	0.0603
	KL ours	0.0825	0.0724	0.0755	0.0721
	Base	0.1249	0.1076	0.0901	0.1102

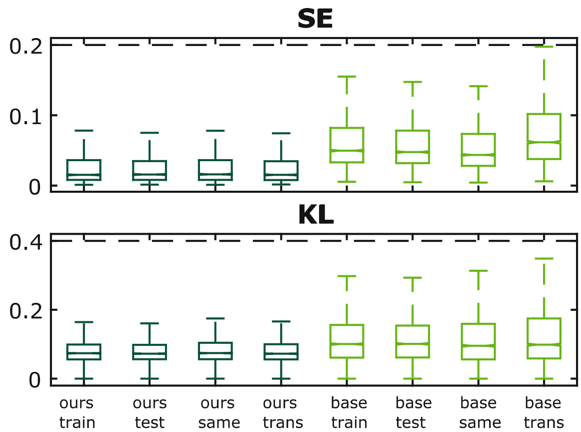

Fig. 10.8 Illustration of the error distribution in both experiments. Boxes indicate the 25 and 75 percentiles, with the median as a horizontal line in between. The whiskers denote 1.5 times the median to corresponding percentile distance

10.6.4 Discussion

In the current section we will consider a significance level of $\alpha < 0.01$ for the corresponding non-parametric tests (signed rank, rank-sum) on the medians.

Our model based on inverse optimal control shows consistently better performance, i. e. it has a lower prediction error, in both evaluations and in both metrics. In the first evaluation, performance of our approach was highly significantly better, what can also be seen in the notches of the boxplot. For both parameter-estimation (ours, base) the regularization was chosen appropriately as no significant performance differences between training and test could be established. The difference between our approach and the baseline likely results from two aspects: First, our steering model takes into account the track curvature of the entire prediction horizon what appears to be a more appropriated model for human foresighted steering. Second, by modelling both steering and gaze behaviour in a joint POMDP, the resulting gaze-switching policy takes into account the *future* consequences of the uncertainty during off-road glancing. In contrast, Johnson et al.'s barrier model is reactive and operates solely on the recent uncertainty and also lacks a link to the steering policy. The second evaluation gives further insight into the differences in prediction quality: First, our approach performs significantly better in almost all (train speed, test speed) conditions. For both approaches significant between-condition-variations could be established by a Kruskal-Wallis test. However, the variance of our model was significantly lower according to an Ansari-Bradley test. Finally, the difference between the median error on unseen speeds and seen speeds was significantly higher for the baseline approach in both metrics. The low variance in prediction error of the IOC based approach can be explained by its higher level of behaviour abstraction: Instead directly estimating a behaviour model in form of a policy, IOC rather estimates the preferences or motivations in form of the reward model that cause the policies. If those preferences and the situational dynamics can be described, IOC can accurately predict the specific policies in a broad range of different scenarios. This could been shown in a variety of modelling problems, e. g. [31], and is confirmed by the good transfer performance in the considered case.

10.7 Conclusion

In this chapter, we presented an approach to model situation specific driver behaviour in visually distracted lane keeping. Based on the paradigm of "the human as an optimal controller and information processor", we first derived a model of the control task in lane keeping and introduced a model for the impaired perception of the driver looking off the road for some secondary task. We used maximum causal entropy inverse optimal control to identify both the driver's reward model and his execution precision from data obtained in a real-traffic experiment. In two numerical evaluations our model consistently show significantly lower prediction error than established behaviour models. This holds true, especially, in the prediction in situations unseen in parameter estimation.

Although the results of the conducted numerical evaluation are very promising, further investigation have to be done. First, we used a simplistic model of the driver's perception that was grounded on reasonable assumptions for the secondary task used in the experiment. However, these assumptions will no longer be valid for other display locations. Therefore, further research has to address the perception model and to develop methods for its inference from data. Second, the scenario addressed in the experiment quite restricted: Constant high speeds 80, 90, 100, 110 km/h. To finalize the validation of the proposed approach, significantly lower speeds as well as accelerations and decelerations have to be addressed. Finally, lane keeping is only one aspect of safe driving, besides headway control or special manoeuvres as lane change. Hence, also models for these actions have to be developed.

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Lane Change Prediction: From Driver Characteristics, Manoeuvre Types and Glance Behaviour to a Real-Time Prediction Algorithm

11

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11.1 Introduction

Lane change manoeuvres pose high demands on the driver [1, 2] and are connected with a substantial accident risk. In Germany in the year 2014, 13% of accidents with personal injury on motorway were associated with lane change manoeuvres, 5% on roads within built-up areas [3]. Lane Change Decision Aid Systems (ISO 17387:[4]) aim at providing assistance for this type of manoeuvres. Estimations of the safety potential for lane change assistance/blind spot warning range up to 24% of addressable lane change-crashes [5] and 25% of crash severity reduction [6]. However, to fully exploit this potential it is essential that drivers accept these systems and use them in daily live. One important precondition for acceptance is the ability of Advanced Driver Assistance Systems (ADAS) to provide reliable assistance specifically when required [7]. False alarms in situations where the driver has no intention to change the lane could annoy, distract and irritate drivers. As a consequence, ADAS could be disregarded or disabled and the potential safety benefit gets lost. Driver intent information is supposed to reduce the mismatch between driver expectations and system reactions. If an intended lane change can be predicted before it is initiated, 1) lane change assistance can be activated specifically at this moment, 2) parameters of other ADAS such as lane departure warning, adaptive cruise control or collision

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warning can be adapted to avoid nuisance alerts and 3) workload-manager can use the information to suppress unnecessary non-driving activity, e. g. messages from the navigation system or incoming calls. Within the German research initiative UR:BAN, the I-FAS investigated lane change intentions at different levels of analysis in order to finally develop a real-time prediction algorithm. The present chapter shows the analysis of lane change predictors on the behavioural, strategic, manoeuvring and control level. Technical details on the real-time algorithm as well as the head-tracking-based glance area estimation can be found in the book-chapter of Leonhardt, Pech, Lindner and Wanielik.

11.1.1 Previous Research

Several studies already focus on the assessment of lane change intentions. Best prediction rates can usually be achieved by data fusion from three sources [8]: 1) driver behaviour observation e. g. eye-tracking or head-tracking, 2) sensor information about the environment, e. g. front/side radar and lane detection and 3) vehicle parameters, e. g. turn signal, speed, acceleration, steering wheel angle … etc. Different algorithms are used to integrate these data sources and predict the intention, e. g. Hidden Markov Models, fuzzy logic, cognitive models, neural networks or regression models [9]. The turn signal appears as rather unreliable indicator for lane changes: In a blind observational study, Ponziani [10] observed 2000 lane changing vehicles at different places and recorded 52% of lawful turn signal usage. Similar values are reported by Lee et al. [11] with 44%, ranging from 11 to 94% for different lane change types. A German study reported a turn signal usage of 55% for lane changes on urban roads and 75% on highways [12]. Similar results were obtained in a second observational study including almost 400,000 vehicles with a turn signal usage of 71% on German highways [13]. Due to this uncertainty, gaze behaviour is considered as a promising predictor at an early stage of manoeuvre planning. The time period of three to four seconds prior a lane change is considered as critical phase of visual search to determine the feasibility of the manoeuvre [8, 14, 15]. As gaze behaviour is linked to the early cognitive phase of information gathering, warnings e. g. from collision avoidance systems are supposed to show a higher impact during this phase compared to action execution at a later stage [16]. Even prior to information gathering, motives for lane changes can be determined. Lee et al. [11] identified a set of 11 reasons for lane changes on interstates and U.S. highways: exit- respectively entry to a highway, slow lead vehicle, return to the original lane, tailgating vehicle, obstacle, merging vehicle, lane drop, added lane, unintended and other. This classification provides a useful basis to distinguish lane change manoeuvres, identify potential predictor variables and perform distinct analysis for each manoeuvre type.

11.1.2 Research Questions at Control, Manoeuvring, Strategic and Behavioural Level

Present study aimed at identifying early predictors of lane change manoeuvres on arterial roads in city areas. By using a systematic and comprehensive approach, possible predictors were investigated at different levels of analysis according to the extended hierarchical driver behaviour model of Michon [17]. Michon [18] distinguished three hierarchical levels of the driving task: The control level operates at time constraints of milliseconds and refers to basal car control processes involving automatic action patterns such as lane keeping. On the manoeuvring level, controlled action patterns in time units of seconds are executed, such as lane change manoeuvres. The strategic level comprises general plans with a longer time horizon, such as route and speed choice as well as pre-trip decisions. As an extension of this model, a fourth "behavioural level" was proposed [17], including rather stable individual dispositions such as sociodemographic factors, personality and attitudes that might influence driving behaviour. All levels are linked and interact with each other, e. g. higher general risk taking tendencies on the behavioural level might lead to higher speed choices on the strategic level, resulting in more frequent overtaking on the manoeuvring level which in turn requires more mirror glances and steering activity on the control level. Due to these interdependencies, analyses of potential lane change predictors on all four levels are required to optimize a real-time prediction algorithm. Thus, the following research questions were addressed in the present study:

- Behavioural level (dispositions): How do driver characteristics such as age, gender, cognitive abilities and personality affect the number of lane change manoeuvres performed?
- Strategic level (trip planning): Does the familiarity with the route play a role for the number of lane changes performed?
- Manoeuvring level (controlled action patterns): Are all lane change manoeuvres similar with regard to intent recognition or do we have to distinguish specific patterns for lane change subtypes? Which rates and timings for turn signal usage can be observed?
- Control level (automated action patterns): Which mirror-glance patterns can be identified prior to lane change manoeuvres? How are the patterns related to lane change types, traffic situation and turn signal usage? How stable are these patterns?

To answer the research questions, an explorative on-road study with 60 participants was carried out with a minimum of restrictions in order to assess real driving behaviour as naturalistic as possible.

11.2 Methods

11.2.1 Participants

Participants were selected in a two-step procedure. In a first short online questionnaire, interested candidates could apply for the study. The questionnaire covered gender, age, driving experience and contact information. Out of the 116 applicants, 60 participants were selected to take part in the study. The aim of the selection was to create two gender-balanced age groups in order to allow for stable statistical analysis of age and gender related issues. The younger age group ranged from 20 to 35 years (M = 28, SD = 4.13) and the older group from 40 to 65 years (M = 51, SD = 6.33). Details on all sample characteristics are presented in Table 11.1. The mean age of the 30 men and 30 women was 39 years (SD = 12.86) with a mean driving experience of 13,500 km per year (SD = 7800).

11.2.2 Study Design and Procedure

The on-road study design was explorative with a minimum of restrictions for the drivers in order to assess natural driving behaviour. Participants were invited for a two hour appointment at the University of Chemnitz. After arriving, information about the aims and procedure was given and all subjects signed the informed consent. Participants were informed that the study aims at acquiring naturalistic driving data (without any reference to lane change manoeuvres). All drivers were instructed to drive as they would usually do and the route was explained. Subsequently, all participants were introduced to the car handling and drove a short test drive of approx. 850 m around the University, accompanied by an experimenter. After clarification of all questions, participants drove the experiment route unaccompanied. Navigation instructions were given by a pre-programmed navigation system in the car. After return, participants filled in the questionnaires and received a remuneration of 20 €.

Table 11.1 Sample characteristics regarding age, gender and mileage per year

Age group	Men			Women			Total		
	N	Age M (SD)	km/year M (SD)	N	Age M (SD)	km/year M (SD)	N	Age M (SD)	km/year M (SD)
20–35	15	28 (4.56)	10,600 (7300)	15	28 (3.60)	10,100 (4800)	30	28 (4.13)	10,400 (6100)
40–65	15	52 (6.15)	17,000 (6800)	15	50 (6.66)	16,300 (9700)	30	51 (6.33)	16,700 (8200)
Total	30	40 (13.34)	13,800 (7700)	30	39 (12.58)	13,200 (8100)	60	39 (12.86)	13,500 (7800)

11.2.3 Route and Test Vehicle

The experiment route had a total length of 40 km and was composed of two identical 20 km parts within the urban area of Chemnitz (Fig. 11.1b). Each 20 km trip consisted of a 2.5 km two-lane stretch with a speed limit of 50 km/h (A to B), a 13.6 km two-lane part with a speed limit of 70 km/h (B to C to D) and a final 3.9 km one-lane stretch with a speed limit of 50 km/h (D to A). Mean driving time was 1:02:12, ranging from 0:51:42 to 1:28:03.

The test vehicle was a standard VW Touran 2.0 TDI with automatic transmission (Fig. 11.1a). The car was instrumented with a data acquisition system including seven video cameras, differential GPS with a precision up to 40 cm, six radar systems and CAN-logger for vehicle data. The images of the driver camera were captured with 40 Hz and a resolution of 640 × 480 pixels. The front- and the interior camera captured images at a maximum rate of 30 Hz with a resolution of 640 × 480 pixels (Fig. 11.2). Further details on the technical specifications of the test vehicle can be found in the following book-chapter of Leonhardt et al.

11.2.4 Questionnaires and Data Preparation

Driver characteristics were assessed using questionnaires and included:

- age, gender and average mileage per year,
- experience with automatic transmission (1 = none to 5 = very experienced),
- familiarity with the route (1 = unknown to 5 = very well known),
- normed Big Five personality trait scores (t-values): agreeableness, openness, conscientiousness, extraversion, neuroticism (NEO-FFI, [19]),
- sensation seeking (Brief sensation seeking scale BSSS; [20]),

Fig. 11.1 Instrumented test vehicle VW Touran 2.0 TDI (**a**) and experiment route, 2 × 20 km in the urban area of Chemnitz, Germany (**b**). (OpenStreetMap contributors, 2016)

Fig. 11.2 Video examples front camera (**c**), interior camera (**a**), driver camera (**b**) and synchronised GPS-track (**d**). (OpenStreetMap contributors, 2016)

- perceptual speed assessed by a normed trail-making-test (Zahlenverbindungstest ZVT; [21]).

Lane change manoeuvres as well as mirror glances 10 s prior to lane changes were manually annotated out of the front/driver/interior video using the Annotation Software ELAN (http://tla.mpi.nl/tools/tla-tools/elan/). Lane changes were defined as the moment when the centre of the vehicle crossed the line between two lanes. Every lane change was categorized according to the classification of Lee et al. [11] additional to the lane change direction (left/right). Mirror glances were manually annotated in a time interval 10 s prior to every lane change using both the face and interior video. Discrete glance areas included ahead, rear mirror, left mirror, left window, right mirror, right window and other. To obtain all mirror glances for the whole trips, an algorithm was developed to estimate driver's mirror glances out of video-based head tracking data. A head tracking application programming interface (API) was used, which provided access to algorithms and methods for head tracking in images. Manual video annotations served as training data for the

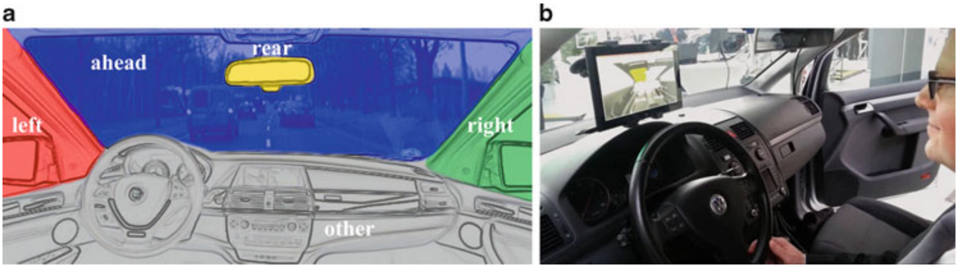

Fig. 11.3 Glance areas (**a**) and demonstration of the real-time head-tracking algorithm for the detection of mirror glances (**b**)

algorithm to map glance areas and head tracking angle data. Details on the algorithm development and evaluation can be found in Pech, Lindner and Wanielik [22]. The real-time mirror glance detection using a mono camera has been demonstrated in the test vehicle during the mid-term and final presentation of UR:BAN (Fig. 11.3b). The complete dataset including video annotations, head tracking angles, GPS-, radar- and CAN-information was stored in a relational PostgreSQL-database. For all glance analyses presented in this chapter, the glance areas "ahead" and "other" were merged to "ahead", "left window" and "left mirror" to "left" and "right window" and "right mirror" to "right" (Fig. 11.3a). As a pre-analysis revealed that only 0.24% of single glances lasted shorter than 100 ms, all data was aggregated to 10 Hz.

11.3 Results

11.3.1 Behavioural and Strategic Level

Analyses on the behavioural level focussed on the influence of driver characteristics on lane change behaviour. On the strategic level, the impact of the familiarity with the route was evaluated. To compare the relative predictive potential, all variables on both levels were included in the same analysis and are therefore presented together in this section. In total, the 60 participants performed 1869 lane change manoeuvres during the 60 trips. The number of lane changes per person ranged from 14 to 47 with a mean of 31 (Fig. 11.4a). Video analysis revealed that some drivers performed fewer lane changes, but drove longer on the left lane of the street (fast lane/overtaking). Therefore, an additional statistic was calculated indicating the percentage of road-kilometres driven on the left lane per trip. The value ranged from 7% to 57% with a mean of 31% (Fig. 11.4b).

To determine the predictive potential of driver characteristics and pre-trip factors on the behavioural and strategic level, a linear regression analysis was computed (Table 11.2). Two separate models were calculated for predicting 1) the number of lane change manoeuvres and 2) the percentage of km driven on the left road side. For the number of

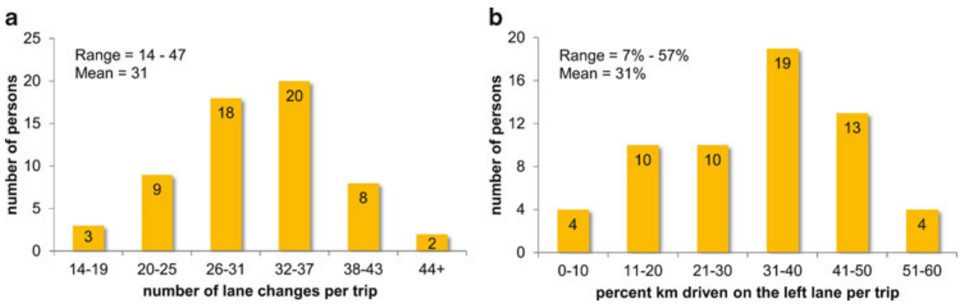

Fig. 11.4 Number of lane change manoeuvres per trip (**a**) and percent of km driven on the left lane per trip (**b**)

Table 11.2 Results of regression analysis predicting the number of lane changes performed and the percentage of km driven on the left road side ($N = 60$)

Predictor	Number of lane changes (LC)					Percent left side				
	B	SE(B)	β	r_{part}	*p*	B	SE(B)	β	r_{part}	*p*
gender	-2.50	1.88	-.18	-.19	.190	-2.11	2.98	-.08	-.10	.483
age	0.08	0.09	.14	.12	.402	0.28	0.14	.27	.27	.062
sec. ZVT (perceptual speed)	-0.11	0.08	-.24	-.20	.163	-0.30	0.12	-.36	-.34	**.015**
experience with automatic transm.	1.02	0.76	.18	.19	.184	3.00	1.20	.28	.34	**.016**
familiarity with the route	3.87	1.24	.45	.41	**.003**	8.38	1.97	.53	.52	**.000**
sensation seeking	-0.33	1.71	-.03	-.03	.850	-3.11	2.71	-.14	-.16	.257
NEO-FFI: extraversion	0.17	0.12	.23	.20	.171	0.48	0.19	.35	.34	**.015**
NEO-FFI: neuroticism	0.00	0.12	0.00	.00	.998	0.07	0.19	.05	.05	.719
NEO-FFI: agreeableness	-0.09	0.10	-0.14	-.13	.364	-0.15	0.15	-.12	-.14	.336
NEO-FFI: conscientiousness	-0.09	0.11	-0.12	-.11	.427	-0.12	0.17	-.09	-.10	.489
NEO-FFI: openness	-0.01	0.11	-0.01	-.01	.927	-0.04	0.18	-.03	-.03	.831
$R^2_{adjusted}$	.177					.402				

Note. $F(11, 48) = 2.16$, $p = 0.034$ for number LC, $F(11, 48) = 4.60$, $p < 0.001$ for percent left side. Statistically significant predictors are highlighted.

lane changes, results showed familiarity with the route (strategic level) as the only statistically significant predictor. The better the knowledge about the route, the more lane changes were performed, regardless of other driver characteristics. The regression model explains 18% of the variance in the data. Concerning the percentage of km driven on the left side, familiarity with the route was still the most important predictor. Additionally, better perceptual speed, higher extraversion and more experience with automatic transmission showed a statistically significant influence in terms of more km driven on the left side. The regression model explains 40% of the variance in the data.

11.3.2 Manoeuvring and Control Level

Analyses on the manoeuvring level (controlled action patterns) focused on subtypes of lane change manoeuvres as well as rates and timings of turn signal usage. Because of the smooth transition from controlled to automated action patterns (control level), mirror-glance patterns prior to lane changes are as well reported in this section.

Fig. 11.5 shows type and number of all lane changes observed in the study, based on the classification of Lee et al. [11]. In total, 1869 lane change events were identified, classified into seven distinct types. Slow lead vehicle includes lane changes only to the left side to overtake a vehicle driving at slower speed, e. g. trucks. Overtaking of parking and standstill vehicles at traffic lights is included as well into this category. Added lane means lane changes to the right or left on additional lanes, e. g. if the road extends from two to three lanes. In our sample, all added lanes were turn lanes (see picture in Fig. 11.5). Lane changes in order to enter a road (e. g. from a feeder road) were coded as type enter.

Lane change type	Picture	Direction and number
Slow lead vehicle		L: n = 507
Added lane		L: n = 242 R: n = 242
Enter		L: n = 239
Obstacle		L: n = 19
Merging vehicle		L: n = 33
Return		R: n = 520
Unknown		L: n = 61 R: n = 6
Total		**1,869 lane changes**

Fig. 11.5 Lane change types, direction and number

On our experiment route, only left lane changes for entering were observed. Construction zones on the right lane forced lane changes to the left due to obstacles. Lane changes because of other vehicles entering the roadway were classified as merging vehicles. Return includes right lane changes to return to the preferred driving lane, e. g. after an overtaking manoeuvre. Unknown refers to all lane changes without identifiable reason.

To investigate mirror-glance patterns and turn signal usage, sequences of max. 10 s prior to a lane change manoeuvre were identified and marked in the database. If another lane change took place within the 10 s interval (multiple lane changes), the second sequence has been truncated. Therefore, sequence length can be shorter than 10 s. Examples of typical sequences for different lane change types are shown in Fig. 11.6. Red, green and blue blocks (respectively patterns) represent glances to the corresponding mirrors whereas the thin yellow line indicates the usage of the turn signal.

Turn signal use: Table 11.3 shows the detailed statistics on turn signal use and glance patterns for all lane change types. The turn signal (column 4) was used in 95% of the lane change manoeuvres, ranging from 78% for the obstacle type up to 100% for merging vehicles. These values are considerably higher than results from other studies [10, 11]. However, turn signal usage rate is comparable to prior studies in Chemnitz with 89% [23]. For further details please refer to the discussion section.

Glances before turn signal: Column 5 reports the percentage of lane changes with at least one corresponding mirror-glance before the activation of the turn signal. For left lane changes, glances to the left mirror were considered, whereas for lane changes to the right side, glances to the right or the rear mirror were taken into account. Aim of the analysis was to reveal the potential of glances as even earlier predictor than the turn signal. Results showed relatively high percentages of glances before blinking for lane changes due to merging vehicles (90%), unknown reasons (left 90%), slower leading vehicles (86%), return (85%) and entering (77%). Less glances prior to the turn signal were observed for added lanes (13% left, 28% right), unknown reasons (right 50%) and obstacles (58%).

Glance patterns before left lane changes: Columns 7 to 10 of Table 11.3 show the mean number of glances to the left, right and rear mirror, whereas columns 11 to 13 list the respective mean total glance duration for each lane change type. Glances ahead are not listed separately; they cover the remaining sequence duration. The first six rows of Table 11.3 show lane changes to the left. Consequently, the number as well as the duration of glances to the left were considerably higher than for lane changes to the right. Especially for entering, unknown reasons and slower lead vehicles more than two left glances per sequence were observed (2.50 to 2.82) with a mean total duration ranging from 1.76 s to 2.27 s. A lower mean number and duration of left glances resulted for the lane changes due to merging vehicles (1.94 times, 1.27 s) and obstacles (1.84 times, 1.14 s). Considerably lower glance activity was observed for lane changes on added lanes with 0.30 left glances per sequence and a total duration of 0.20 s. There were almost no glances to the right during left lane changes. Glances to the rear mirror ranged from 0.13 to 0.40 times with a total duration from 0.06 s to 0.23 s.

Glance patterns before right lane changes: Lane changes to right appeared as combination of glances to the right and the rear mirror (Table 11.3, rows 7 to 9). For the return

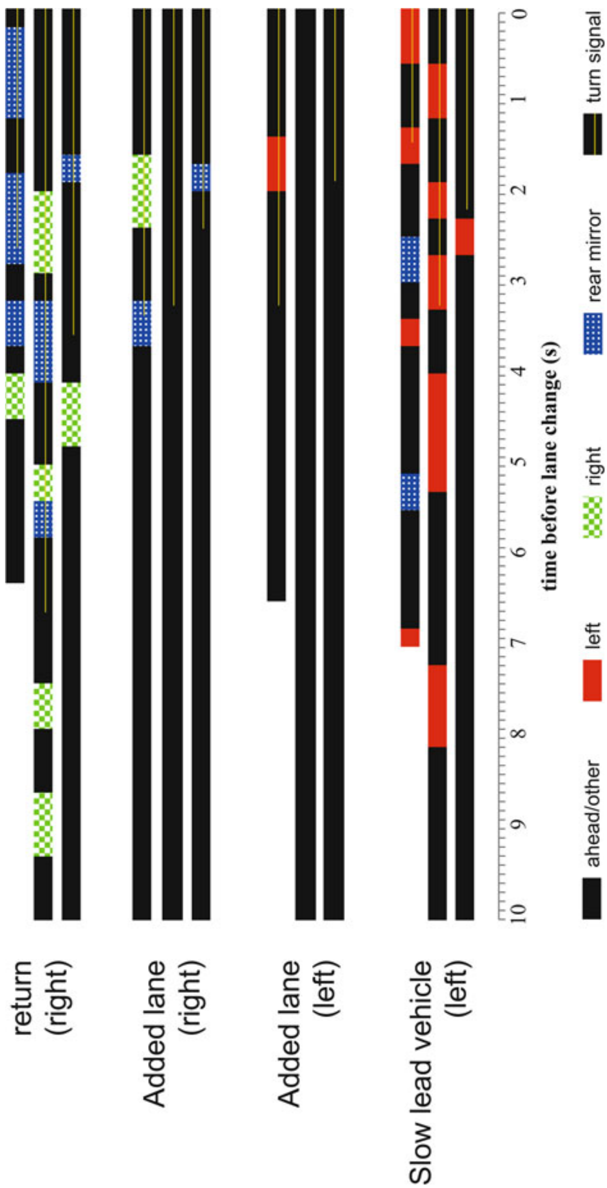

Fig. 11.6 Examples of typical sequences for different lane change types (12 sequences total, 3 for each of the 4 lane change types)

Table 11.3 Lane change types, turn signal use and glance statistics

Lane change type	Direction	Num. of events	Turn signal use (%)	Glances before turn signal (%)	Glance sequences 10 s prior to lane changes						
					Sequence length (s) M(SD)	*Number of glances M(SD)*			*Total glance duration (s) M(SD)*		
						Left	*Right*	*Rear*	*Left*	*Right*	*Rear*
Slow lead vehicle	Left	484	95	86	9.70 (1.08)	2.50 (1.40)	0.02 (0.18)	0.40 (0.73)	1.76 (1.15)	0.02 (0.15)	0.23 (0.45)
Added lane	Left	230	85	13	5.87 (2.74)	0.30 (0.54)	0.04 (0.20)	0.14 (0.40)	0.20 (0.43)	0.03 (0.13)	0.07 (0.18)
Enter	Left	227	99	77	10.00 (0)	2.82 (1.14)	0.01 (0.09)	0.13 (0.37)	2.27 (0.90)	0 (0.05)	0.06 (0.18)
Unknown	Left	59	94	90	9.92 (0.65)	2.75 (1.26)	0 (0)	0.38 (0.73)	1.90 (0.99)	0 (0)	0.21 (0.47)
Obstacle	Left	19	78	58	9.95 (0.23)	1.84 (1.46)	0.16 (0.50)	0.16 (0.37)	1.14 (0.96)	0.07 (0.26)	0.07 (0.18)
Merging vehicle	Left	29	100	90	9.86 (0.74)	1.94 (0.75)	0.03 (0.17)	0.27 (0.45)	1.27 (0.63)	0.02 (0.14)	0.17 (0.30)
Added lane	Right	230	98	28	9.77 (1.15)	0.17 (0.42)	0.38 (0.65)	0.75 (0.86)	0.08 (0.23)	0.26 (0.59)	0.39 (0.49)
Return	Right	496	96	85	10.00 (0)	0.08 (0.31)	1.47 (0.93)	1.13 (1.09)	0.05 (0.23)	1.15 (0.81)	0.63 (0.68)
Unknown	Right	6	83	50	10.00 (0)	0 (0)	1.17 (1.47)	0.50 (0.55)	0 (0)	0.93 (1.31)	0.35 (0.46)
		1780	95		9.21 (1.98)						

Note. Three trips (89 lane change manoeuvres) had to be excluded from this analysis due to technical problems with the turn signal recording to the preferred lane, 1.47 glances to the right and 1.13 glances to the rear mirror could be observed with a total duration of 1.15 s (right) and 0.63 s (rear). Similar values resulted for right lane changes due to unknown reasons with 1.17 right glances and 0.50 glances to the rear mirror, lasting 0.93 s (right) and 0.35 s (rear). The lowest glance activity was observed for right lane changes on added lanes: The number of glances ranged from 0.38 (right) to 0.75 (rear) with durations of 0.26 s (right) and 0.39 s for glances to rear mirror.

Overall, lowest glance activity could be observed for lane changes on added lanes, either to the right and the left side. Glance patterns for left lane changes show a high proportion of left glances with some few glances to the rear mirror, whereas right lane changes appear as a combination of right and rear glances.

In addition to these descriptive statistics, the evolution of glances and turn signal use provides hints on the timing of the parameters. Fig. 11.7 shows exemplarily the cumulative percentage of mirror glance time (right y-axis) and turn signal use (left y-axis) for the lane change type slow vehicle ahead and added lane left. The cumulative percentage of glance time refers to the whole 10 s interval, i. e. a value of 18% at time 0 (moment of lane change) for left glances means that 1.8 s of 10 s were spent with glances to the left mirror. The rise of the curves give insights on the overall amount and timings of the parameters.

For the lane change due to a slower vehicle ahead (left chart), the black turn signal curve shows a sharp increase at about three to two second before changing the lane, ending up at 95% at the moment of crossing the lane. The red (dashed) line for left glances shows a substantial increase already before the activation of the turn signal with an additional growth at the same time period of turn signal activation. Rear view mirror glances (2% at time 0) and right mirror glances (0% at time 0) don't play a substantial role for left lane changes due to a slower vehicle ahead.

In comparison to left lane changes on an added lane (right chart), turn signal activation starts at comparable times two to three seconds before crossing the lane, however, ending at a lower rate of 85% at time 0. All mirror-glance curves remain below 4% of total time, indicating generally low glance activity for this lane change type.

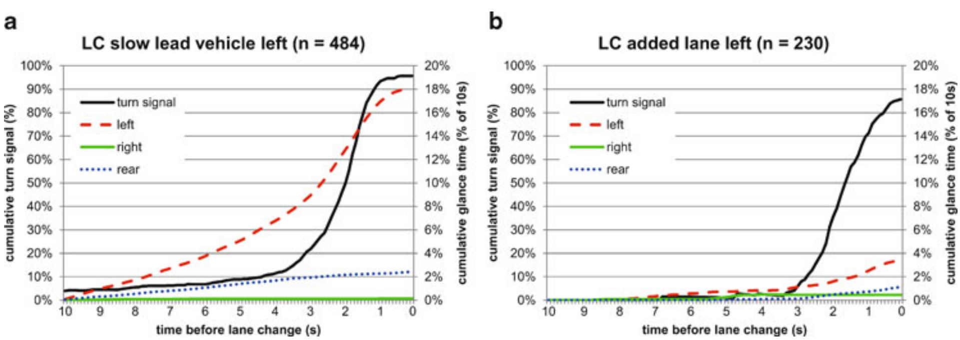

Fig. 11.7 Evolvement of turn signal use and cumulative percentage of mirror glance time for lane change type slow vehicle ahead (**a**) and added lane left (**b**)

11.4 Discussion and Conclusions

The present study aimed at identifying early predictors of lane change manoeuvres on arterial roads in city areas. By using a systematic and comprehensive approach, possible predictors were investigated at the behavioural, strategic, manoeuvring and control level according to the extended hierarchical driver behaviour model of Michon [17].

Results on the behavioural and strategic level revealed familiarity with the route as the most important predictor for the number of lane changes performed. The better the knowledge about the route, the more lane changes were performed, regardless of other driver characteristics. Moreover, not only the number of lane changes was affected by the familiarity with the route, but also the driving style connected to the selection of the driving lane: Driver with better route knowledge spent significantly more time on the left road side (overtaking), especially when they were familiar with the car handling (automated transmission), had better cognitive abilities (perceptual speed) and showed more energetic and assertive behaviour in general (extraverted personality). However, familiarity with the route still remains the most important predictor for these driving style related changes. Therefore, a lane change prediction algorithm could potentially be improved by including (historical) data about the frequency of driving on a certain route for a particular driver.

Analyses on the manoeuvring and control level focused on subtypes of lane change manoeuvres, rates and timings of turn signal usage as well as predictive glance patterns. Lane changes occur due to different reasons and this motivational factor plays a central role in predicting the manoeuvres. Thus, a classification was used to categorize lane change manoeuvres on urban arterial roads, based on the approach of Lee at al. [11]. Despite the classification was established for lane changes on highways and freeways, most of the categories can be applied as well in the urban context. Differences arise especially with parking and standstill vehicles on traffic lights, which were both integrated into the category of a slower lead vehicle. The classification itself gives already hints on potential early intent indicators for the different lane change types. Inevitable lane changes due to infrastructure changes, such as entering a road when driving on a feeder road or to some extent obstacles (e. g. known construction zones) could best and earliest be predicted by GPS and map information. For all the remaining lane change types, map information does not provide intent information unless a specific route is known (e. g. set by the driver or inferred from historical data such as daily work trips).

In order to reveal potential predictors for the remaining lane change types, rates and timings for turn signal usage as well as mirror-glance patterns were analysed using a sequence approach. The turn signal was used in 95% of the lane changes, ranging from 78% for the obstacle type up to 100% for merging vehicles. These values are considerably higher than results from other studies: US studies report the turn signal as rather unreliable indicator of lane changes with usage rates of 44% [11] and 52% [10]. German studies found higher rates of 55% for lane changes on urban roads and 75% on highways [12]. However, turn signal usage rate in the present study was comparable to prior studies in Chemnitz with 89% [23]. A possible reason for the higher turn signal rate could be the experimental setting. Therefore, we analysed the turn signal usage of other drivers during lane change manoeuvres using the video of the four external cameras [24]. The analysis of 2787 "external" lane change manoeuvres showed a comparable turn signal usage rate of 87%. An explanation for the generally high turn signal usage could be related to the traffic situation in Chemnitz: Since the urban traffic in a mid-size German city is relatively calm and less demanding compared to traffic in metropolitan areas, driver may show more often learned and automated turn signal behaviour. However, the high turn signal usage allowed for additional analyses on mirror-glances as even earlier manoeuvre predictors than the turn signal. Results showed that for specific lane change types (slow leading vehicle, merging vehicle, return, unknown reason left) in more than 85% of the manoeuvres at least one corresponding mirror glance could be observed in the 10 s interval before crossing the lane. This gives an indication that glance patterns could provide even earlier intent information than the turn signal for certain lane change manoeuvres. Cumulated plots for turn signal activation and glance activity in the 10 s interval support these findings, showing an increase of mirror glances already before activating the turn indicator for lane changes due to a slower lead vehicle. However, it must be considered that not every solitary mirror glance is associated to a subsequent lane change.

Detailed analysis of mirror-glance patterns showed the lowest glance activity for lane changes on added lanes, either to the right and the left side. A plausible explanation for this fact could be the absence of traffic from behind. Glance patterns for left lane changes showed a high proportion of glances to the left with some few glances to the rear mirror, whereas right lane changes appeared as a combination of right and rear mirror glances. A more detailed analysis of glance timing for the "classical" lane change type slow vehicle ahead showed results that are mainly in line with previous studies [8, 14, 15]: A considerable increase in glance activity could be observed three to four seconds prior to the lane change, but glance activity was also noticeable beforehand. Compared with the previous study [23], these glances patterns resulted as quite stable. However, the variance of glance patterns within the distinct lane change types was still relatively high. Exploratory visual inspection of the video files revealed that, in addition to the mentioned patterns, the number of glances in a sequence was primarily associated with the traffic density on the target lane. The more vehicles on the target lane, the more and longer mirror glances.

The main conclusions out of these findings are that glance patterns are promising lane change predictors for certain types of lane changes. However, the interpretation of single glances as indicator for lane change intention is vague and difficult without the integration of information about the driving situation. Additional information from sensors monitoring the vehicle environment allow for better interpretation of mirror glances, e. g. by providing the number of driving lanes available, the possibility of changing the lane (i. e. traffic density on the target lane) and the presence of a slower leading vehicle. Therefore, the I-FAS concept of a real-time lane change prediction algorithm integrates driver behaviour, vehicle parameters as well as data from the vehicles' surroundings in a Bayesian Network (Fig. 11.8). Technical details on the implementation of the algorithm can be found in the subsequent book-chapter of Leonhardt et al. The inclusion of predictors on

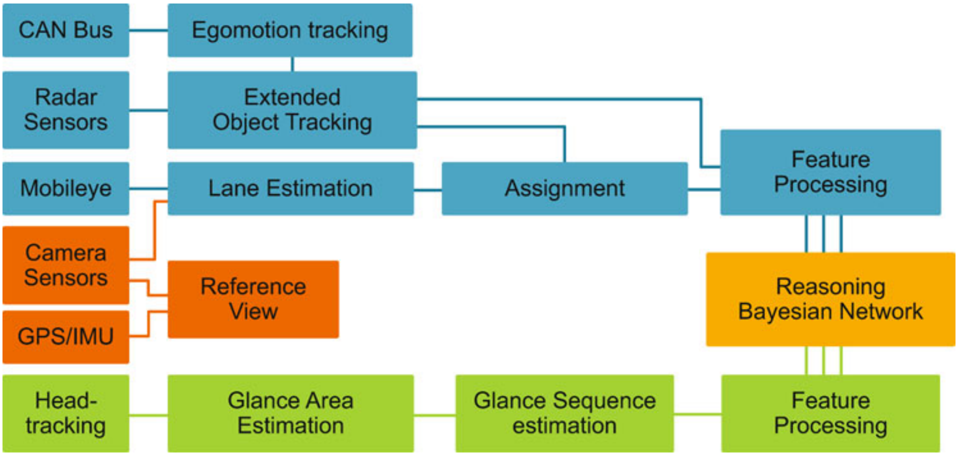

Fig. 11.8 I-FAS concept of a real-time lane change prediction algorithm integrating driver behaviour, vehicle parameters and data from the surroundings in a Bayesian Network

the strategic level (driver profile/familiarity with the route) could improve the performance of a lane change prediction algorithm. However, recording a comprehensive driver profile including the history of performed trips was not a research focus within UR:BAN and should be subject of further studies.

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12 Fusion of Driver Behaviour Analysis and Situation Assessment for Probabilistic Driving Manoeuvre Prediction

Veit Leonhardt, Timo Pech, and Gerd Wanielik

12.1 Introduction

Driving in urban traffic situations is a highly demanding task. The driver continuously has to observe and assess complex and dynamic traffic situations and intervenes by performing driving manoeuvres. Due to the limited capabilities of the driver there is a significant risk of accident. In 2014, 3377 people died and 67,732 people were injured seriously in connection with road traffic accidents in Germany [1]. 15.7% of all accidents caused by inappropriate driving behaviour happened while performing driving manoeuvres. Especially for accidents related to lane changes, Bayly et al. [2] expect a 25% reduction of the severity of accidents by means of providing lane change assistance.

This reflects the significant need as well as the potential to assist the driver during these manoeuvres. Consequently, modern cars are equipped with advanced driver assistance systems (ADAS) aiding the driver in maintaining situational awareness and performing driving tasks. However, optimal assistance depends on the situation and the driver's intentions. Moreover, it is important to assist timely and reliably to be actually accepted and used by the driver. Unneeded or inadequate information, warnings and interventions could distract the driver and cause driving errors. Hence, modern driver assistance systems also have to adapt to driver intentions and situations to match the driver's actual need for assistance. As a result, future assistance systems themselves need knowledge about the driver's intentions.

The real-time prediction of lane change intentions and manoeuvres is a complex and demanding task. It depends on the variety of influences, situations and driver characteristics as well as on the availability of suitable sensor data and computing capacity. That's why early scientific work started to predict lane change manoeuvres using CAN data ex-

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clusively. The steering angle, the steering angular velocity and the steering force were used to detect the realization of lane change manoeuvres [3]. However, relying solely on steering data causes a lack in terms of robustness [4] and in earliness. Studies as conducted by Oliver and Pentland [5] indicated the capability of environmental information about the road's geometry and surrounding traffic to improve the detection's performance. Schubert and Wanielik [6] used environmental recognition to assign tracked objects to specified lanes and derive lateral manoeuvre recommendations. Parallel research involved the gaze behaviour of drivers [7–9]. It was proven that this gaze behaviour related to lane change manoeuvres is characteristic and can be used to predict them in particular situations as well. In algorithmic terms, authors usually consider the estimation of a driver's intention as a task of classification. Hence, classification methods as for example Support and Relevance Vector Machines [10, 11], Fuzzy Logic [12] and Bayesian networks [6] as well as Hidden Markov Models [3, 4] are applied.

Consequently, the next steps to enable future driver assistance systems to adapt to drivers on the basis of knowledge about their intentions to change lanes have to aim at fusion and integration. Complementary features of the environmental situation and the driver's gaze behaviour have to be fused to obtain an early as well as reliable prediction of driving manoeuvres. Subsequently, a real-time prediction has to be implemented, to be integrated into a vehicle and to be applied to real driving data. Both aspects, the feature fusion and the integration, were considered and implemented as presented below.

12.2 Preliminary Considerations

12.2.1 Term of Intention

The challenge of detecting intentions is based on their intrinsic character. They can be understood as endeavours of drivers for certain actions, and by this way, they are influenced by the drivers themselves as well as by external factors. Intentions strongly affect the driver's acting but normally are not expressed and not directly measurable. So to predict and detect them it is necessary to understand how they work. Which measurable factors affect their emergence and which factors are affected by them?

In connection with driving the intentions of drivers are determined by the objectives of reaching a particular destination and of reaching it as fast, safely and comfortably as possible. If they regard an adjacent lane as more suitable, they will probably aim at performing a lane change manoeuvre to that lane. Hence, the algorithmic task to be solved is detecting those situations.

12.2.2 Lane Change Process

For lane change intentions, three consequent phases can be distinguished: intention formation, manoeuvre preparation and manoeuvre realization.

First of all, environmental influences trigger the formation of an intention. Motivating factors encourage the emergence of an intention while others impede the desire for changing the lane in a certain situation [13]. Hence, the process of formation itself is unobservable but is dominated by environmental features perceived by the driver. Because these motivating and impeding features are simultaneously part of the vehicle's visible environment, they can be detected and be used to infer the intention. If there is actual an intention to change the lane, the driver starts to prepare the manoeuvre. This becomes visible by the driver's gaze behaviour to make the lane change in a safe way. As shown in previous work this behaviour is characteristic in connection with different types of lane change manoeuvres (see preceding chapter of Beggiato et al.). Significant for the phase of manoeuvre realization is the movement of the vehicle controlled by the driver. Thereby the controlling includes directing interventions as well as changes in the vehicle's speed.

The three phases differ in the way they are able to indicate the presence of a lane change intention in terms of explicitness and time horizon. While the formation of the intention happens first but needs determination by reasoning, the manoeuvre realization can be detected directly but only at a late stage. The qualities of the phase of manoeuvre preparation are in between. In consequence, it seems to be useful to concentrate on detecting the intention's formation and the manoeuvre preparation and then to combine the strengths of both aspects by probabilistic fusion.

12.2.3 Scenario

In the study conducted for this work different types of lane changes occurred. As described in the preceding chapter of Beggiato et al., one of the most common types of lane changes observed is the lane change induced by a vehicle driving ahead slowly. The present work focuses on predicting this type of lane change.

The corresponding environmental situation is characterised by a multi lane setup with at least one slow vehicle within the driver's lane. The assumption made about this situation is that the vehicle driving slowly is considered to be an obstacle by the driver. It works as a motivator for changing the lane. If, in addition, there is another lane available that is assessed as more suitable, the driver will tend to change to that lane as soon as a safe lane change is possible. In contrast, lane markings that forbid a lane change or heavy traffic on the target lane that makes the change unsafe impede the formation of a lane change intention.

12.3 Recognition of an Intention to Perform a Manoeuvre

12.3.1 Approach

On the basis of the understanding of the process of the intention's formation, the manoeuvre preparation and realization, the task supposed to be solved can be formulated in algorithmic terms. It consists in detecting situations of upcoming driving manoeuvres as soon as possible in order to predict the following realization of a manoeuvre. This only can be done based on information about the environment and the driver that is obtainable by the vehicle's sensors. Environmental sensor data allow the recognition of influences that motivate or impede the formation of manoeuvre intentions. Observing the driver with vehicular sensors enables the system to detect behaviour that is characteristic for manoeuvre preparation. However, all information has to be considered as being uncertain due to the process of acquisition and the limited significance of the features. To handle and to preserve these uncertainties all processing should be done in a probabilistic way. Consequently, the process of intention recognition for lane changes can be interpreted as pictured in Fig. 12.1.

For the scenario of predicting lane changes the driver's intention can be described as the preference of the driver for a certain lane. Focusing on adjacent lanes only, a random variable X_M can be defined that describes the driver's intention to change the lane. It can have up to three possible states: Intention $X_M = x_{\mathrm{KL}}$ for keeping the actual lane and intentions $X_M = x_{\mathrm{LCL}}$ and $X_M = x_{\mathrm{LCR}}$ for changing the lane to the left and right, respectively. Due to the description of the actual state using probabilities this leads to the determination of probabilities $P(X_M)$ with the restriction Eq. 12.1.

$$P(X_M = x_{\mathrm{LCL}}) + P(X_M = x_{\mathrm{KL}}) + P(X_M = x_{\mathrm{LCR}}) = 1 \tag{12.1}$$

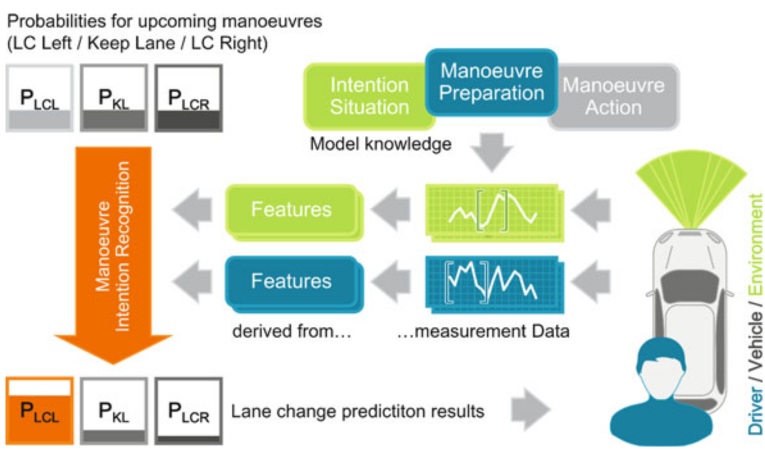

Fig. 12.1 Process of recognizing the manoeuvre intention

Calculating these features requires the measurement data to be interpreted and assessed. A suitable approach is to model both aspects by means of features extracted from those data. Each feature represents a single aspect that is capable to discriminate the presence of at least two states of intention. Their selection follows analyses of naturalistic driving data. Further details can be found in the preceding chapter of Beggiato et al. However, the features are simplifications and the contribution of a single feature to the intention recognition process often strongly depends on the situation, on the availability and the uncertainty of information used and the quality of processing achievable. For that reason sets of multiple features have to be used. This, in turn, makes it necessary to weight and fuse the feature values in order to compute estimations for $P(X_M = x_{\text{LCL}})$, $P(X_M = x_{\text{KL}})$ and $P(X_M = x_{\text{LCR}})$ as early and reliable as possible.

12.3.2 Assessment of the Environmental Situation

The aspect of environmental situation assessment aims at deducing features that describe influences motivating and impeding the formation of lane change intentions.

Motivator for changing the lane within the given scenario is a vehicle driving ahead slowly and using the ego lane. The ego lane is defined as the lane the driver's vehicle, the ego vehicle, is driving along. Hence, features are required that quantify if there is a vehicle driving in front and if it will be sensed as an obstacle or danger by the driver. Suitable measures to categorize a vehicle driving ahead as obstacle O can be its relative velocity $v_{\text{Rel}} = v_E - v_O$ and its distance s to the ego vehicle E. Furthermore, drivers normally tend to avoid critical situations and rough manoeuvres. Accordingly, a situation that would imply the need of such a situation or manoeuvre by keeping the lane can be assumed as not to be intended by the driver. The driver preferably will solve the situation by changing the lane. The roughness of such a braking manoeuvre behind another slower vehicle can be quantified by means of the idea of Deceleration to Safety Time (DST), introduced by Hupfer [14].

As described by Leonhardt et al. [15] it can be adapted to the given scenario. The Adapting Deceleration to Safety Time (ADST) proposed considers the ego vehicle E and an obstacle O driving in front of the ego vehicle. For time t_0 their positions are assumed to be given by points E_0 and O_0 with the vehicle's initial distance $s_0 = \overline{E_0O_0}$. Obstacle O moves at a constant speed v_O. The ego vehicle E approaches obstacle O with velocity $v_{E0} > v_O$ so that it has to decelerate over a period of time t_d. At time $t_1 = t_0 + t_d$ the vehicles reach the points E_1 and O_1 with velocity $v_{E1} < v_{E0}$ and v_O, respectively, as visualised in Fig. 12.2.

In this way, vehicle E decelerated over a distance of $\overline{E_0E_1}$ to hold a safety distance of $\overline{E_1O_1}$. In accordance with Fig. 12.2 $\overline{E_0E_1}$ can be calculated using equations Eq. 12.2 and Eq. 12.3, respectively.

$$\overline{E_0E_1} = \overline{E_0O_0} + \overline{O_0O_1} - \overline{E_1O_1} \tag{12.2}$$

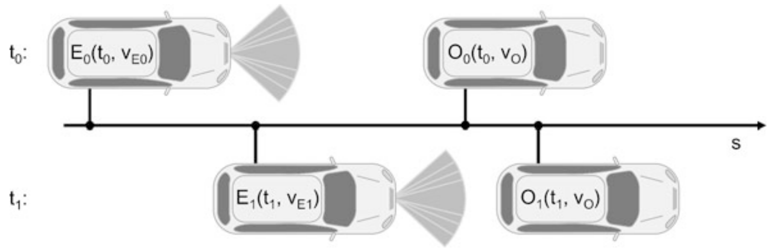

Fig. 12.2 Relations of ego vehicle E and obstacle O driving ahead slowly

$$\left(\frac{a_{\text{ADST}}}{2}t_d^2 + v_{E0}t_d\right) = (s_0) + (v_O t_d) - (v_{E1}t_{\text{Safety}}) \tag{12.3}$$

$$v_{E1} = v_{E0} + a_{\text{ADST}}t_d \tag{12.4}$$

The Adapting Deceleration to Safety Time a_{ADST} needed to meet a safety time t_{Safety} can be obtained by combing equations Eq. 12.3 and Eq. 12.4 leading to Eq. 12.5. Supposing that the ego vehicle adapts to the velocity of the vehicle it is approaching, so that $v_{E1} = v_O$, Eq. 12.5 can be further simplified to Eq. 12.6.

$$a_{\text{ADST}} = \frac{v_{E0}^2 - v_{E1}^2 + 2v_O(v_{E1} - v_{E0})}{2(v_{E1}t_{\text{Safety}} - s_0)} \tag{12.5}$$

$$a_{\text{ADST},vO} = \frac{(v_{E0} - v_O)^2}{2(v_O t_{\text{Safety}} - s_0)} \tag{12.6}$$

The motivating influences described by these features not necessarily result in a lane change intention. Depending on the situation, further influences – impediments – can impede a safe and legal lane change. The possibility of a legal lane change to the left or right, respectively, in urban areas is ruled by lane markings. As dashed lane markings indicate that lane changes are allowed, solid markings prohibit them. Provided lanes in urban areas always have markings and the driver complies with them they can be used as indicating features. The driver's assessment of a lane manoeuvre's safety is strongly related to the amount of traffic noticed there. Changing to a lane of dense traffic is less probable than changing to low traffic due to the larger space between two vehicles. So, in algorithmic terms the traffic density can be modelled by the presence, position and motion of vehicles within a lane section. In accordance with the features describing the vehicle driving ahead this assessment is done utilizing the distances s_i and Adapting Decelerations to Safety Time $a_{\text{ADST},vi}$ of all vehicles i that are detected within a nearby lane.

In summary, for the lane change prediction the environment of the ego vehicle is described by the vehicles around and the types of adjacent lane markings. Thereby, vehicles are assessed by their lane classification and a set of features consisting of distance, relative velocity and Adapting Decelerations to Safety Time. Therefore, it becomes necessary to detect and track vehicles around their relative positions and to acquire information about the lane number, geometry and type of lane marking. Because the vehicle's velocity usually depends on the maximum value that is allowed, a last environmental feature, the local speed limit v_{Max}, is incorporated as well.

12.3.3 Assessment of the Driver Behaviour

If there is the actual intention to change the lane, the driver starts to prepare the pending manoeuvre action. Part of this manoeuvre preparation is the observation of the environment to detect a point in time when a safe lane change manoeuvre would be possible. This process is accompanied by glances in the directions of the vehicle's windows and mirrors. As this gaze behaviour is proven by related research to be characteristic and as it implies noticeable head and eye movement, it can be used as a further early indicator for predicting lane changes [7–10].

On the feature level, the gaze behaviour in general can be reduced to the area a driver currently looks at. The alteration of this area over time can be modelled as a sequence of areas. Viewing areas G_i that are distinguished are the front, left and right windows G_{FW}, G_{LW} and G_{RW}, respectively, and the left mirror G_{LM}, right mirror G_{RM} and rear view mirror G_{RVM}.

The area G_i, a driver looks at, can be derived from the direction of looking. To focus a specific area the driver uses head and eye movement in a cumulating manner. Because the eye movement is much harder to detect than the head movement and as Pech et al. [16] have shown that head movement can be used to classify the area G_i, the approach presented relies on detecting and classifying head movement exclusively. For this purpose, it uses the horizontal rotation of the driver's head around the yaw rotation axis $\theta_{y,\text{HRot}}$ of its Euler angles to define the direction the head points at.

Hence, the calculation of the feature area G_i, the driver looks at, can be interpreted as a classification problem. An input angle $\theta_{y,\text{HRot}}$ has to be assigned to one out of the six area states G_i can have. It is solved by using a naive Bayesian classifier [17] defined according to Eq. 12.7.

$$P(G_i|\vartheta_{y,\text{HRot}}) = \frac{p(\vartheta_{y,\text{HRot}}|G_i)P(G_i)}{\sum_{j=1}^{6} p(\vartheta_{y,\text{HRot}}|G_j)P(G_j)} \tag{12.7}$$

A probability $P(G_i|\vartheta_{y,\text{HRot}})$ expresses the probability that a given value range of the yaw rotation axis $\vartheta_{y,\text{HRot}}$ is related to the observation of a glance area G_i. Thereby, $p(\vartheta_{y,\text{HRot}}|G_i)$ is the conditional probability density describing the probability that looking at an area G_i will lead to an angle $\vartheta_{y,\text{HRot}}$. The probability $P(G_i)$ corresponds to the absolute probability drivers look at the given area. Both parameters were determined by training a corresponding classifier. The training applied the Maximum-Likelihood-Estimation method on the training subset of the annotated naturalistic driving data gained by the study related to this work. As depicted in Fig. 12.3 and discussed by Pech et al. [16],

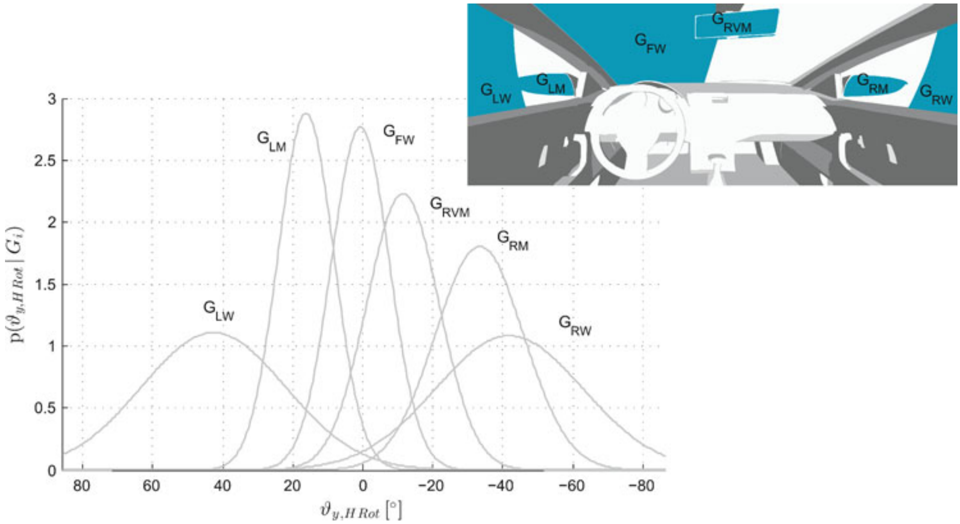

Fig. 12.3 Probabilistic relation of yaw rotation of head and glance area assignment

this led to a set of probability distributions describing the probabilistic relation between $\vartheta_{y,\mathrm{HRot}}$ and $p(\vartheta_{y,\mathrm{HRot}}|G_i)$.

It can be seen that the diversity of situations and individual driver characteristics cause the probability distributions to overlap. Hence, the assignment is not clearly cut in any case but adds probabilistic evidence for the preparation of an upcoming lane change manoeuvre. The probabilities $P(G_i)$ correspond to their relative frequency of incidence within the training data set.

In spite of single glances giving evidence for observation behaviour, they are not necessarily part of the preparation of a lane change manoeuvre. So, it is reasonable to take the context of the glances into account as well. For this purpose the glance area sequence is observed and is compared with sequences typically related to lane change manoeuvres to the left and right, respectively. It is done by utilizing a first-order Hidden Markov Model approach.

Hidden Markov Models as described by Rabiner and Juang [18] are capable of estimating states of random variables that cannot be determined directly. The estimation is made on the basis of causally linked observations and in consideration of state transition probabilities. The transition probabilities significantly affect the quality of estimation so that in case of multiple competing model hypotheses the better hypothesis will show better results over time. This effect is exploited to differentiate between glance sequences related to preparations of lane changes to the left and right, respectively. For the glance area G_i to be estimated a hidden state $X_{\mathrm{HMM}}(t)$ for a time t is defined. The causally linked observations $y_{\mathrm{HMM}}(G_i, t)$ are calculated by means of $\vartheta_{y,\mathrm{HRot}}$ and $P(G_i|\vartheta_{y,\mathrm{HRot}})$. The state transition probability matrix T holds two competing variants T_{LCL} and T_{LCR}.

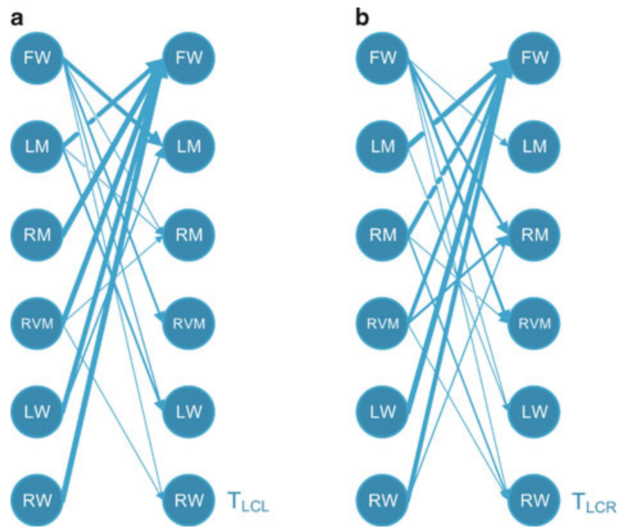

Fig. 12.4 Glance area transition probabilities before lane changes to the left (**a**) and right (**b**)

The parameterization of the matrix T_{LCL} is based on the training data subset and the relative frequencies of transitions between glance areas G_i related to lane change manoeuvres to the left, while matrix T_{LCR} was specified accordingly for upcoming lane changes to the right. Glances are defined as related to a particular manoeuvre if they occur within a time span of 10 s [19] ending when the vehicle's longitudinal axis passes the lane markings of the ego lane. Fig. 12.4 visualises the trained transition probabilities of both matrices with the help of arrows of modulated widths.

Hence, two Hidden Markov Models exist that are used to calculate state sequence probabilities $P(S_{\mathrm{LCL}})$ and $P(S_{\mathrm{LCR}})$ and that express the extent to which the models of lane change preparation to the left and right, respectively, are being met.

As a further feature the indicator signal could be used. It indicates lane change intentions by definition. However, it was aspired to evaluate the algorithm's performance independently from the usage of the indicator signal. That is why it was decided to refrain from using it.

12.3.4 Feature Fusion and Probabilistic Reasoning

To assess and combine the features describing the environmental situation and drivers' gaze behaviour and to reason for lane change intentions subsequently, a Bayesian network was implemented. This concept was chosen because it is able to do probabilistic reasoning using heterogeneous evidences of varying uncertainty and availability.

A Bayesian network (BN) is an acyclic graph $G = \{\chi, \epsilon\}$ consisting of n nodes $\chi = \{X_1 \cdots X_n\}$, linked by directed edges $\epsilon = \left\{X_i \rightarrow X_j | X_i, X_j \in \chi, i \neq j\right\}$. Each node represents one random variable by means of its set of possible states and the corresponding state probabilities. Edges model the probabilistic dependence of causally linked nodes or random variables. Each of them points to a child node X_j from a parental node X_i being defined by a matrix of conditional probabilities. Because of that linkage, the incorporation of evidence of one node's state is able to spread to related nodes and to give evidence of their states. In this manner the BNs can be utilised for probabilistic reasoning and for estimating random variables that cannot be observed directly as an intention for changing the lane.

Formally the state of a BN is defined by the joint probability $P(X_1, \cdots, X_n)$ of all nodes. With the help of the Bayes' theorem the parameter $P(X_1, \cdots, X_n)$ can be factorized as formulated in Eq. 12.8.

$$P(X_1, \cdots, X_n) = \prod_{i=1}^{n} P(X_i | X_{i-1}, \cdots, X_1) \tag{12.8}$$

In accordance with the issue being modelled by a BN, a given node X_i is not necessarily causally linked to all nodes χ but only to a subset $\chi_{p_i} \subset \chi$ of immediate parental nodes it directly depends on. Mathematically, this means assuming the local Markov property. It says that a random variable can be assumed as being independent of all others variables as long as its direct neighbour variables are given. This leads to Eq. 12.9 so that Eq. 12.8 can be reduced to Eq. 12.10.

$$P(X_i | X_{i-1}, \cdots, X_1) = P(X_i | \chi_{p_i}) \tag{12.9}$$

$$P(X_1, \cdots, X_n) = \prod_{i=1}^{n} P(X_i | \chi_{p_i}) \tag{12.10}$$

To sum up, the probabilistic reasoning determining any state probability $P(X_i)$ of a random variable X_i in demand needs evidence about the state probabilities of all parental random variables X_{p_i} and about the conditional probability distribution of $P(X_i | \chi_{p_i})$. The state probabilities of the parental random variables either are determined the same way or are updated using external evidence. As the conditional probability distribution is part of the network's structure, it has to be given and is subject of the design process.

Concerning the probabilistic reasoning for the driver's intention, the probability $P(X_M)$ with its possible states $X_M = x_{\text{LCL}}, x_{\text{KL}}, x_{\text{LCR}}$ has to be the random variable and BN node in demand. The external evidence the reasoning bases on, is provided by the features used to model the environmental situation and the driver behaviour as described before. To make that evidence accessible by the BN, the network holds corresponding input nodes, one for each single feature. This assignment requires a mapping of the features' value ranges on a set of discrete state classes as used by the BN nodes to describe their states. For the not naturally class-based feature variables this takes place by subclassifying the variables' value range. In order to minimize the loss of information caused by this discretization, the mapping of the value ranges happens probabilistically using smooth transitions between the state classes. Corresponding to the three subtasks of assessing the environmental situation, assessing the driver's behaviour and of combing the assessments to one statement, the BN is divided into three sections of nodes that, in turn, include further internal nodes representing partial outcomes.

The first network section weighs up influences motivating a lane change to the left or right against impeding influences based on the environmental feature set described above. The outcome of this weighing process can be reduced to an estimation of the driver's actual preference for a particular lane. Considering direct lane changes exclusively, this leads to assessments of the ego lane and the adjacent lanes to the left and right, respectively, to calculate the according probabilities $P(X_{M,\text{Environment}} = x_{\text{KL}})$, $P(X_{M,\text{Environment}} = x_{\text{LCL}})$ and $P(X_{M,\text{Environment}} = x_{\text{LCR}})$.

It is assumed that the preference for a particular lane significantly depends on the presence and criticality of the vehicles driving there. Hence, the state of a lane is modelled as a level of its occupancy. In doing so, three levels of occupancy are distinguished as proposed by Schubert et al. [20]. State $X_{\text{Lane}} = x_{\text{Free}}$ marks free lanes without any obstacle detected. Lane state $X_{\text{Lane}} = x_{\text{Occupied}}$ characterises situations with vehicles present that still allow a safe use of the corresponding lane. And the third state $X_{\text{Lane}} = x_{\text{Dangerous}}$ indicates lane situations where other vehicles prevent the driver from changing to the lane or using the ego lane further on safely and comfortably. For adjacent lanes that state space is expanded by a fourth state $X_{\text{Lane}} = x_{\text{NonExistent}}$ indicating the absence of such a lane.

Following the environmental section's structure of the network, depicted in Fig. 12.5, the assessment of the ego lane relies on the feature variables Adapting Deceleration to Safety Time $a_{\text{ADST},vO}$, distance s_O and the relative velocity v_{Rel0}. The feature's values are converted to levels of lane occupancy and subsequently are combined by the BN to an occupancy estimation of the ego lane.

The estimation of the occupancy levels of the two adjacent lanes is done by two further subsections of nodes. As shown in Fig. 12.5 each of them includes three input nodes. The nodes qualify the occupancy of the respective lane in terms of ADST values, distances of the vehicles located there and in terms of the type of the lane markings separating the respective lane from the ego lane. In doing so, for all vehicles detected inside a delimited area of the respective lane the Adapting Decelerations to Safety Time $a_{\text{ADST},vi}$ and distances s_i, respectively, are calculated and converted into levels of occupancy by using the most critical value that occurs. The information about the absence of an accessible adjacent lane, determining the state $X_{\text{Lane}} = x_{\text{NonExistent}}$, is provided by the estimation of the type of lane markings which, in turn, is derived from observations of the respective lane markings by diagnostic reasoning.

To conclude on the driver's intention of a lane change manoeuvre based solely on environmental assessment, the probabilities $P(X_{M,\text{Environment}})$ are finally obtained by contrasting the states of the different lanes with each other. For weighing competing lane states the order of states $X_{\text{Lane}} = x_{\text{Free}}$, x_{Occupied} and $x_{Dangerous}$ is assumed as complying with descending preference by the driver. However, the fourth state $X_{\text{Lane}} = x_{\text{NonExistent}}$ is able to overrule all the other states by preventing any intention for changing to the accord-

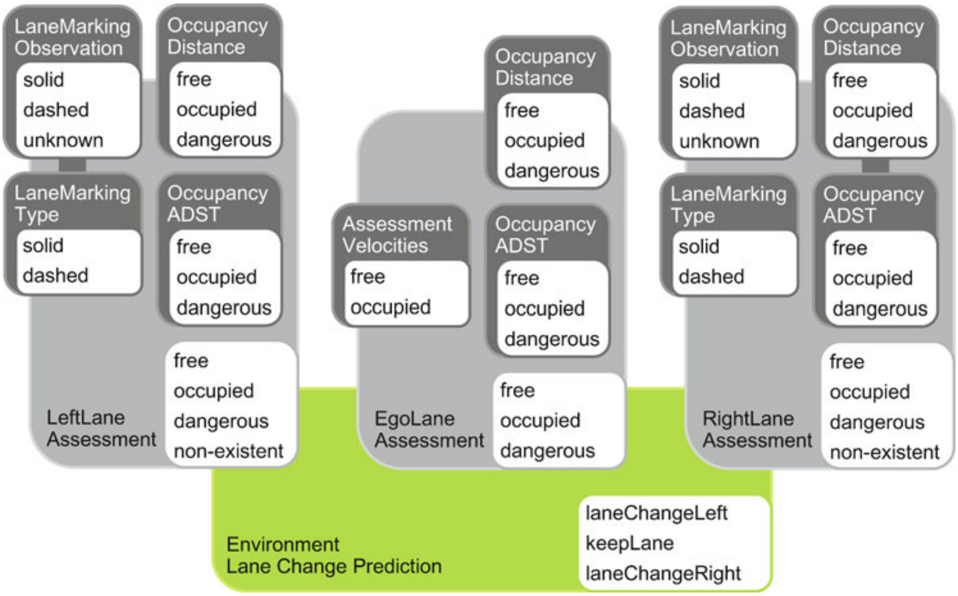

Fig. 12.5 Bayesian network, section for assessing the environmental situation

ing lane. If two lanes compared reach the same level of occupancy, the lane the driver is already driving, the ego lane, is defined as to be preferred. Two adjacent lanes of the same level are considered being equal.

The second section of the BN aims at reasoning for the driver's intention probabilities $P(X_{M,\text{Driver}} = x_{\text{KL}})$, $P(X_{M,\text{Driver}} = x_{\text{LCL}})$, and $P(X_{M,\text{Driver}} = x_{\text{LCR}})$ based on the gaze behaviour only. As described before, the gaze behaviour is modelled by the area G_i the driver actually looks at and by the sequence of the areas the driver looked at before. To include those features into the BN and to calculate the probabilities for $P(X_{M,\text{Driver}})$, four input nodes are defined as shown in Fig. 12.6. Two of them represent the probabilities $P(S_{\text{LCL}})$ and $P(S_{\text{LCR}})$ that describe the probability the sequences observed match to the respective variant of the HMM. However, detecting those sequences requires to observe the areas a driver looks at over a longer period of time. Consequently, the process of predicting lane changes will be delayed, even if a single glance already contains information about an intention, although with less significance. Hence, the second pair of input nodes evaluates the probabilities that the area the driver actually looks at can be related to a lane change intention to the left and right, respectively. To achieve this, all areas G_i are classified in accordance to their probability appearing in connection with lane changes to the respective direction.

Comparisons using the naturalistic driving data obtained by the study that is related to the work pointed out that the possibility to predict upcoming lane changes by assessing the environmental situation or driver behaviour strongly depends on the specific lane change

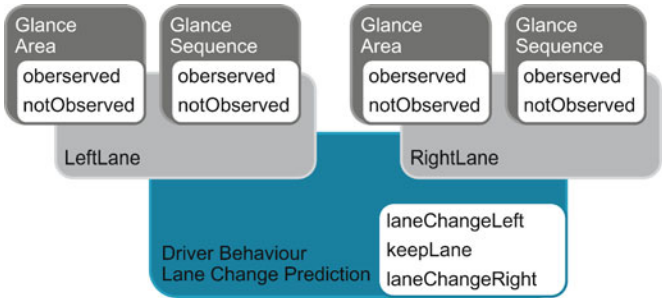

Fig. 12.6 Bayesian network, section for assessing the driver's gaze behaviour

situation. Specific situations can differ with regard to the individual assessment by the driver as well as in the way the features used for the prediction are available and detectable by the sensors. In consequence, neither the environmental observation nor the observation of the driver are able to guarantee an early as well as robust lane change prediction on its own.

That is why the network's final section deals with the fusion of the estimates of $P(X_{M,\text{Environment}})$ and $P(X_{M,\text{Driver}})$ to combine their complementary strengths in terms of prediction time and quality. In doing so, conflicting lane change predictions, for example $P(X_{M,\text{Driver}} = x_{\text{LCL}})$ and $P(X_{M,\text{Environment}} = x_{\text{KL}})$, may occur and have to be weighed. That weighing is described by a set of rules underlying the related conditional probability table of the network. It weights lane change predictions of opposing directions in equal parts as it favours the prediction of any lane change against the prediction of keeping the lane. However, $P(X_{M,\text{Driver}})$ is only allowed to outvote $P(X_{M,\text{Environment}})$ if an according lane is available. Hence, the information about the presence of adjacent lanes, given by $X_{\text{Lane}} = x_{\text{NonExistent}}$, has to be passed on to the fusion node. For that purpose, the set of the states of $P(X_{M,\text{Environment}})$ is extended by additional states indicating lane change directions being allowed as shown in Fig. 12.7. The result of fusing $P(X_{M,\text{Environment}})$ and $P(X_{M,\text{Driver}})$ is $P(X_M)$ with possible states $X_M = x_{\text{KL}}$, x_{LCL} and x_{LCR}.

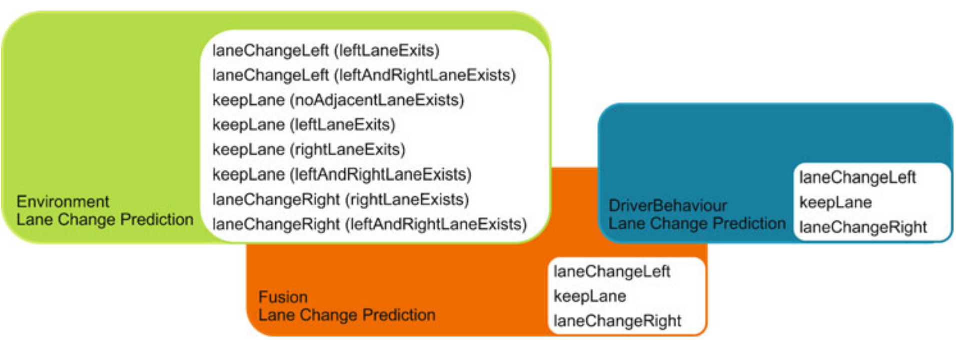

Fig. 12.7 Bayesian network, section for fusing the assessments

12.4 Real-Time Application

The lane change prediction algorithm presented was implemented as a real-time application running under real conditions as a built-in vehicular system. For that purpose, a test vehicle was equipped with sensors providing measurement data of the environmental situation and the driver's behaviour. In addition, a set of pre-processing modules was implemented to derive the features needed by the probabilistic reasoning. The complete lane change prediction system was finally demonstrated live at the public presentation of the UR:BAN project as can be seen in Fig. 12.8.

12.4.1 Test Vehicle and Technical Setup

The test vehicle is a VW Touran 2.0 TDI depicted by Fig. 12.9. To detect and track surrounding objects the vehicle is equipped with automotive sensors. Two long-range radar and four blind spot radar sensors cover 360 degrees of the environment. The 77 GHz long-range sensors are mounted at the front and rear of the vehicle, respectively, and have a detection range of up to 200 m and a detection angle of ±28°. The blind spot radars mounted sideways, two on each side, work with 24 GHz and are able to detect objects up to 27 m providing a detection angle of ±40°. The lane mark detection needed for assigning detected objects to specific lanes is done by a commercial camera-based system called Mobileye. Mounted in the direction of travelling, it provides information about the lane's curvature and the relative position of the ego vehicle within the lane. The vehicle is equipped with seven cameras to obtain information about the situation around and inside the vehicle to support the process of annotation and development. Two of them are additionally used for processing. The first one facing in the direction of travelling is also used to identify the type of lane markings while the second camera facing the driver provides video data for the head tracking with 40 Hz and a resolution of 640 × 480 pixels. The lo-

Fig. 12.8 Demonstration of the integrated algorithm detecting lane change intentions

Fig. 12.9 Test vehicle and sensor configuration

calization of the ego vehicle is done by means of an inertial measurement unit supported by Differential GPS information with a positioning accuracy of 40 cm in total. Finally, the CAN bus of the vehicle provides information about the velocity and yaw rate of the ego vehicle. The processing is done by a standard desktop machine.

12.4.2 Pre-processing and System Architecture

To get the values of features required by the Bayesian network to predict lane changes using the measurement data, several pre-processing modules are implemented and connected following the structure shown in Fig. 12.10.

The upper section of the module view aims at estimating the features for assessing the environmental situation. Most of them, the Adapting Decelerations to Safety Time, distances and relative velocities of surrounding vehicles separated by their lane assignment, rely on the knowledge about the position and the movement of all surrounding objects. It is obtained by means of a multiple-sensor-multiple-object-tracking of the radars' measurement data [21]. In doing so, the Unscented Kalman Filter (UKF) is applied and motions are modelled with the Constant Turn Rate and Velocity (CTRV) model [22]. Tracks are created and updated by radar target measurements of all radar sensors using individual sensor models and applying the Generalized Probabilistic Data Association (GPDA) [23]. Moreover, to relate the tracks to the movement of the ego vehicle, the ego motion is estimated. It is based on the velocity and turn rate delivered by the ego vehicle's CAN bus and applies UKF and CTRV as well. Parallel to this, the lane estimation module combines the information about the position of the lanes obtained by the lane mark detection system with the information about the types of adjacent lane markings. The lane marking types are subsequently transferred to the BN while the lane positions are used by the as-

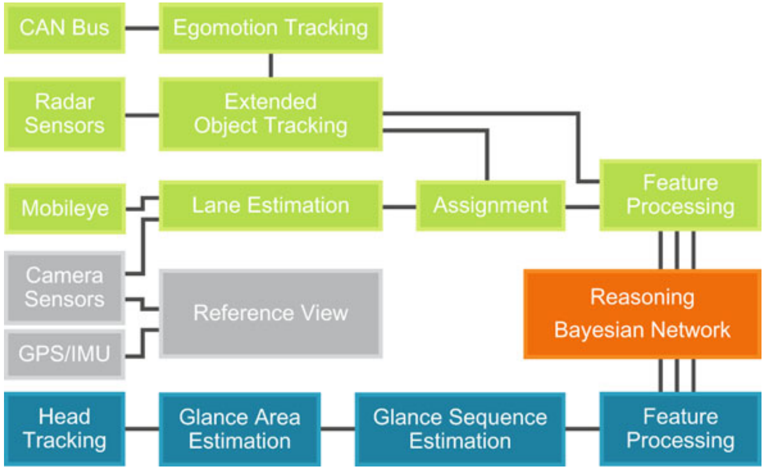

Fig. 12.10 Structure of the algorithm detecting lane change intentions

signment module. This links the tracks with the information about the lanes' structure in order to specify the respective lane they belong to. Besides, the distance, relative velocity and ADST are calculated for each track. The closest track within the lane the ego vehicle is driving along, is finally used to detect the presence of a vehicle driving ahead slowly, while the features of the other tracks are fused per lane to get occupancy assessments for the adjacent lanes to the left and right, respectively.

The lower section deals with the estimation of the glance areas and glance areas sequences indicating a driver's intention to change the lane to the left and right, respectively. It starts with a head tracking module applying a commercial head tracking algorithm called Seeing Machines faceAPI on the video data captured by the camera facing the driver. The rotation of the driver's head around its yaw rotation axis obtained this way is passed on to the modules for estimating the glance area and the glance sequence. Both modules work as described in Sect. 12.3.3.

To sum up, for each feature the different state probabilities are calculated as expected by the input nodes of the Bayesian network and are used to infer the probabilities $P(X_M = x_{\text{LCL}})$, $P(X_M = x_{\text{LCR}})$ and $P(X_M = x_{\text{KL}})$ that there is actual an intention to change the lane or not, respectively. All processing in connection with the whole algorithm is done in a probabilistic manner. It means that the uncertainties are taken into account that are inherent in the data captured, in the models used, and in the process of processing.

12.5 Experimental Results

The performance of the implemented lane change intent estimation algorithm was tested by means of an evaluation data set. The set was generated from measurement data collected during the driving study. The measuring drives were performed with the help of the research vehicle under real traffic conditions on mainly two-lane urban roads. The whole amount of the driving study comprises measurement data of 60 test persons, who drove along a 40 km long predefined route with 1865 lane changes in different traffic situations. Finally, the measurement data was divided into two data sets. One data set was used for development and training of the driver behaviour estimation and the other set to evaluate the algorithms.

The evaluation of the results of the lane change prediction can be carried out by using various quality attributes and methods. The choice of the methodology to assess the quality characteristic of the implemented algorithm depends on the potential application that should use the results of the lane change prediction. However, in most cases the prediction time and the validity of the prediction are of critical importance.

To analyse the results, the parameters $P_{\text{Threshold}}$ and $t_{\text{Threshold}}$ have been introduced, describing the significant probability and the continuity of the prediction result. $P_{\text{Threshold}}$ indicates the probability value from which the prediction can be interpreted as valid. To filter scattered peaks of the algorithm the time threshold $t_{\text{Threshold}}$ defines the minimum time span the probability has to remain above $P_{\text{Threshold}}$ to be considered as a stable result, see Fig. 12.11. By applying the thresholds a binary result signal arises.

For the evaluation of this binary result value, the receiver operating characteristic (ROC) method was applied. And in order to get a ground truth to compare the algorithmic prediction results with real lane changes, the measurement data of the study conducted was enriched by semantic information. The time spans that are considered to be related to a lane change situation are defined by means of the same time intervals of 10 s as described before.

The cases of the confusion matrix required by the ROC are defined in accordance with Fig. 12.12. In the first quadrant, the rising and associated falling edge derived from the lane change prediction value of the algorithm lies outside the occurring lane change situation. This case is defined as a false positive sample. Lane change situations as the one next to it, without any edge of the binary signal that can be related to the 10-second interval, count as being false negative samples. If a pair of a rising and the associated falling edge of the

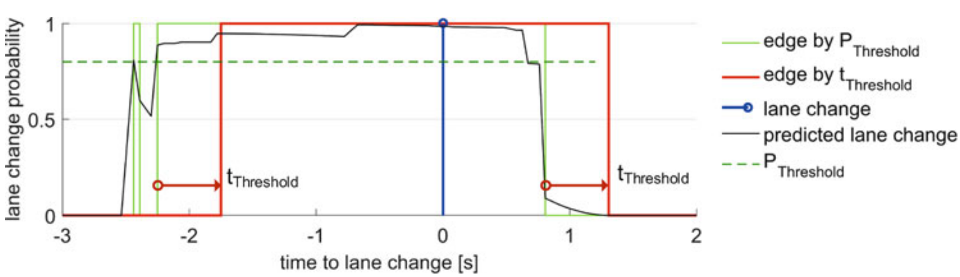

Fig. 12.11 Definition of thresholds for evaluation

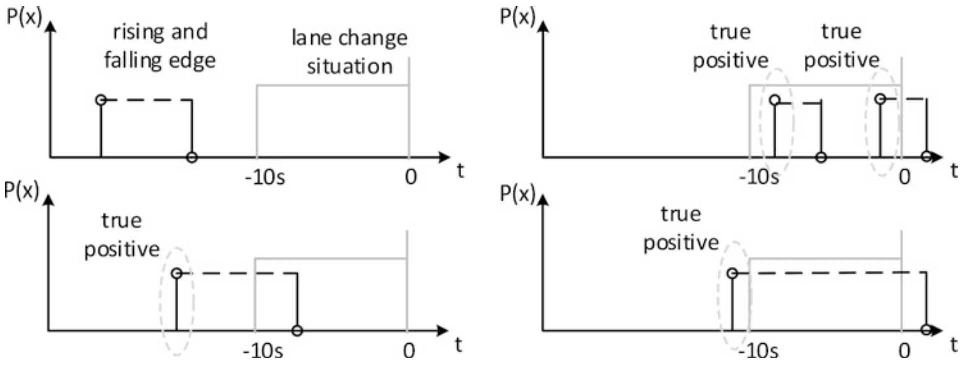

Fig. 12.12 Definition of the relation of prediction and ground truth

estimation overlaps with a lane change situation, as shown in the remaining quadrants of Fig. 12.12, the rising edge is considered to be a true positive sample. Any further point in time, without being related to any positive prediction result or lane change situation, is considered as a true negative sample.

To apply the receiver operating characteristic, the complete evaluation data set was used which represents a part of the measurement data collected during the measurement study. Only about 2% of the time of the real driving data recorded are characterised by lane change manoeuvres. As a result, the ratio of true positive and true negative values are unbalanced. The high number of true negative examples would reduce greatly the resulting false positive rate of the ROC curve. Thus, the algorithm would be taken as highly efficiently. By using this classic method, false negative rates of $1 \cdot 10^{-3}$ occur for the lane change prediction algorithm. However, in the field of advanced driver assistance systems the false alarm rate plays an essential role in the evaluation of technical systems and algorithms. To get a more meaningful representation, the false alarms can be referred to a real time value, for instance as false alarms per hour [10].

Fig. 12.13 represents the modified ROC curve of the developed lane change prediction based on the fusion of environmental and driver behaviour information. Here the number of false positive predictions is shown per hour. The different curves are based on different time thresholds $t_{\text{Threshold}}$. It can be seen that a growing time threshold reduces the false positive samples. All curves reach a true positive rate over 0.87.

On the left hand side of Fig. 12.14 the ROC of the lane prediction by driver monitoring only is shown. In comparison with the figure depicted on the right which represents the lane change prediction using environmental information exclusively, it can be seen that driver information alone performs better in terms of true positive rate than environmental information alone. However, both are outperformed by the combination of environmental and driver information as shown in Fig. 12.13.

Another quality parameter of algorithms for estimating manoeuvre intentions is the prediction time which indicates how early an event can be forecasted. The prediction time

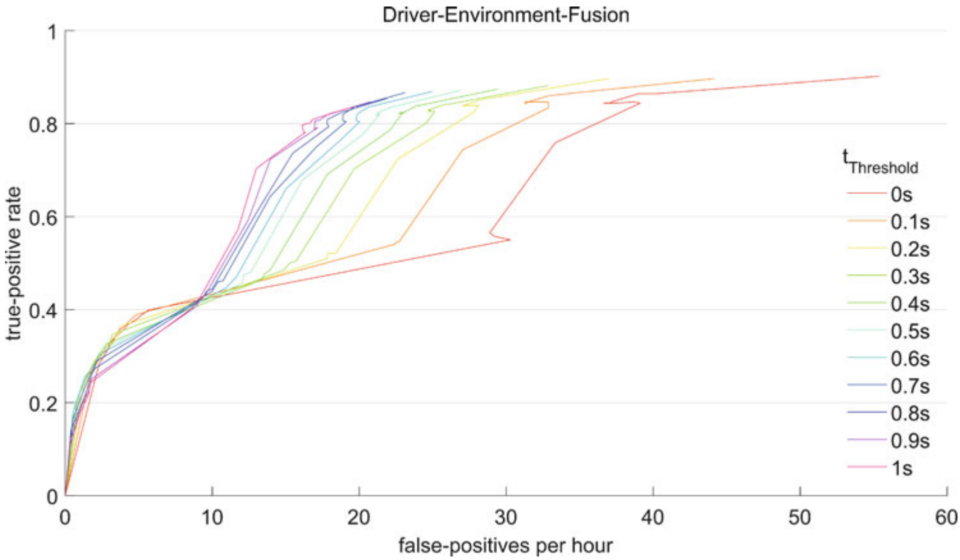

Fig. 12.13 ROC curves for $P(X_M)$ assessing driver and environment depending on $t_{\mathrm{Threshold}}$

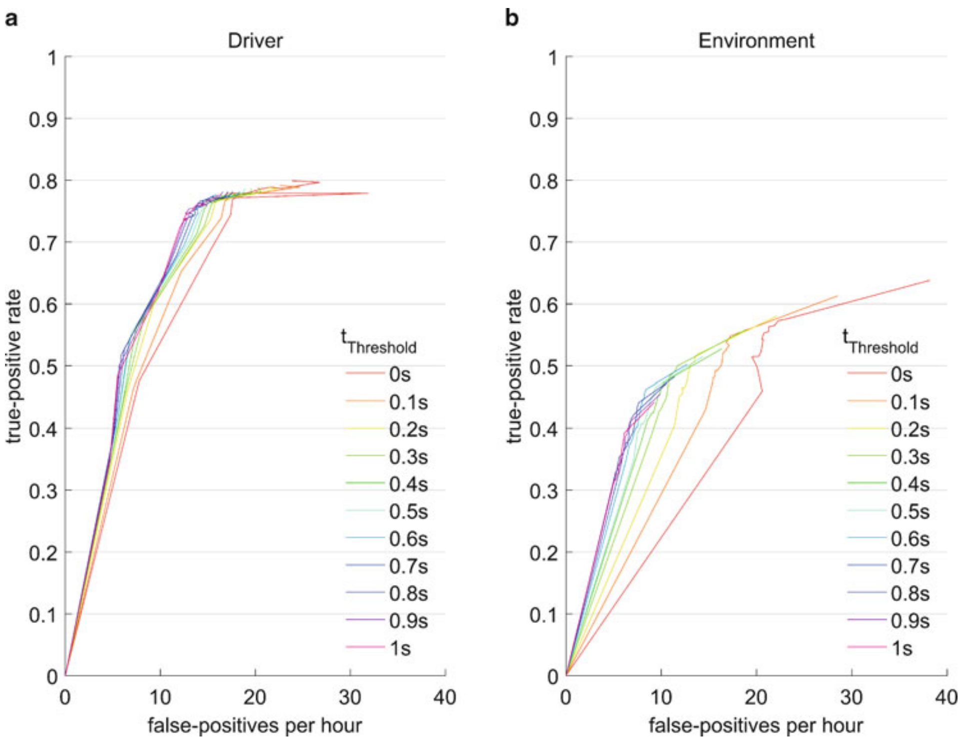

Fig. 12.14 ROC curves for $P(X_{M,\mathrm{Driver}})$ (**a**) and $P(X_{M,\mathrm{Environment}})$ (**b**) depending on $t_{\mathrm{Threshold}}$

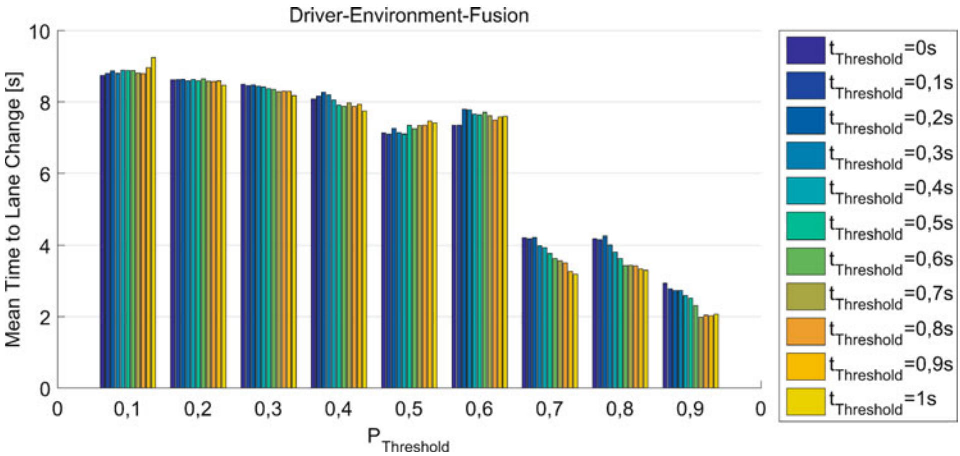

Fig. 12.15 Evaluation of prediction time depending on $P_{\text{Threshold}}$ and $t_{\text{Threshold}}$

influences the accuracy of the estimation result. In general, it can be assumed if the event to predict lies further in the future, it is less likely that it really happens that way. But, in turn, if the prediction is carried out too late it loses its benefit.

Fig. 12.15 shows the average time of the first true positive edge for a related lane change manoeuvre depending on the threshold values of $P_{\text{Threshold}}$ and $t_{\text{Threshold}}$. As expected, an increasing value of threshold $P_{\text{Threshold}}$ influences the temporal prediction horizon in a negative way. However, a higher $P_{\text{Threshold}}$ also decreases the rate of false positives, compare Fig. 12.13. In comparison to similar research publications [4, 10, 11], the average prediction times of the algorithm are significantly earlier. Doshi, Moris & Trivedi [10] get a maximum true positive rate of 0.7 at a prediction time of 3 s before a lane change. Connecting the data in Fig. 12.15 and Fig. 12.13 at a true positive rate of 0.7, the implemented algorithm predicts a lane change triggered by slowly driving vehicles in front with an average time of 7.8 s before it is executed. At this point the threshold parameters are $P_{\text{Threshold}} = 0.5$ and $t_{\text{Threshold}} = 1s$.

To sum up, under the circumstances specified, lane change situations with a slower vehicle in front can be predicted earlier and more reliable by combining information about the environmental situation and information about the driver's gaze behaviour.

12.6 Summary and Conclusions

The work presented aimed at implementing a real-time application predicting upcoming lane changes on the basis of assessing the environmental situation and observing the driver's gaze behaviour.

Bearing this in mind, a full approach for predicting lane change manoeuvres was proposed. It relies on two sets of specific features. The first set that is suggested models the motivating and impeding influence of the environmental situation on the formation of manoeuvre intentions. This is done by involving the distance, relative velocity and deceleration to safety time of surrounding vehicles. In conjunction with the knowledge of the lanes' geometry and markings, all objects are assigned to the lanes to estimate the driver's lane preference. For this, gaze areas and gaze area sequences are estimated by means of head tracking and are applied on two competing estimation models. In order to achieve an early as well as reliable lane change prediction a Bayesian network approach was proposed to fuse all the features in a probabilistic manner.

The algorithm was completed by post-processing modules to derive the features from radar and camera based measurement data. The resulting lane change prediction algorithm was implemented and optimized to run in real-time. Subsequently, it was integrated into a test vehicle equipped with corresponding sensors. Finally, the whole prediction algorithm was evaluated using naturalistic driving data obtained by the study related to this work.

It has been shown that the feature set proposed is suitable to predict lane change manoeuvres caused by a vehicle driving ahead slowly. The prediction can be done in real-time by a standard desktop machine interpreting sensor information that is usually available in modern vehicles. Furthermore, it could be shown that combining the observation and assessment of the environmental situation with the driver's gaze behaviour is able to outperform the individual performances by improving the prediction's overall performance. In addition, there are indications that the prediction of driving manoeuvres of other types would also benefit from this approach. Although an adjustment of the parameterization and additional features as the driver's point of destination could become necessary. Due to the individual differences in the driving behaviour another possible improvement could be to respect specific driver characteristics in the definition of parameter sets. In general, the prediction's performance significantly depends on parametrization which, in turn, strongly depends on the data set used to classify and to parametrize the modules of the prediction application. Consequently, future work should concentrate on parameter optimization using naturalistic driving data covering a variety of situations as broad as possible.

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Human Focused Development of a Manoeuvre Prediction in Urban Traffic Situations Based on Behavioural Sequences

13

Jens Heine, Ingmar Langer, and Thomas Schramm

13.1 Motivation and Goal

Driven by the vision zero, the vision for a reduction of serious injuries and casualties in road traffic [1] there has been done much work on active safety systems. Advanced driver assistance systems (ADAS) played a major part in the last years to reduce the number of seriously wounded and killed people in road traffic [2]. Many ADAS warn if critical situations occur and intervene during a situation where the driver is not able to avoid a collision by himself [3].

The driver's chance of solving a critical situation without the help of an ADAS intervention increases if the driver is warned at an earlier point of time. That however raises the possibility of unnecessary warnings. For example an attentive driver is aware of the upcoming conflict and does not need to be warned. He even may recognise these warnings as false alarms, leading to the so called warning dilemma [4]. With a rising number of those subjectively perceived unnecessary warnings the system might be seen as annoying or is turned off, which leads to a reduced warning character of the system [5].

Hence, the goal is to support the driver with a warning as early as necessary and as late as possible. That implies a minimum number of both unnecessary and false warnings [6].

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A possible approach towards that goal is to detect the driver's intention and to predict future human behaviour [5]. Intention detection measures early indicators of performing a driving manoeuvre and tries to predict the following manoeuvre. A driving manoeuvre is an enclosed operation concerning the guidance of a vehicle [7]. It consists of a number of different actions a driver performs to conduct such manoeuvre. The driver intention belongs to the group of short term changing driver states which changes regularly within a few minutes or seconds [8]. It is not possible to detect the driver intention directly, but the actions a driver is performing in traffic situations can be set in relationship to performed driving manoeuvres and inferred with observations to deduce the future behaviour of the driver (Sect. 13.4).

There are many known motivators which influence the driver by forming his intention. Motivators may be the desire to drive safely and comfortably to a chosen destination [9]. There are also inhibitors which restrict the driver in his behaviour, e. g. the characteristic of the road, the weather or other road users. To infer the driver's intention these motivators and inhibitors have to be measured and have to be put in reference to each other. This combination can be interpreted as a mental model of the driving behaviour. With such mental model it is possible to infer the driver's intention.

The driver's intention influences the behaviour of the driver on the three levels of vehicle guidance [10]. On the strategic level e. g. the driver determines the route to go to his preferred destination. On the tactical level he performs actions like conducting driving manoeuvres to reach his strategic goals. On the operational level he stabilizes the vehicle to perform the tactical manoeuvres. The described approach concentrates on the tactical guidance level.

If the driver's intention is known with a time horizon of a few seconds, it is possible to improve the performance of an ADAS [8] to support the driver on the tactical guidance level, because unnecessary warnings can be suppressed and more user suitable warnings can be generated. It is possible to infer the driver's intention by using in-car Controller Area Network (CAN-bus) data [11]. It can be decided if a warning is necessary and the optimum point in time and intensity of a warning can be defined. Unnecessary warnings can be suppressed.

In addition to the driver's intention there are other driver conditions like drowsiness or distraction which influence the driving behaviour [8]. They are not in focus of this work. Hence, the aim was to provide constant experimental conditions with the least possible variation in drowsiness and distraction. To address all driver conditions including the cross-connections between them, they have to be studied while varying them in a controlled way.

The goal of the described work is the development of an algorithm to predict driving manoeuvres in urban traffic situations with regard to driver's behaviour. Therefore a study design is created that comprises a set of four different driving manoeuvres (Sect. 13.3). Addressed manoeuvres divide in critical and uncritical manoeuvres in order to identify potential differences in detection performance. Analysed critical manoeuvres are emergency braking and evasion, uncritical manoeuvres are stopping at a traffic light and changing lane. Subsequently, the algorithm's performance is analysed by quality measures such as time horizon, specificity and sensitivity. The vehicle used for data collection uses sensors that are available in production. Additionally, the vehicle is equipped with head- and eye-tracking.

Since the algorithm shall be implemented in a vehicle for demonstration purposes, real-time capability is a requirement. This allows the driver to be warned exactly at the calculated point of time.

13.2 Method of Development and State of the Art

Various research has been going on in the area of driver's intention detection for a manoeuvre prediction with real-time capable algorithms. A good overview can be found in Doshi and Trivedi [9]. There is no known technology to measure the driver's intention directly and exact in every possible situation. So far, only predictions with incorporated uncertainty are possible. A possible way of driver's intention detection can be done by building up a mental model from data inheriting examples of certain behaviour and then classify the observed behaviour to estimate his future behaviour based on the previous observations. The classification algorithms can be divided into discriminative (e. g. support vector machines) and generative (e. g. Hidden Markov Models). Generative algorithms model the probability distribution of input and output variables by finding parameters, fitting class-conditional densities and class priors separately and combining them with the use of Bayes' theorem. In contrary, discriminative algorithms model the posterior probabilities directly by maximising a likelihood function with conditional probability distribution needing less parameters to be determined [12]. Both algorithms are trained using experimental data to generate their knowledge inductively in a supervised training procedure. With these procedures it is possible to generate a human model for predicting human behaviour without the need of generating a full mental model deductively.

13.2.1 Development Process

With the mentioned restrictions and opportunities there is a common method for building up a human model for a manoeuvre prediction. It is called machine learning. To use methods of machine learning to create a human model inductively, there needs to be a representative set of data with examples of human behaviour you want to detect or predict. These data need to be collected. There are many ways in generating driving data for a manoeuvre prediction. You can perform a simulator study or measure human behaviour in real driving situations. We conducted a controlled field study (see Sect. 13.3) to concentrate on the human behaviour and the underlying inter- and intraindividual differences. There are not only differences between human drivers in performing similar manoeuvres but even the same drivers tend to show intraindividual differences in performing the same driving manoeuvre. This needs to be considered, when synthesizing an algorithm for manoeuvre prediction. Because we want to detect a certain behaviour in defined situations, e. g. before and while the driver is performing a lane change, we use a supervised machine learning procedure. In supervised machine learning the examples of input vectors need to be connected to the desired output vectors. Hence, the gathered training data needs to be labelled with discrete categories (e. g. the manoeuvre which is performed) to learn underlying similarities in the data to be able to classify driver's behaviour for a manoeuvre prediction. When there is also a need for having not only a discrete result but to get a continuous variable, e. g. the time until the driver is staring to performing a certain manoeuvre, a regression needs to be done.

A driving manoeuvre prediction needs to classify a certain manoeuvre with a certain probability. Furthermore, it must be able to calculate a regression of the time to the start of the manoeuvre while dealing with the complex and individual different behaviour of the driver.

13.2.2 Algorithm for Manoeuvre Prediction

In this work a white box algorithm should be developed to model the driver's behaviour in a comprehensible and traceable way. In contrast to a black box model, e. g. an artificial neural network, a white box model can be observed and interpreted all the time while doing calculations and the trained parameters of the model are present in a comprehensible way. So you are able to extract the knowledge from a white box model to analyse and interpret it for further research. Further on, the complexity of the algorithm needs to be a dimension that it can be executed in real-time on the desired hardware.

To generate a white box model of human behaviour the theory of Fuzzy Logic is feasible. The theory of Fuzzy Logic was first described by Zadeh [13]. Fuzzy Logic enables us to design a control system by using expert knowledge [14] and be able to model the human way of understanding and interpreting signals and variables. Fuzzy Membership Functions (MF) reduce the range of the input variables to a defined number of sets, similar to the comprehension and mental representation of a human expert. However, Fuzzy Logic is not able to deal with time series data without any adaptions, because it calculates output data without considering past inputs or results. Bauer [15] proposed an alternative to handle time series data with Fuzzy Logic without having to deal with the enormous complexity of recurrent Fuzzy Logic systems [15]. The Fuzzy rule base is thereby interpreted as a state machine, incorporating one Fuzzy rule per state. The rule with the highest aggregation value represents the active state of this state machine and with the time flow and activation of different rules the time series behaviour can be modelled with these adaptions.

The structure and operation mode of our algorithm for manoeuvre prediction can be found in Sect. 13.4.

13.2.3 Performance Metrics

When synthesising an algorithm, a validation needs to be done to estimate the performance of the algorithm. Different metrics were used to measure performance of a binary classification and are useful for a performance estimation of this manoeuvre prediction. The sensitivity, also known as the true positive rate, defines the proportion of correctly identified positive classifications whereby the specificity, also known as the true negative rate, defines the proportion of the correctly classified negatives [16]. The true negative value can also be calculated by subtracting the proportion of false positives from "1". These numbers can be used to calculate a receiver operator characteristic (ROC) to illustrate the classification performance by varying a discrimination threshold [17]. The ROC enables us to find an optimal trade-off for the decision threshold concerning the sensitivity and specificity.

Another important performance metric when talking about a manoeuvre prediction is the prediction horizon, also known as the earliness of a prediction. When determining the mean prediction time horizon, e. g. at what time the car will cross the lane marking while performing a lane change manoeuvre, we are able to estimate the possible positive effects of an algorithm for manoeuvre prediction to a certain ADAS.

13.3 Experimental Study

In order to gather behavioural data (incl. eye tracking data) for the planned development of a machine learning algorithm an experimental study was conducted. The study was carried out in a controlled area on the test track of the Technische Universität Darmstadt, because not only situations like stopping or changing a lane, but also critical situations like emergency braking or evasion had to be analysed. It was not possible to perform these critical situations in real traffic due to the risk they present.

The situations were set up on a fixed course on the test track (see Sect. 13.3.1) and the subjects had to perform a total of ten laps, so that intraindividual differences in the behaviour could be analysed. Interindividual differences were a result of the 97 subjects that performed the study. Of these 97 subjects, 56 were males and 41 were females. The mean age of the subjects was 39.3 years with a standard deviation of 13.4 years.

13.3.1 Study Design

The fixed course used in the study can be seen in Fig. 13.1. The course started with a traffic light at an intersection, followed by a total of four lane changes. The lane changes were divided into "forced" and "free" lane changes. Due to space and time limitations, the forced lane change was limited to approx. 30 m, while the area for the free lane change was approx. 85 m. After a curve at the end of the straight road the subjects had to drive

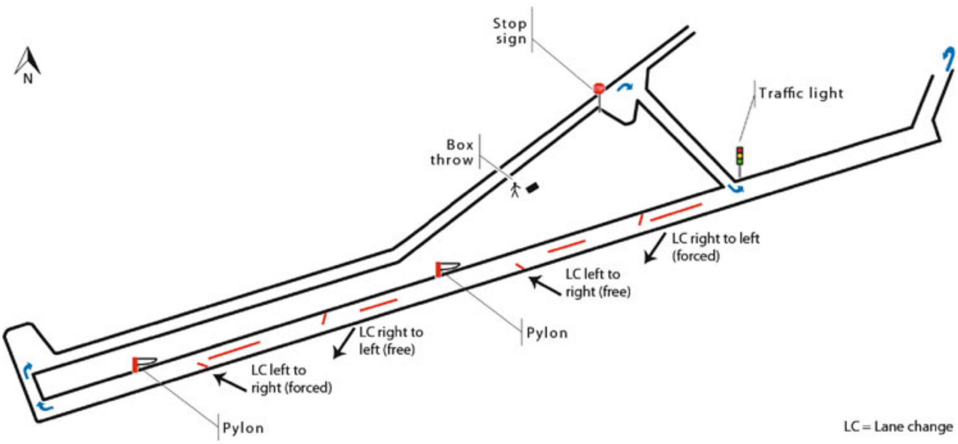

Fig. 13.1 Overview of the course at the test track

to a stop sign and cross the intersection with the traffic light to their left side. At the start of the straight road the subjects had to drive back to the beginning where the next round started.

The traffic light stayed green for six laps, changed from yellow to red in two laps and changed to red immediately in order to provoke emergency braking reactions in another two laps. Between the second and the third lane change and after lane change number four a pylon was placed on the track and both were activated once. On the way back to the intersection, there was an area where a box was thrown on the lane. Details of the three critical situations traffic light (immediate red signal), pylon and box are given in the following chapter.

13.3.2 Creating Emergency Behaviour in Critical Situations

The main challenge regarding the critical situations was not to simply ask the subjects to perform an emergency braking, but to provoke such a reaction in order to be able to analyse a realistic reaction behaviour (see also [18]). One method was to unfurl a pylon which was integrated in a striped barrel from the roadside, blocking the track and forcing the subjects to brake or evade the obstacle in order to prevent a collision. Another method we used, was to change the traffic light at the intersection to red suddenly, provoking a braking reaction. The third method involved a box that was thrown onto the track in front of the car. Fig. 13.2 shows the design of these critical situations.

In order to get proper reactions and useful data, it was critical to activate the different situations at the right time. To find the perfect timing, pre-tests that included time-to-collision (TTC) were performed. For the pylon the TTC was set to about 1.2 s in order to see more evasion reactions than braking reactions (see also [2]). The traffic light suddenly

Fig. 13.2 Overview of the critical situations pylon (**a**), traffic light (**b**) and box (**c**)

turned red when the car was about 21 m away from the light – while driving 50 km/h this equals approx. 1.5 s. The box was thrown onto the track with an approx. TTC of 1.2 s in order to have comparable results with the pylon.

13.3.3 Validity of the Controlled Field Study

An analysis of the reactions to the critical situations of $N = 53$ subjects (first test series) showed that 50% (26 out of 52) of the subjects made an emergency brake when the traffic light turned red suddenly. About 10% (5 out of 52) made a partial braking. The second critical situation at the traffic light resulted in 86% (43 out of 50) emergency brake reactions and only 10% (5 out of 50) showed no reaction at all. The subject's reactions to the triggering of the pylon are dominated by a combination of braking and evading (55.8% (29 out of 52) respectively 59.5% (22 out of 37) in the two events). Evading is the reaction in 26.9% (14 out of 52) respectively 21.6% (8 out of 37) while braking was done in 11.5% (6 out of 52) respectively 18.9% (7 out of 37). 36 of the 53 subjects (67.9%) reacted with a combination of braking and evading to the thrown box, 26.4% (14 out of 53) braked and 5.7% (3 out of 53) evaded at the critical situation. To summarize, the reactions of the subjects were as expected and valuable data was collected. Additional details (with slightly different numbers due to smaller mistakes) can be found in Langer et al. [18].

In a questionnaire, which had to be completed after each critical situation, the subjects had to mention situations out of real traffic which are comparable with the critical situation in the tests. The main answers were:

- Traffic light,
  - inattention of the driver ($N = 13$),
  - imminent crossing of a red traffic light ($N = 10$),
  - harsh Braking of the vehicle ahead ($N = 6$).
- Pylon,
  - child or ball on street ($N = 18$),
  - animal crossing street ($N = 13$),
  - car leaving parking space/car door opened ($N = 12$).

- Box,
  - child or ball on street ($N = 12$),
  - load/object on street ($N = 8$),
  - animal crossing street ($N = 7$).

The answers show that typical and critical situations out of real traffic are comparable with the situations in the test study.

Overall the study with the critical situations seems to be valid concerning the results of the subject reactions, the compared situations out of real traffic and the expert feedback of the pre-tests of the study.

13.3.4 Experimental Conclusions

In the experimental study valuable data of driver behaviour was collected from 97 subjects. Besides data on steering or pedal behaviour, eye tracking data was collected. The fixed course of the study contained normal situations like changing a lane and braking, as well as critical situations. With the broad variety of the collected data it is possible to analyse the behaviour and to find important indicators for the following behaviour in order to develop a solution for a manoeuvre prediction which can be used in order to improve the effectiveness and acceptance of ADAS.

13.4 Development of an Algorithm for Manoeuvre Prediction

In this chapter the design and the functionality of the algorithm are described. At first, there must be a selection of used input variables. This procedure is often known as feature engineering and is not an easy process. Then the fuzzification, modelling of driver's behaviour with behavioural sequences is described, the inference with a k-nearest-neighbour method using Edit Distance as distance metric is explained, and the validation using the leave-one-out cross validation method is shown. These elements need to be selected to define the desired output of the algorithm with regard to the existing input variables.

13.4.1 Select Input Variables/Feature Engineering

At the beginning of the development of an algorithm, the available input data has to be selected. It seems to be logical, that using all data you have to predict a driver's intention is the best, but according to Occam's razor [19] it is best to choose only the best input variables as features and to concentrate on fewer and stronger input variables. This should lead to the best compromise between prediction quality and computational effort [20] and should raise the performance in detecting manoeuvres on unknown data sets in a future application. This work focusses on the driver's behaviour and the clues he delivers for a manoeuvre prediction. Not only the steering and pedal input of the driver have to be considered, other values also influence the driver in his behaviour, because they were used to identify the car's reactions to the driver's inputs to stabilize the vehicles course. The data was collected with the vehicle's CAN-bus and an optical car mounted driver monitoring system with the ability to detect the driver's head movement and gaze behaviour. With the use of a non-intrusive eye-tracking system you can measure the attention focus of the driver for estimating which information he is gathering, because nearly 90% of the gathering of information by a driver is done with the eyes [21]. Due to the reduction of driving comfort, when using intrusive methods, only non-intrusive methods were chosen. For the feature selection a method to evaluate features on statistical basis was developed by Heine et al. [22]. This feature selection focusses on the detection rates and time horizon a single feature is able to perform concerning the detection of a certain driving manoeuvre. With this method it is possible to identify the most promising and valid features to use for the manoeuvre prediction. The best features for the lane change prediction (within our research) are the features from the lane detection camera system. These are the lateral distance to the lane marking, the heading angle of the vehicle to the lane marking and the time to line-crossing (TLC), a feature introduced by Lin and Ulsoy [23]. The best features for the stopping manoeuvre are the velocity of the vehicle and a combined pedal position, which is calculated as the difference of the accelerator pedal position and the brake pedal position to reduce the number of input signals by one without losing any information, because none of the participants showed behaviour in which both pedals were activated simultaneously. The best signals to detect the emergency braking manoeuvre were the velocity of the vehicle, the combined pedal position and the gradient of the accelerator pedal. The emergency evasive manoeuvre was best predicted by the steering angle and the TLC.

13.4.2 Fuzzification of Input Variables

The number of Fuzzy membership functions (MF) per input variable were identified with a heuristic approach in combination with expert's knowledge, the intersections between the MFs were trained with the use of the training data. A number of five Fuzzy MFs per input variable assured the best compromise between performance and computational effort [24, 25]. Similar to the work of Hulnhagen [26] manoeuvre specific MFs were trained. The input variables were analysed across all participants for the regions with the most and less change to get a high number of MFs in the region with the fastest change to be sensitive for these changes and fewer MFs in areas with less change to reduce the computational effort. Therefore, the mapping of the deviation of a certain input signal to its course is analysed, divided into five equally sized integrals and the boarders of these integrals are used as the intersection of the MFs.

After defining the intersections of the Fuzzy MFs the exact course needs to be set, by defining the fuzziness between the MFs with a parameter within the range of [0.1], whereby 1 represents the highest possible fuzziness, leading to very smooth transitions between the MFs. The best value for this parameter was found to be 0.5 [24, 25], which represents a medium amount of fuzziness incorporated in the Fuzzy Logic system.

13.4.3 Behavioural Sequences and k-nearest-neighbour

Driving manoeuvres are located on the tactical guidance level and consist of different action steps a driver performs sequentially to control the vehicle with a time horizon of a few seconds. Each action step can be modelled by the activation of a certain Fuzzy rule. Hence, a driving manoeuvre can be described as a sequential activation of Fuzzy rules over time. These sequences represent the driver's behaviour independent from other driver's behaviour and is more suited to describe the time series properties with respect to the inter- and intraindividual differences in human behaviour than state machines.

Every sequence is generated by transforming the actions the participant was performing within the test track study while performing the certain manoeuvre into Fuzzy rules. The rules with the highest aggregation value were the active one and were connected according to their appearance in time thus creating a sequence of Fuzzy rules. Each state in this sequence inherits the active Fuzzy rule, the mean Fuzzy aggregation value and the duration of activation. All sequences of all participants form a database of driver's behaviour in one certain driving manoeuvre inheriting manoeuvre specific behavioural patterns. Even very rare patterns were not rejected and kept in the database to have the chance to detect a greater variety of manoeuvre conduction.

Fig. 13.3 shows an example for a behavioural sequence for a stopping manoeuvre. In this graph, the accelerator and brake pedal are shown individually to allow a better comprehension. The course of the vehicle's velocity, the accelerator pedal and brake pedal position were fuzzified into five Fuzzy sets each. However only three of them are visualised in the graphic. The resulting behavioural chain can be seen at the bottom of the figure, inheriting the specific behaviour of the driver at this stopping manoeuvre.

After all sequences from all driving manoeuvres were analysed and stored into each driving manoeuvre specific database the training of the algorithm is completed.

To predict a driving manoeuvre the actual driver's behaviour has to be compared in real-time to the trained behaviour in the databases to infer the driver's intention. The k-Nearest-Neighbour (kNN) algorithm, a non-parametric method for pattern detection is used to infer this information. It is superior to a parametric method in regard to the representation of the probability density, but needs a high amount of memory and computational power to execute. KNN algorithms compare an unknown sample of data with stored samples of a database in a multidimensional feature space with the use of a distance metric to calculate the similarity between the unknown sample and all known samples. It classifies the unknown sample by assigning the specific class label to that sample by calculating the most occurred label within the k similar or nearest samples concerning the distance metric.

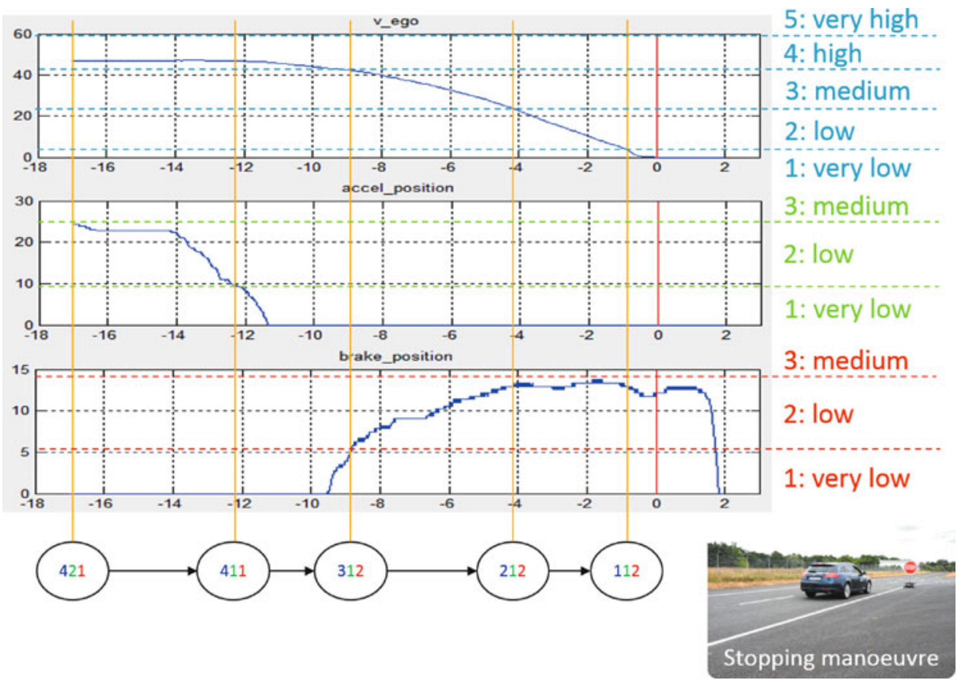

Fig. 13.3 Behavioural chain at a stopping manoeuvre

13.4.4 Edit Distance

To use the kNN method for pattern classification a suited distance metric needs to be selected. A commonly used metric for continuous variables is the Euclidean distance [12]. To compare sequences of discrete elements, e. g. text recognition or to compare two sequences of states another distance metric will perform better. Because of the inter- and intraindividual differences in performing driving manoeuvres it is nearly impossible to find identical sequences. The Edit Distance [27] seems to be the feasible solution. Bunke and Csirik [28] used the Edit Distance for general feature detection and Chua et al. [29] and Navarro [30] extended it to be used for different applications, e. g. by adding the capability of comparing sequences of different lengths and a real-time capable calculation. It calculates the minimal effort to convert one sequence of elements into another by using different defined transformations like delete, insert or switch to determine the similarity of these sequences. Thereby, every transformation is defined with certain costs and the sum of the costs of all necessary conversation steps correlates with the distance. In this work the costs are related to the appearance of the states in the database, so that the insertion of a state, which happens to exist very seldom in the database, is much more expensive than inserting a state which is represented very often.

Some driving manoeuvres, e. g. a lane change manoeuvre, can be conducted at every point in time and space as long as the road offers the needed requirements, e. g. a useable target lane for a lane change manoeuvre. Hence, a continuous manoeuvre classification is needed. Because the computation of the Edit Distance in combination with the kNN algorithm is computationally expensive, another method for moderating the computational complexity is needed. For this purpose the edit distance is calculated continuously only when needed. To determine, if the calculation is necessary a state machine for every manoeuvre is implemented. It consists of the states which are element of the corresponding behavioural sequences. The calculation of the edit distance for a certain manoeuvre is started, when specific states within the state machine, which are marked as starting states, are activated. The calculation is stopped when marked ending states were reached or a defined number of forbidden transitions were detected. This adaption enables us to classify driver's behaviour with kNN and Edit Distance in real time.

13.4.5 Manoeuvre Probability and Time Horizon

The state machine to manage the computational effort also enables us to calculate the probability of the classification. The algorithm provides us with a distance value to compare, how similar the actual behavioural sequence of the driver is to a certain stored sequence within the database. The measure thereby correlates with the statistical probability, that the actual behaviour is similar to the ones learned in the training step. The correlation between the Edit Distance measure and the probability is analysed and stored in a look-up table for the calculation of the manoeuvre probability. Therefore, the activations and deactivations of the state machine in regard to the distance measurement were used to calculate this look-up table.

When using the algorithm in the real-time detection, it is possible to directly calculate the manoeuvre probability from the calculated Edit Distance value. The same method is used to calculate the time horizon until a certain driving manoeuvre is going to be conducted. Thereby, the reference time will be calculated in regard to a certain fixed point in time during the analysed manoeuvre, e. g. the time when the front left wheel touches the lane marking at a lane change to the left. The time horizon is as important as the manoeuvre probability, because it allows us to trigger a certain action of an ADAS, like an early warning, at the right point in time to give the driver enough time to act on a certain situation, without providing the warning too early or too late.

13.4.6 Design Parameter Optimization

The algorithm inherits parameters to adjust the behaviour and calculations. These design parameters were used at a certain part of the algorithm to get the chance of choosing a set of parameters to adapt the algorithm to certain needs of an ADAS. E. g. you can adjust the complexity of the algorithm by choosing more fuzzy sets per input variable and thus creating more complex manoeuvre sequences, or you can change the fuzziness between these sets to incorporate more fuzziness in the algorithm leading to smoother transitions and a greater diversity. The parameters were optimized with the use of the training data to find the optimal parameter set. But they can be adjusted in further research to adapt to other use cases or specific desired ADAS behaviour.

13.4.7 Validation of the Algorithm

For validating the performance of an algorithm for manoeuvre prediction a receiver-operator-characteristic (ROC) is suitable to find an optimal trade-off for the decision threshold concerning the sensitivity and specificity. Therefore, the numbers of the manoeuvres through the controlled field study were calculated and compared with the output of the algorithm concerning the true positive rate (TP) and the false positive detections (FP). With the variation of the probability threshold, a value to decide whether the driver is performing a certain manoeuvre or not, comparable to a binary classifier, a full ROC can be calculated. The ROC can afterwards be used to find the optimal trade-off between sensitivity and specificity for toggling an ADAS. When using ROC-curves for validating the performance, another value can be used: the area-under-curve (AUC). Because of the characteristic of the ROC-curve the area under this curve delivers another performance criteria. The closer this characteristic gets to the value of 1, the better is the performance of an algorithm concerning the sensitivity and specificity. More information regarding ROC-analysis can be found in Fawcett [17].

As stated before, another important performance metric is the prediction horizon t_h or the earliness of a detection. With finding the optimal trade-off between sensitivity and specificity, the decision probability can be used to calculate the mean time horizon for the prediction of a driving manoeuvre, by calculating for each true positive detection the time until the certain manoeuvre fixed point in time is going to be reached. Another important value to validate the performance is the correctness of the provided time horizon. The algorithm is calculating a time to manoeuvre value in each step. To validate this calculation the mean quadratic error between the provided time horizon and the true value $t_{h,\mathrm{err}}$ is calculated.

To give an estimation of an algorithm's performance concerning its generalization ability with regard to an independent data set, cross-validation methods are used. The leave-one-out cross-validation (LOOCV) is an exhaustive cross-validation method for using all the available data for training and testing. Other than non-exhaustive cross-validation methods, e. g. k-fold cross-validation, it uses all possible ways of splitting the data into training and validation sets, without suffering from a very high complexity like leave-p-out cross-validation. It gives a realistic performance estimation of one driver performing several driving manoeuvres and the detection quality of an algorithm trained with as many training data as possible.

Table 13.1 Performance metrics of the manoeuvre prediction

	TP	FP	AUC	t_h	$t_{h,\mathrm{err}}$
Lane change left	96.2%	10.7%	0.95	1.35 s	1.48 s
Lane change right	94.4%	9.4%	0.95	1.02 s	0.27 s
Stop	98.8%	4.5%	0.97	1.91 s	0.57 s
Emergency Braking	97.2%	1.4%	0.98	1.74 s	0.94 s
Emergency Evasion	69.4%	1.7%	0.83	0.37 s	0.75 s

In Table 13.1 the performance metrics of the algorithm detecting lane change manoeuvres to the left and right, stopping manoeuvres at intersections, emergency braking and emergency evasive manoeuvres can be seen.

To detect the lane change manoeuvres, following signals were used: the angle of the vehicle to the lane markings, the TLC and the activation of the indicator switch. To detect the stopping manoeuvre, the vehicle's velocity and the accelerator and brake pedal position are used; to detect the emergency braking manoeuvre, the same signals as for the stopping manoeuvre, and additionally the accelerator pedal's gradient are used. To detect the emergency evasion manoeuvre, the steering wheel angle and the TLC is used.

The performance shows high true positive rates for every manoeuvre except the emergency evasive manoeuvre by keeping quite low false detection rates. The mean time horizon for predicting the lane change is a little over 1 s, before the vehicle touches the lane marking with the correspondent front wheel. Because of the low number of evasive manoeuvres in combination with a very high variance in interindividual behaviour during execution by the participants, a detection rate of only 69.4% was achieved.

More information about the development of the algorithm and the performance can be found in [14].

13.4.8 Integration of Driver Monitoring

To include more early features indicating future driving manoeuvres, driver monitoring data was analysed. With this information it is possible to raise the mean time horizon, and to provide an earlier prediction of the driver's behaviour to a certain ADAS. The head and gaze behaviour of the driver may indicate, which manoeuvre the driver is planning; thus, being able to predict it earlier. In comparison to vehicle data, features from driver monitoring tend to happen earlier, but unfortunately seem to be more unreliable concerning the prediction of the next driving manoeuvre. In the experimental study the data including head and gaze behaviour was analysed. The features derived from the horizontal head rotation delivered the highest accuracy and time benefit. The features including gaze behaviour seemed to deliver features with a little improvement in earliness but a downfall in reduced accuracy [32, 33].

The integration of head features for the driving manoeuvre prediction was done by stacking a decision tree with the head features to the previously shown algorithm. With the integration of the analysed features we were able to improve the detection quality and earliness of the lane change prediction but did not improve the performance of the longitudinal and emergency manoeuvres.

Among our experimental study described in Sect. 13.3, the participants showed no specific features in their head or gaze behaviour, which could help to improve the manoeuvre prediction in comparison to vehicle based features. This may also have occurred because of the setup of the experimental study and the little time the participants have had to react to our critical obstacles. We also found no significant features in head or gaze behaviour to improve the performance of the detection of the stopping manoeuvre. The participants started the slow down at the approach of the intersection, which was measurable with signals from the vehicle's CAN-bus more early than a specific gaze behaviour to check for other vehicles approaching the intersection. But this could also have occurred because of the artificial setup of the controlled field study.

With the integration of a 2-class decision tree using head based features the true positive rate for the lane change detection to the left decreased to 91% while reaching a better false positive rate of 3.1%. The biggest benefit was the raise in the prediction time horizon [32, 33]. With the use of head based features in combination with vehicle based features a mean prediction horizon of 2.5 s was achievable (Heine, i. V.). This supports the hypothesis that early features gathered by monitoring the driver's head and gaze behaviour lead to an increased detection horizon for a manoeuvre prediction concerning lane change manoeuvres.

13.5 Integration in Demonstrator Vehicle

As a final step the algorithm was integrated into a demonstrator vehicle with a prototype installation of hardware to test the performance and real-time capability under realistic conditions. The real-time capability was tested through a test drive in real traffic situations in the city of Rüsselsheim. In this test drive all uncritical manoeuvres were performed. The mean calculation time of the algorithm was 17 ms on a Core i5-3210 M Car-PC within a Java environment. Accordingly, the algorithm was found to be real-time capable for providing information about the next planned driving manoeuvre to a certain ADAS in uncritical situations.

The next step was an expert evaluation of the algorithm and was carried out on a closed test track environment. To conduct a proper test the status and operating mode of the algorithm has to be visualised. For this purpose a prototype visualisation was developed and integrated (see Fig. 13.4). It visualises the probability and time horizon of the predicted manoeuvres in the centre information display.

The vehicle is displayed statically in the lower left corner. If an upcoming driving manoeuvre is predicted, it is displayed visually in the form of a traffic sign. The distance of

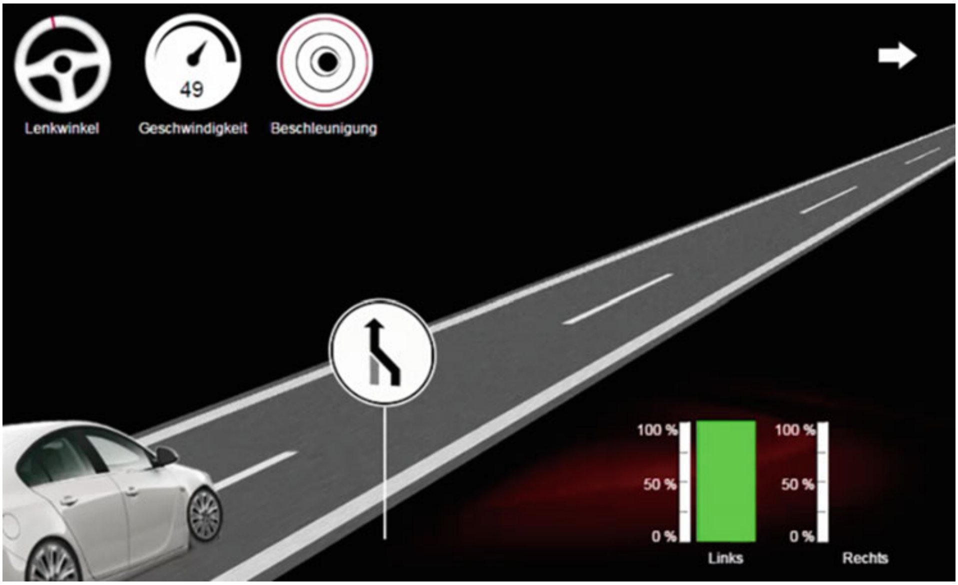

Fig. 13.4 Real-time visualisation of algorithm while performing a lane change to the left

the sign to the vehicle represents the computed time horizon to the onset of the manoeuvre. Since the manoeuvre probability is not the same for every manoeuvre, the traffic signs can be shown transparent to illustrate that effect. In the lower right corner the probability of the lane changes were displayed in form of a bar graph.

This visualisation should not be a real HMI, but enables the experts with knowledge of ADAS to evaluate the performance of the algorithm in real-time while driving the demonstrator vehicle. On this test track validation/evaluation all uncritical and critical driving manoeuvres were performed. The algorithm was assessed in terms of robustness, earliness, sensitivity and specificity. The algorithm showed a good performance for vehicle velocities between 30 kph and 70 kph. With vehicle velocities lower than 30 kph and higher than 70 kph the positive detection rate decreases, because the behaviour of the driver at these velocities differs significantly from the behaviour during the experimental trials recorded at 50 kph.

The prototypic integration into a demonstrator vehicle enables us to conduct further testing and calibration of the algorithm. In this demonstrator vehicle the integration into a certain ADAS is possible to test the potential of driving manoeuvre prediction for improving the performance of an ADAS. For this purpose another experimental study for comparing an ADAS with and without a driving manoeuvre prediction should be realised.

Finally, the demonstrator vehicle was displayed on the final dissemination event of the UR:BAN project in October 2015 in Düsseldorf [31], where a live demonstration of the algorithm and the visualisation were given to interested guests.

13.6 Use of Driving Manoeuvre Prediction

Like discussed in Sect. 13.1, driving safety can be increased by an earlier display of driver warnings. However, they are connected to a potential annoyance which can lead the driver not to adhere to warnings any longer. In addition, a driver who is "in the loop" may not need a warning to draw attention to a certain locus that he already is aware of. With the information about the driver's actions within the next seconds, unnecessary warnings can be suppressed and necessary warnings intensified. That may lead to an increase in acceptance of the ADAS.

13.6.1 Benefit in Non-critical Situations

The time benefit of displaying a driver warning is higher in non-critical situations compared to critical situations. If the driver shows an action that can be interpreted as an upcoming lane change, an intensification of a Side Blind Zone Alert can be useful. The benefit of such an application appears even larger compared to state-of-the-art side blind zone alert systems, when the information about a future lane change is computed without the information about the turn indicator stalk. On the other hand, if there is no sign that the driver plans to perform a lane change, unnecessary warnings can be suppressed.

The discussed logic can be transferred to a Lane Departure Warning system. If no lane change intention is detected and the driver is in process of inadvertently departing the lane, warnings can be intensified. In contrary, if the driver indicates an upcoming lane change, a LDW warning can be suppressed.

For assistance systems that display warnings concerning longitudinal manoeuvres, e. g. a red light or a stop sign warning, the warning can be intensified, if the driver shows no action than can be interpreted as a brake intention. For intersections that necessitate a driver to brake in order to give way to another vehicle, the same logic applies. The driver's behaviour is analysed with regard to accelerator and brake pedal usage and a future manoeuvre prediction can be derived. In case the driver is likely to obey the stop sign, a warning can be delayed or omitted. If the driver shows no intention of stopping, an intensified warning can be shown.

13.6.2 Benefit in Critical Situations

In critical situations such as a potential forward collision, the prediction of driver's intention may deliver a time benefit compared to the case without intention prediction. With this information a Forward Collision Alert (FCA) could provide the driver with an earlier warning without risking to produce an unnecessary warning, if he shows no intentions to resolve that situation. In the contrary case, if a braking intention or an intention to do an evasive manoeuvre is detected with a certain probability value, a warning could be delayed to the latest point in time or even be suppressed.

However, the time benefit is very small compared to intentions in uncritical situations, which are better predictable. If a feature with automatic collision avoidance with braking or steering actions is considered, which avoids collisions at the last point in time, the main advantage consists in solving acceptance issues derived from a possible difference in intended actions between the driver and a collision avoidance ADAS. If the intention detection reveals, that the driver is likely to choose a different strategy than the vehicle, it will change its strategy to the driver's strategy in order not to override the driver. If e. g. the driver's intention reveals an evasive manoeuvre to the left, whereas the vehicle plans to perform an emergency braking manoeuvre, the vehicle could adapt its strategy to the driver's intent and will support the driver in evading. In case the predicted intention of the driver is in accordance with the evasion or braking strategy of the vehicle, it will support the driver in steering even faster or braking even harder. In case there is no driver intention detectable, the vehicle will brake or evade on its own.

13.7 Conclusion and Outlook

In this chapter we described the human focused development of an algorithm for driving manoeuvre prediction in urban critical and uncritical situations with the use of behavioural sequences, Fuzzy Logic and Edit Distance. The development was based on the data of a controlled experimental study. The developed algorithm is able to predict uncritical lateral driving manoeuvres before the front wheel touches the corresponding lane marking with a true positive rate of over 90%. The earliness for the detection of the lane change could be improved with the use of head based features from a remote driver monitoring system to 2.5 s. The algorithm is real-time capable and could be used to provide the information of the driver's intention to addressed ADAS to improve the driver warnings in terms of earliness and reduction of false positive warnings. With the integration of this information, more driver suitable warnings can be generated in terms of presenting a warning at an earlier point in time or suppress an unnecessary warning or action from an ADAS to reduce a possible warning dilemma and raise the effectiveness of modern ADAS.

13.7.1 Discussion

The information gathered by analysing the driver's behaviour and predicting his future behaviour is a probabilistic information. With a higher detection earliness before the start of a certain manoeuvre the dependability on this information decreases. Also some features of the driver's behaviour tend to be happening not all the time, e. g. head rotations to look over one's shoulder to scan for vehicles in the blind zone or the activation of the indicator switch. This leads to a high variation in detection quality and earliness of a manoeuvre prediction.

The conducted experimental study enabled us to concentrate on driver's inter- and intraindividual behaviour in a controlled setup. As a next step the driver's behaviour should be analysed in real traffic situations throughout the very complex and highly changing situations of urban traffic to achieve a realistic performance measurement for the manoeuvre prediction feature.

Hence, future research is necessary to prove the reliability and to improve the detection quality of driver's intention detection and behaviour prediction.

13.7.2 Outlook

The next steps are the integration of the manoeuvre prediction to a certain ADAS, and to test within a study if the theoretical calculated benefits are suited to the driver's needs and lead to a better acceptance of certain ADAS from the point of the customer. Therefore, a comparison between an ADAS with and without the support of a driver's intention detection feature should be conducted. The results will show, if a feature can be improved with the use of driver's intention detection, but one must be aware of the bias in the results coming from the initial quality of the ADAS. The improvement of ADAS by using driver's intention detection can be small in comparison to the annoyance of a sub-optimum HMI of ADAS. Further steps are the extension to a wider range of velocities, to be able to predict driver's intentions in a bigger range of driven velocities, the extension to a wider range of roads and the extension to all driving manoeuvres by adding intention detection at intersections for left and right turn manoeuvres, following and passing other vehicles.

Human focussed intention detection will also be important when thinking about automated driving in urban traffic situations. But the preconditions are different, because the driver is not permanently in control of the vehicle, so that further research in the field of driver's intention detection is necessary.

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Application of a Driver Intention Recognition Algorithm on a Pedestrian Intention Recognition and Collision Avoidance System

14

Frederik Diederichs, Nina Brouwer, Horst Klöden, Peter Zahn, and Bernhard Schmitz

14.1 Driver Intention Recognition for Pedestrian Collision Avoidance Systems

Driver intention recognition can contribute to better driver assistance and transitions to and from automated driving. The prediction of intended driving manoeuvres allows adjusting the timing of an assistance system and to initiate or cancel interventions. Recognition of driver's intention also allows assistance which does not contradict the driver's expectations and planning and shall in consequence make assisted driving more intuitive. Driver intention recognition has an interesting potential especially for automated emergency manoeuvres, such as automated braking.

This chapter is dedicated to recognise driver's intention to avoid a collision with a pedestrian. A recognition algorithm is used to adapt the timing and frequency of collision warnings and automated emergency braking.

Accident statistics reveal the vulnerability of pedestrians on our roads. In 2012, in Germany 14.6% of all road fatalities were attributed to pedestrians, and within the EU Poland has the worst statistics with 32.4% [1]. 95% of those accidents happened in urban areas [2] which indicates the need of safety systems for complex and densely populated locations. Pedestrians who are distracted by smartphones are even more likely to become involved in an accident [3]. In this context, the spreading of smartphones and the emerging wearable

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devices raise the need for better protection of pedestrians. Active pedestrian protection systems are emerging which detect pedestrians and estimate their intention to enter the road. A wide market introduction of pedestrian collision avoidance systems can be expected, especially since Euro NCAP [4] has been including active pedestrian protection systems in the Euro NCAP test catalogue.

State-of-the-art pedestrian collision avoidance systems are designed to brake automatically in case of a critical situation in order to avoid an accident. Since an emergency brake bears also a certain risk due to following traffic, it should only be activated if the collision could not be prevented otherwise. One option for deescalation is to warn the driver of an impending collision. The driver stays "in-the-loop", which makes the system more comfortable for the driver and increases the acceptance. But since a warning has to occur before an emergency brake, the time, between the prediction and the expected collision has to increase. Unfortunately, an earlier warning time will also lead to an increasing amount of false alarms. Too many false alarms will reduce the system's acceptance and in the worst case the driver will switch it off and will not use it [19].

State-of-the-art collision avoidance systems provide a warning of at most 2.7 s before a possible collision and activate automated braking interventions about 1.1 s before a collision [5]. The timing depends on the conflicting situation and the system's tradeoff between timing and the rate of false alarms per time. Obviously, the maximum warning time is reached if the pedestrian stands in the middle of the vehicle's trajectory. However, if a pedestrian is approaching from the right, the warning time is reduced to the point that gives a significant probability that the pedestrian will cross the road. This point is typically defined by kinematic parameters like the lateral speed and the proximity to the vehicle's path.

Recent studies [2] of accident research have shown, that the current series systems address a large number of pedestrian accidents. In the research projects UR:BAN MV [6] and UR:BAN KA [7], further methods have been investigated that show a significant potential to improve the performance of the current state-of-the-art systems. This includes pedestrian intention recognition as well as driver intention recognition.

Pedestrian intention recognition enables the system to improve the prediction of the future position of a pedestrian. While current systems rely on the position and the speed of the pedestrian, it has been shown that humans adopt further information such as the movement behaviour, e. g. the head movement, and contextual information about the scene, e. g. the curvature of the sidewalk or typical destinations of a pedestrian such as a bus stop. Additional sensors and algorithms enable capturing data about the pedestrian and estimating the pedestrian's intention. Different pedestrian models have been developed in the past to predict the future position of a pedestrian. In combination with state-of-the-art vehicle models, a probability that the predicted position of the vehicle and the pedestrian will result in a collision can be estimated. Different kinds of information are used for the pedestrian model. Dynamic models use data about position and velocity of the pedestrian. Approaches that use physiological information about the human body, add constraints based on the human ability of acceleration and changing the direction. Improving sensor systems and classification algorithm provides additional environment information. Therefore, new pedestrian models are based on information about sidewalk and curb position, the existence of obstacles in the pedestrian trajectory and even information about head orientation of the pedestrian. Studies [8] show, that especially the later, is an important indicator used by human drivers to predict the crossing intention of a pedestrian. First experimental results confirm the advantages of including this information in pedestrian models to increase the prediction time, which allows an earlier warning while keeping a constant false alarm rate. As mentioned, these models only include a prediction of the pedestrian behaviour and the vehicle dynamic but no information of the driver state. In correlation with an earlier warning, the probability that the driver will react in time increases. To realise a system with an early warning, information of the driver intention to brake are essential.

Driver intention recognition, which is not redundant to drivers intention, shall include the driver's intention to perform evasive manoeuvres as well as his intention to decelerate in case of recognised objects. This allows the system to prune unnecessary warnings or braking manoeuvres. Additional sensors and algorithms are needed to capture data about the driver and to estimate the driver's intention. The chapter presents an approach how to detect the driver's intention to brake due to a pedestrian.

Fig. 14.1 explains the situation. The need for a warning is calculated when the pedestrian is recognised by the camera system. At the same time the driver intention recognition estimates the driver's intention to brake due to this pedestrian. In case the pedestrian shows intention to enter the road an early warning can be emitted. This allows more comfortable reaction by the driver. In case the driver shows an intention to brake this warning can be delayed until shortly before an automated emergency brake (AEB). Depending on the situation even the emergency brake might be delayed. During the delay the need for a warning is constantly re-calculated and, if the situation does not require a warning anymore, the

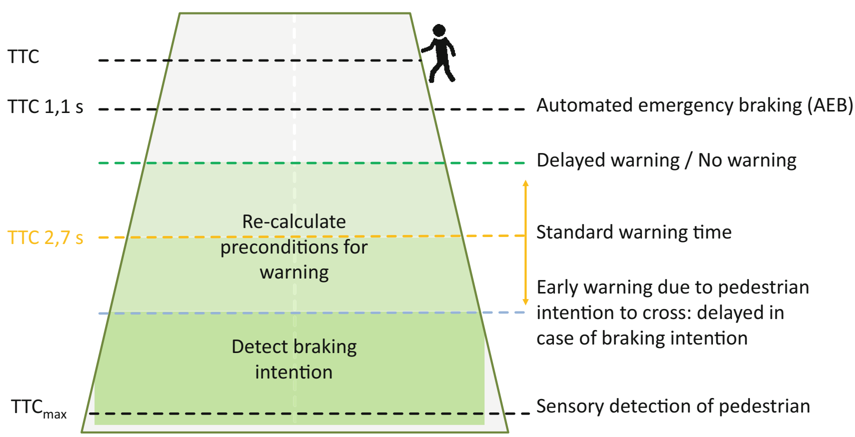

Fig. 14.1 Adaptation of warning time due to pedestrian and driver intention

warning is skipped. Such an adaptive warning increases the number of comfortable timely warnings and decreases the number of unnecessary warnings.

In this chapter we report how a driver intention algorithm has been developed and how it was used to recognise driver's intention to brake due to a pedestrian. The algorithm was first developed in driving simulator experiments and then integrated into a vehicle which possessed a pedestrian collision avoidance system and a pedestrian intention recognition algorithm prototype [9].

14.2 Theoretical Concepts of Intention Recognition and their Measurement Potential

Driver intention is a terminology which needs definition. Existing definitions of intention stress the awareness and planning of an action as part of a cognitive construct. A summary of definitions is provided by Kobiela [10]. Intents have been made to assign intentions only to navigation and manoeuvring tasks [11]; however Kobiela [10] measured driver's intention to override an automated emergency braking which is a stabilization task.

In our case we use the term intention recognition, when we want to express that a future behaviour of a human shall be predicted. We assume that intentions may last for a long while, but they become observable in the individual's behaviour usually at a time shortly (few seconds) before the intended action is carried out.

Beside a commonly accepted definition of the term intention in relation to manoeuvre prediction, the research conducted on the topic of driving manoeuvre intention is also missing a theoretical framework. A model of human behaviour which refers explicitly to intention is the rubicon model [12, 13]. According to this model, intention is created by personal values and goals and by the opportunities to reach these goals. Created intentions are then transferred into a planning phase before actuation carries them out. A control phase finalizes the process. An attempt to apply the rubicon model to observable behaviour related to a driving manoeuvre intention could be like this:

Personal values and goals may be guessed from past actions, habits or personalised settings in a system. Opportunities for certain actions can be measured with machine sensing and interpretation of the scenery. With those preconditions the rubicon model assumes, that a decision to carry out a manoeuvre is taken by the driver. The planning phase includes driver actions, which are aiming for exploration of the situation in order to plan when and how to conduct the action. It also contains preparation for the action, e. g. in terms of bringing hands and feet into a suitable position. Those are observable behaviour and can be measured in order to conclude on intention and predict action. The third phase of the rubicon model describes the actual process to carry out the intended action. In case of driving manoeuvres this action usually is reflected in steering wheel and pedal activity which can be analysed for typical characteristics that precede a manoeuvre in certain situations. The last phase of the rubicon model is controlling the success of an action and may deactivate the intention or stimulate alternative intentions or planning. For driver assistance it may be very helpful to sense unsuccessful manoeuvres in order to offer specific support in such stressful situations.

When it comes to driver intention recognition, the rubicon model provides an adequate fundament, even though it was originally designed to explain intentions and actions at strategic level and it lacks an assumption how intention can be externally observed and measured. As Ajzen stated in 1991 in the context of his theory of planned behaviour, we also assume that for our application, intention can only be detected by observable behaviour. Measuring intentions is only possible by measuring empirical evidence. In the attempt to describe the observable behaviour of the process that leads to carrying out a manoeuvre, Diederichs and Pöhler [14] observed the behaviour of 40 drivers when carrying out three manoeuvres for several times in a driving simulator. Their behaviour was classified in small movements in order to allow a detailed analysis of their observable behaviour, before a driving manoeuvre is actually performed.

This analysis led to the postulation of the "*jordan model*", named after an historical river in honour of the inspiring rubicon model. The jordan model describes the observable behaviour leading to an intention and leading from the intention to a manoeuvre [15] (see Fig. 14.2).

As a precondition for the intention, personal stimulus response characteristics can be observed in the past behaviour of a person. Knowledge about the preconditions of a manoeuvre is needed to assess the possible manoeuvres.

Out of the preconditions and the personal stimulus response characteristics shown in the past, the likelihood for a manoeuvre intention can be calculated which represents the jordan. Unlike the rubicon we do not assume that the jordan is crossed once and no return is possible. We rather see the jordan as a prevalence telling us about the likelihood of a specific action in the future. At the stage of the jordan, however, it is not possible to predict the time until the action is performed.

The next stage of the jordan model considers the observable behaviour, especially behaviour that prepares a specific manoeuvre action and behaviour that is classified as initiating a behaviour. The behaviour classification of the driving simulator study by Diederichs and Pöhler [14] supports on the one hand both stages as individual stages, but on the other hand reveals that both behaviour classes can occur in parallel or in random order [15].

Manoeuvre prediction is actually possible, when action preparing and action initiating behaviour becomes observable. At this point the manoeuvre is immediately to follow and becomes observable by behaviour on the control elements of the car as well as in the analysis of vehicle parameters.

In consideration of the rubicon model, also the jordan model assumes a stage to control the success of the behaviour. Not having empirical data to support this, we assume so far that behaviour control occurs throughout the complete process from intention to manoeuvre execution.

The jordan model is a theoretical model that explains, how driver's intention to carry out specific manoeuvres can be structured and how intentions can be measured by observation of driver's behaviour.

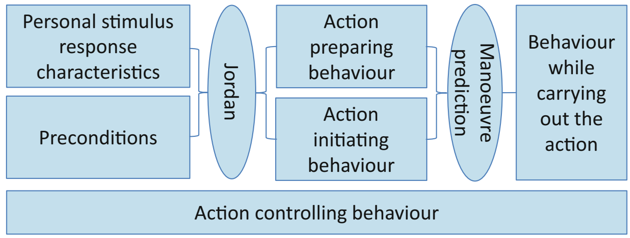

Fig. 14.2 Jordan model for driver intention

The metaphorical name "Jordan" suites the model. The People of Israel had crossed the river jordan and showed observable behaviour which can be allocated to the phases of the jordan model. Personal stimulus response characteristics are given, since the People of Israel had crossed the Red Sea before, hence a likelihood to cross the river jordan could be deduced from the past behaviour. As a precondition for the crossing, the water of the river disappeared allowing for the manoeuvre of crossing and the priests announced their intention to cross to the People in a meeting (action preparing behaviour). Then the priests entered the river bed (action initiating behaviour). At this point the crossing of the People was predictable to happen promptly (manoeuvre prediction). When the People crossed the river, they left twelve stones which can be observed as an empirical evidence of their behaviour.

14.3 Measure Driver Intention to Brake

In order to develop an algorithm for measuring driver intention to brake due to a pedestrian, a sample of data was recorded and analysed for typical events which indicate such an intention [16]. It is assumed that the influence of real world traffic and its complexity on driver behaviour is unpredictably big. Since the algorithm is the very first attempt on this topic, a controlled environment has been selected. A driving simulator provides also further important advantages. Pedestrian collision situations imply no physical risks and possible collisions can be simulated as almost-accidents in order to avoid collision impressions and to minimize mental strain for test participants. Scenarios can be repeated within and in-between test participants. At this point of development, the aim is to identify measurable indicators and to demonstrate a transparent algorithm, hence a driving simulator study is a reasonable starting point.

As shown in Diederichs, Schüttke and Spath [16] the principal indicators to measure driver's intention to brake due to a pedestrian are pedal movement, foot activity, hand activity and visual activity. In the driving simulator we were able to sense the foot activity that was affecting the pedals position. The activity of the hands could not be measured with sensors and the use of such data remains an open research issue. As a characteristic signal for visual activity, we measured gaze direction with the fixed based eye tracking system faceLAB 4.6, which was calibrated for every test participant individually.

Systematic calibration tests before the experiment revealed, that the precision of the setup ranged between 0.5° and 5°, depending on the participant and gaze direction. Hence, for robust data analysis a precision of 5° can be realistically assumed with the available setup. All data and the video images of three driver monitoring cameras were sufficiently synchronised at recording.

In order to record a data base for the development of the algorithm, 38 test participants aged between 23 and 45 years and with at least 5 years of driving experience including 5000 km minimum in the past year were recruited in the data acquisition reported by Diederichs, Schüttke and Spath [16]. The 16 female and 22 male participants were further balanced roughly in driving style. All participants received sufficient training in the driving simulator before the test. Six drivers were excluded from the analysis due to technical problems or simulator sickness.

The simulated scene was set in an urban environment with a 7.3 km driving course. At 50 km/h the trip took approximately 9 min. Several pedestrians inhabited the city, crossing the road sporadically when no data was recorded. Two precisely planned scenarios where fitted into the course which were used to record the data. The scenarios included pedestrians that predictively could enter the ego vehicle's trajectory and would induce a warning followed by automated braking (see Fig. 14.3). Each scenario was repeated three times per participant, separated by similar scenes. This setup results in six measured sections per participant and 192 sections for the overall analysis.

In scenario 1, a pedestrian enters the road in order to pass a parking truck. In scenario 2, a pedestrian walks in a 90° angle towards the road, then stops at the border of the road. Both scenarios were familiar to the test participants. They had passed the sceneries before and had seen several pedestrians crossing or not-crossing the road. This experience made the pedestrian's behaviour unpredictable for the drivers and stimulated a braking intention.

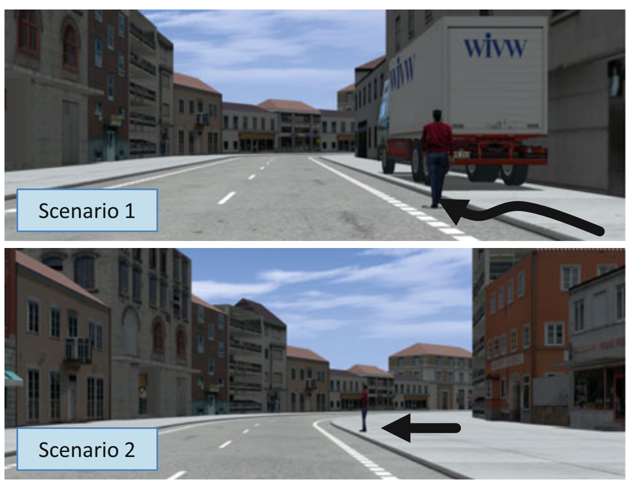

Fig. 14.3 Scenario 1 and 2 to provoke a pedestrian collision avoidance system to warn and to provoke a driver's intention to brake

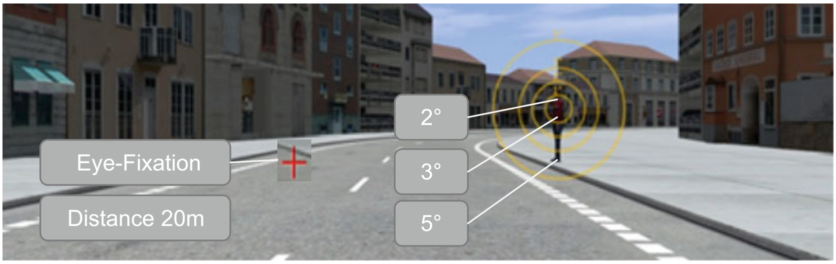

Fig. 14.4 Gaze analysis and dynamic area of interest around the pedestrian

For the eye gaze data a dynamic area of interest (AoI) around the pedestrian was defined. The distance of the actual fixation point to the centre of the pedestrian was measured. In Fig. 14.4 the yellow circle around the pedestrian represents 1°, 2°, 3° and 5° of deviation from the centre point of the pedestrian model.

Typical eye gaze behaviour and pedal behaviour are exemplary shown in Fig. 14.5 in a combined diagram.

The vertical axis on the left side of the diagram indicates the distance between eye fixation and centre of the pedestrian in degree [°]. This distance is represented by the green line. The vertical axis on the right side indicates the position of the pedals with 0 as not applied and 1 as applied to the maximum. The horizontal axis indicates the 10 s before passing the pedestrian.

The exemplary data show how the eye's fixation point drops in the 5° AoI at 7 and 6 s and between 4 and 3 s again. After this, the gas pedal is completely released and a small brake pedal activation is measured. About 1 s before passing the pedestrian the gaze withdraws from the pedestrian towards the centre of the road.

The analysis of all eye gaze data shows that in both scenarios all participants had eye fixations within this 5° AoI in the 10 s before passing the pedestrian. Besides the fact

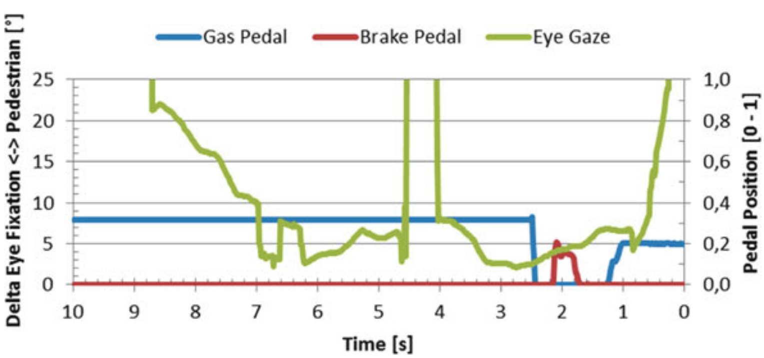

Fig. 14.5 Exemplary gaze and pedal behaviour when approaching a pedestrian

that the pedestrian was presented in the simulation as a very salient stimulus, also the overlapping of the area of interest around the pedestrian and the lane was a major reason for this (see Fig. 14.6).

As the specificity of the eye fixation classification was a weak point in the first data collection, a second simulator study was performed with a detailed focus on the eye fixation [17]. In this data acquisition, 18 drivers (9 male and 9 female, age range 23–43 years old and min 5000 km/last year) participated. A 5.2 km trip was driven with different scenarios. Each scenario included a version with a clearly visible pedestrian intending to cross the road and a version of the same scenario with a fully transparent invisible pedestrian. This methodological approach allowed a comparison of eye gaze when monitoring a pedestrian and when not monitoring it. The scenarios included different criticality of the pedestrian, driving speed at 30 and 60 km/h, and visual distractors.

In scenarios with a highly critical pedestrian on the right side of the road at a driving speed of 60 km/h without other visual distractions, differences in eye gaze behaviour where found. Among other calculations the most promising approach was a comparison of cumulated eye fixation duration on the pedestrian. Fig. 14.7 shows the cumulated fixation times for a scenario with a crossing pedestrian for the 18 participants. The diagrams show how long and how often random fixations towards the transparent invisible pedestrian occurred while the vehicle approached the pedestrian in comparison with fixations towards the visible pedestrian.

The visible pedestrian is fixated for longer times and fixations lasted until the pedestrian had crossed the road at a distance of 40 to 10 m. Most drivers also slowed down the speed of the vehicle (curves go up). The invisible pedestrian is fixated for shorter times and most of those fixations happen at a distance of 130 to 70 m distance to the pedestrian. At this distance the area of interest around the pedestrian is overlapping very much with the road. A reasonable approach for distinguishing an intentional monitoring of a pedestrian and an unconscious gaze in the same direction is hence an analysis of the cumulated fixation time.

With respect to the analysis of the pedal activity Diederichs, Schüttke and Spath [16] identified five typical categories in the data of 32 test participants, while approaching a pedestrian in two different scenarios (see Fig. 14.3), each repeated three times. The categories are explained in Table 14.1.

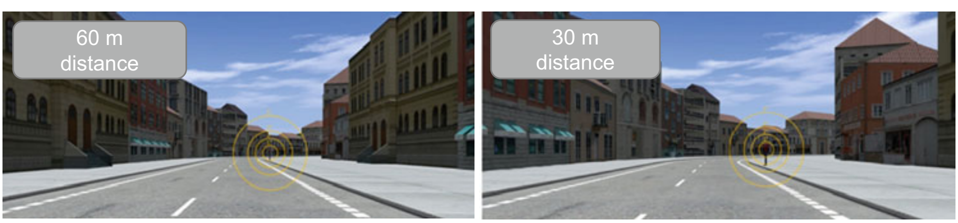

Fig. 14.6 Overlapping of dynamic area of interest and ego lane at 60 and 30 m distance

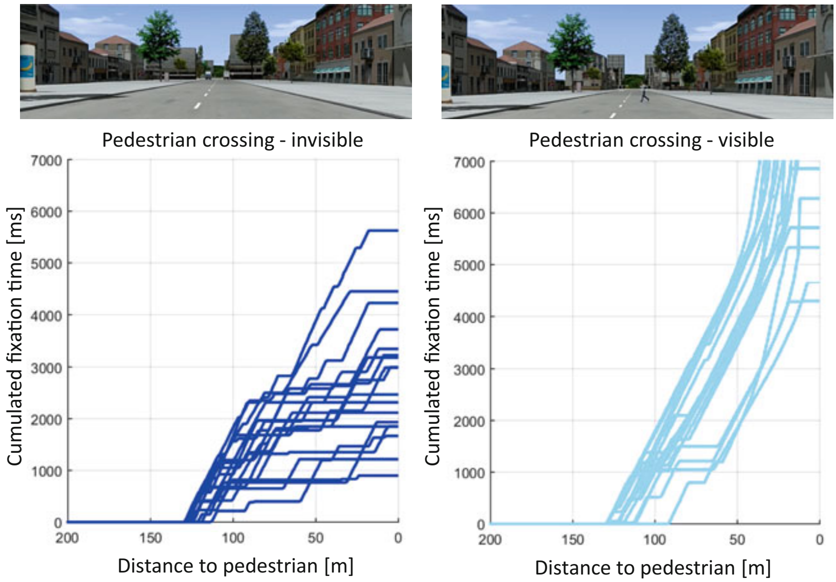

Fig. 14.7 Cumulated fixation time of pedestrians crossing *from left to right* for all participants

Scenario 1 with a pedestrian on the road passing a parking truck stimulates in 54 out of 95 pedestrian encounters a pedal reaction, which is attributed to braking intention. In scenario 2 with a pedestrian approaching the road from the right this was true for 71 out of 95 pedestrian encounters. Together, in 125 out of 190 cases and thus in 66% of the encounters, a pedal reaction indicating braking intention was recognised.

In a further analysis, the eye fixation and the pedal reaction showed a causal relation. A pedal reaction which indicated braking intention is almost always preceded by an eye fixation. The time between a pedal reaction and the last eye fixation varies between 0.4 to

Table 14.1 Pedal activity classification

Category	Description	Conclusion
Gas increased	Increasing gas pedal (throttle) in order to accelerate	Indicator for no brake intention
No changes	No abrupt changes in pedal activity at all	Indicator for no brake intention
Gas reduced	Driver releases the gas pedal abruptly but not totally	Indicator for brake intention
Gas to 0	Driver releases the gas pedal totally, or gas pedal is and remains in position 0	Indicator for brake intention
Braking	Driver presses the brake pedal	Indicator for brake intention

2.4 s, with only four outliers in the available set of data. Hence, pedal reactions below 0.4 s and above 2.4 s should not be attributed as a causal consequence of a pedestrian fixation. A pedal reaction as consequence of an eye fixation was detected in 121 out of 190 cases which equals a rate of 64% of observable braking intentions.

The reference method by Diederichs and Pöhler [14] was applied on the set of data and detected in 111 out of 190 cases a braking intention based on the judgement of a trained observer. A pairwise comparison matched in 94% with the causal relationship.

Based on the theoretical assumptions of the jordan model and the empirical results from the experiments a rule based algorithm to detect intention to brake is deduced. The preconditions for this algorithm are:

- A pedestrian is detected by the vehicle sensors.
- The pedestrian is classified as critical to enter the ego vehicle's trajectory.

If these preconditions are fulfilled, the following indicators reveal the driver's intention to brake:

- The pedestrian is monitored with a cumulated fixation time above a given threshold.
- One of the following pedal movements occurs within 0.4 to 2.4 s after the fixation: "braking", "gas to 0", or "gas reduced".

Fig. 14.8 shows the algorithm. In case of an intention to brake the warning can be adjusted as displayed in Fig. 14.1.

The algorithm and the parameter values are based on data recorded in a highly controlled driving simulator environment and the test participants were a homogenous group of middle aged male and female drivers. Higher variance is to be expected in real world driving and by unexperienced and by older drivers. In order to test the capability and applicability of the algorithm and sensors in a real vehicle, we implemented it into a prototype vehicle with a pedestrian detection system and pedestrian intention recognition algorithm.

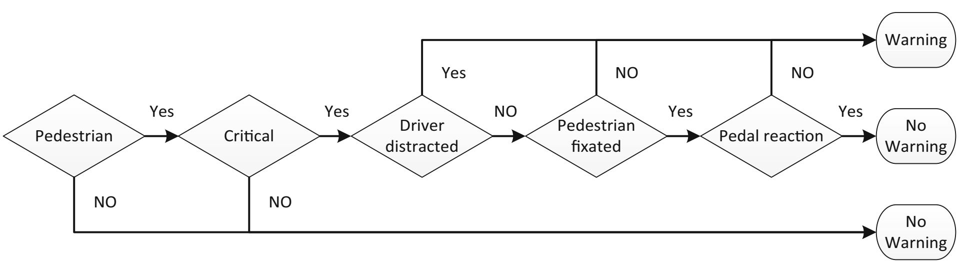

Fig. 14.8 Algorithm to determine driver's intention to brake

14.4 Application and Demonstration for Pedestrian Collision Avoidance System in the Vehicle

The algorithm for recognizing whether the driver is showing an intention to brake due to a pedestrian was implemented in an experimental vehicle equipped with a pedestrian recognition system and pedestrian intention recognition algorithm. Fig. 14.9 shows the vehicle setup. The visualisation screen shows the recognition results in pictograms. A standing pedestrian symbolises that the pedestrian detection was successful. The crossing pedestrian pictogram indicates whether a pedestrian intention to cross the road is estimated. The standing pedestrian with an eye symbol on top indicates whether a driver intention to brake due to the pedestrian is estimated. An eye tracking device was mounted behind the steering wheel and two cameras for pedestrian recognition and pedestrian intention estimation were mounted behind the rear view mirror.

Pedestrian intention recognition enables the system to improve the prediction of the future position of a pedestrian. As introduced by Rehder et al. [18], an algorithm for estimating the pedestrian's head orientation allows a better estimation of pedestrian intention to cross the road. This requires a sensor setup which goes beyond state-of-the-art sensors. For pedestrian's head orientation estimation, a sufficient number of pixels is required at any relevant distance. This can be illustrated by the following calculation: If an algorithm for head orientation estimation needs a minimum resolution of 25×25 pixels for a true size of 25×25 cm and if this condition is valid for a horizontal opening angle of the camera of 40° and a distance of up to 55 m, then the camera imager needs a horizontal resolution of about 4000 pixels (corresponding typically to $4000 \times 3000 = 12$ MPx imager).

The driver's intention to brake was measured with a state-of-the-art bar type eye tracking device, which was implemented above the steering wheel at an approximate distance

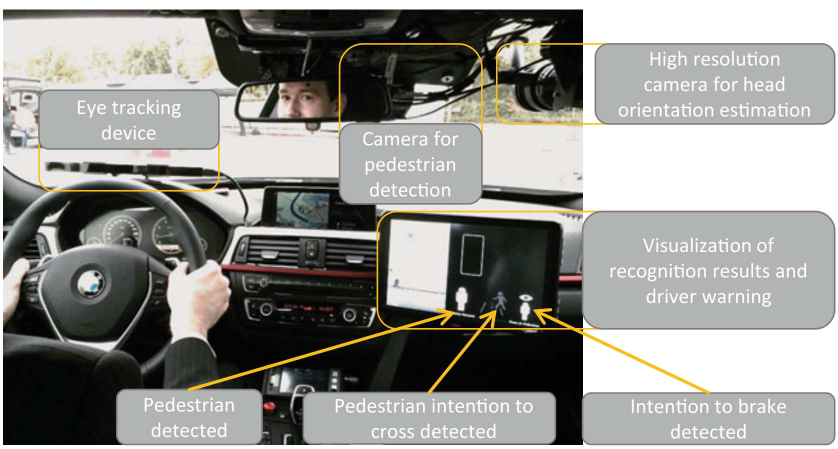

Fig. 14.9 System setup in vehicle prototype

of 70 cm from the driver's eyes. The tracking device was mounted on a flexible rack which allowed tilting around the longitudinal axis in order to adapt to different drivers.

Both the pedestrian recognition system and the eye tracker operate independently of each other, thus operating in different coordinate systems. The eye tracker, being a device which was originally built for screen-mounted operation, gave access to an x-y screen coordinate system. Eye tracking coordinates and the data received from the pedestrian recognition system (coordinates, size and pedestrian ID) were constantly queued in the implementation together with brake and gas pedal data. This allowed a dynamic area of interest following the pedestrian in real time. A sliding window approach is then applied to the queue, checking for correlations between eye coordinates and pedestrian coordinates, and additionally for relevant changes in the pedal data.

The setup of the experimental vehicle differs from the simulator setup regarding both the accuracy of eye movement and pedestrian detection, and the distance in which a pedestrian can be detected. In the real world setup the eye tracking accuracy was lower and data was not available at all times. The pedestrian recognition was available with varying likelihood for detection and available with short interruptions from around 50 m distance to the pedestrian. Thus, the specific parameter values obtained in the simulator were updated by in-situ experiments, while following the algorithm displayed in Fig. 14.8. The parameters of the algorithm can be categorized into two sets: Timing parameters and calibration parameters.

The calibration parameters are responsible for the coordinate transformation between the eye coordinates and the pedestrian coordinates. As the transformation depends on the position of the driver's head, they need to be recalculated for different drivers/driving positions. In a more sophisticated environment with a head position detection, this calibration step would not be necessary, as the different coordinate systems can be transformed into each other mathematically. A custom tool was used to determine the required parameters from a calibration setup, where the driver followed a pedestrian moving along a predetermined route in front of the standing car. Fig. 14.10 shows the horizontal correlation between a detected pedestrian and the eye movement of the driver. The first column shows the eye coordinate and the second shows the position of the pedestrian. As the quality of the pedestrian detection varies depending on current real-world conditions, an additional parameter allows accumulating the required fixation time instead of requiring a steady fixation over a certain period of time. This allows detecting a correlation even when the pedestrian detection is not steady.

The timing parameters determine the sliding window and thus directly influence when an intention to brake is recognised. For the eye-tracking based detection, the parameters determine the minimum cumulated time for which the pedestrian must have been fixated, and a window of time before a pedal reaction, during which this fixation must have occurred. For the pedal reaction, a threshold of reduction (gas) or increase (brake) can be set, which must be reached by a time inside a specific time window after the fixation.

The system test was performed on a test area with no other traffic participants. According to accident statistics and EuroNCAP tests [4], the test scenario consisted of a pedes-

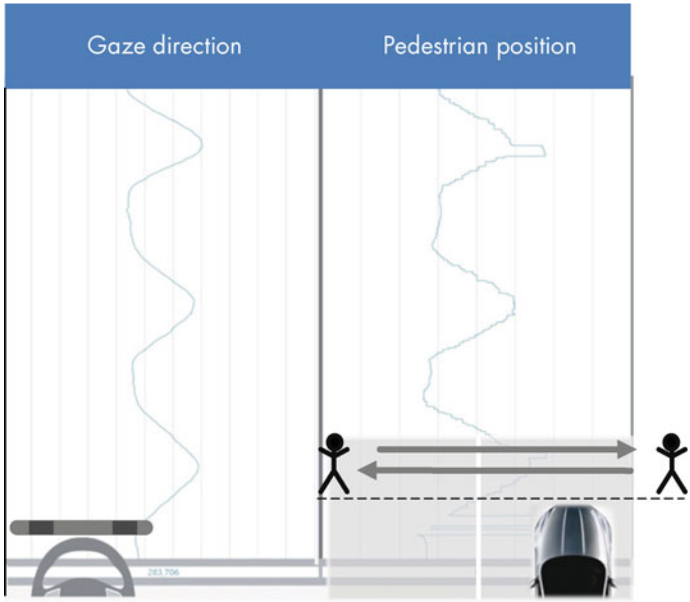

Fig. 14.10 Correlation of gaze direction and pedestrian position

trian coming from the right and crossing in front of the car (Fig. 14.11). This scenario had already been used in the driving simulator study (Fig. 14.7). The pedestrian was instructed to walk with normal speed, while the car approached at 20 km/h. The pedestrian enters the driving corridor in 10 m distance to the car, so that a car driver could stop the car with a hard braking in front of the pedestrian with a safety distance of 3–5 m. Soft deceleration allows the vehicle to pass behind the crossing pedestrian without a full stop. The pedestrian head orientation was detected by the high resolution camera and the pedestrian's intention to cross the road was estimated by the pedestrian intention detection algorithm.

In Fig. 14.12 two different versions of the scenario are shown. In the first case (top row), the driver is looking straight, while the pedestrian is moving towards the road without looking at the vehicle. Then, the warning algorithm detects that the pedestrian wants to cross and is not fixating the car by estimating the head orientation. Then the driver looks to the pedestrian. Before the warning algorithm warns the driver, the algorithm for detecting driver's intention to brake, recognises a braking intention and the warning is not activated, since the driver's focus is already on the pedestrian and a braking intention is classified.

In the second case (bottom row), the driver is again looking straight on the road and the pedestrian starts to cross without looking at the vehicle. The warning algorithm detects the pedestrian's intention to cross. In contrast to the first scenario the eye gaze of the driver stays straight on the road and not oriented to the pedestrian. The driver intention algorithm detects no braking intention, because the driver is not fixating the pedestrian and the warning algorithm warns the driver.

Fig. 14.11 Pedestrian Head Orientation Estimation to detect the pedestrian's intention to cross for earlier warning system

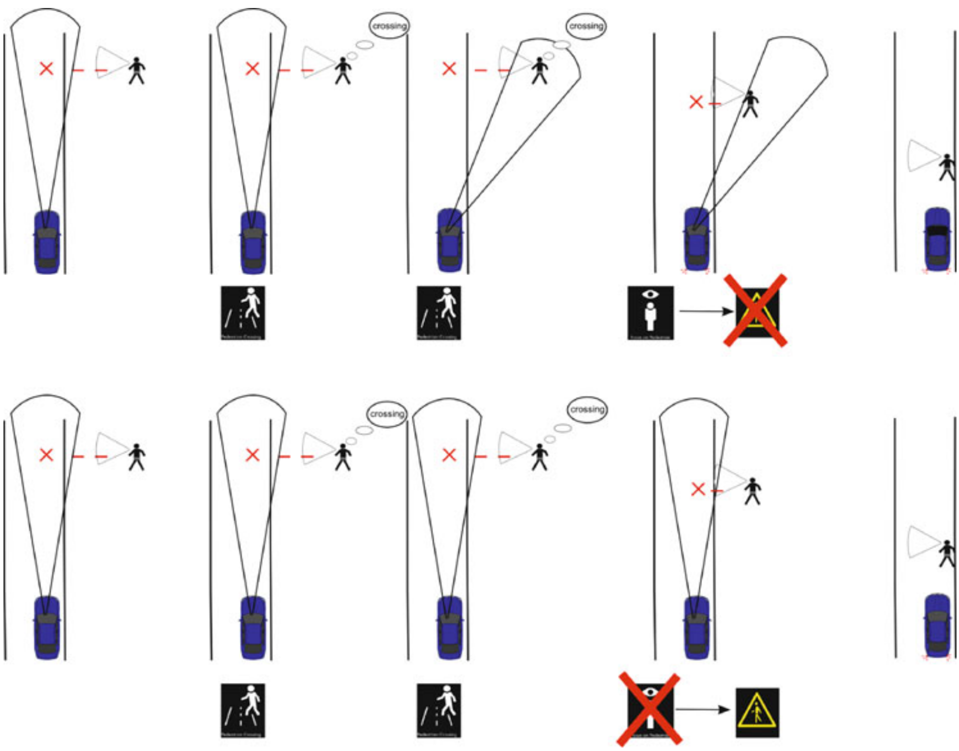

Fig. 14.12 Test cases for the algorithm to detect if the driver will brake

According to these scenarios the requirements of a warning are:

- The time to collision is below 2 s (time to collision is defined as relative car-pedestrian distance/relative car-pedestrian velocity).
- Pedestrian intention to enter the road without being aware of the vehicle detected: Specifically the pedestrian is not fixating the oncoming car for more than 0.5 s meaning that no intention of the pedestrian to stop is detected OR the pedestrian is already inside the driving corridor.
- No driver intention to brake detected: Specifically the pedestrian was not fixated by the driver for longer than a certain timespan AND no pedal reaction which indicated a braking intention was measured.

For safety reasons, certain constraint has to be made in the execution of the real world testing: Pedestrians and the driver of the test vehicle were fully instructed and trained. The driver was instructed to look either into the direction of the pedestrian or straight on the road, acting a braking intention or not in the respective test cases.

Under these conditions the driver intention recognition algorithm was able to distinguish between the driver looking into the direction of the pedestrian and the driver focusing on the road. It was successfully combined with the earlier warning algorithm for pedestrian intention and reduced "false" alarms in cases, where the driver was already looking in the direction of the pedestrian. For safety reasons, the test scenario only permitted instructed drivers. For further experiments a safe setup needs to be identified allowing pedestrian head orientation estimation as well as non-instructed drivers. This will allow identifying an improved set of parameters.

14.5 Outlook: Acceptance and Safety

The road design in urban areas with close coexistence of vehicles and vulnerable road users results in many situations which would justify a warning to the driver, especially if the warning algorithm is assessing the situation only based on the position and potential trajectory of the pedestrian. Early warnings may allow for safer and more comfortable reactions but also may increase the frequency of inappropriate or unnecessary warnings due to higher prediction uncertainty when triggered. Drivers probably would adapt to such frequent warnings with increased disregard or switch off the function. In order to warn as early as possible while keeping the amount of warnings at an effective and acceptable frequency, estimated pedestrian's intention to enter the road can be considered as a promising criterion as well as driver's intention to brake. In combination they allow for an efficient classifier used to trigger early warnings at acceptable frequencies only in situations that are likely to require preventive action, while avoiding warnings in situations, where the pedestrian would not enter the road or when the driver is ready to react already. This approach increases the driver acceptance and the compliance to react to a warning, and consequently increases safety.

Adaptive warnings can however also decrease system transparency. Excessive adaptation may contribute to confusion, distraction and decreased trust in function. For this reason a thorough balance between easy predictability on one side and situation-dependent benefit optimisation on the other side is crucial for an effective design of an adaptive system. HMI (human machine interface) plays an important role to maintain system transparency at a decent workload price, fostering attention when needed while keeping unneeded system output forgivable in the meantime. Combining intention detection with a suitable HMI would probably increase safety and avoid collisions more often than systems which are not adaptive.

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Part V

Simulation and Modelling of Road Users' Behaviour

Simulation and Modelling Within the UR:BAN Project

15

Silja Hoffmann and Fritz Busch

Urban Traffic is characterised by many interactions between different types of road users. All the applications that were developed within the UR:BAN project were developed with the aim of improving complex urban traffic situations. New driver assistance systems and intelligent transport systems influence the behaviour of their users as well as create new requirements for the models to simulate them. These applications and situations could not be handled anymore by conventional traffic and driving simulations.

Therefore, this sub-project Simulation (SIM) focuses on the analysis and descriptive modelling of the behaviour of individual road users and their interactions with one another. This is done in consideration of newly developed driver assistance systems and intelligent transportation systems. The objective of the sub-project is to improve and extend driving simulators and microscopic traffic simulation in order to simulate and study the resulting behaviour of the road users in a more realistic way.

The driver-vehicle-environment system is investigated in detail using three different research environments:

- controlled test sites,
- driving simulators,
- and microscopic traffic simulations.

At the controlled test site the interactions between various road users is observed and investigated. Behaviour data from real traffic situations is collected and interpreted to better understand interactions between drivers and crossing pedestrians. In a second phase, traffic observations of interactions between motor vehicles and bicyclists are used to analyse behaviour models.

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Connected driving simulators offer a new method for analyzing the interactions between road users in traffic. This method enables multiple test subjects (at least two) to move simultaneously in a virtual traffic scenario. In this way, the interactions between the road users are no longer modelled but rather "humanized". Detailed investigations of the following interactions are carried out within SIM: car-pedestrian, car-motorcycle, car-car, car-truck and platoons of cars.

In the area of microscopic traffic simulation, improved models of bicyclists and pedestrians as well as their interactions are developed. These models will make it possible to assess the impact of driver assistance systems and intelligent transportation systems in large and complex scenarios.

The following chapters within the simulation section of this book represent different areas of simulation and modeling. It begins with the observation of user behaviour at **controlled testsites**, then the modeling of user behaviour in **traffic simulations** is described. Finally, detailed studies using different connected driving simulations lead to general methodological considerations in building connected simulators.

In Chap. 16, insights on **pedestrian-vehicle interactions** are given based on three different methodical approaches. The conducted studies focus on the pedestrian crossing intention in situations with an approaching vehicle. Pedestrian interactions with car drivers were observed under real traffic conditions with sensor-equipped vehicles and in a controlled environment where the behaviour of the driver was systematically varied. The results serve as an important input for the interaction detection and the behaviour modelling during crossing scenarios.

Bicycle traffic continuously increases and becomes a very important aspect for the development of intelligent transport systems. Chap. 17 describes the observation of a busy traffic intersection in Braunschweig to investigate interaction patterns between **bicyclists and motorists**. As a result, the knowledge may be used to implement strategies and technologies for the prevention of fatal crashes.

The improvement of microscopic traffic simulation tools for a more realistic **simulation of bicycle traffic** is shown in Chap. 18. An integrated approach for modelling the tactical and operation behaviour of bicycles at urban intersections is presented. The integrated model was validated in a microscopic traffic simulation environment using the observed trajectory data from 5000 bicyclists.

Chap. 19 focuses on connecting a **driving simulator with real pedestrians**. A car driver in a driving simulator encounters a pedestrian in a second simulator, allowing them to meet and interact in the same simulated environment.

The influence of assisted drivers on non-equipped drivers can be studied using **multi-driver simulators**. In Chap. 20, a multi-driver simulator study is described where two naïve non-equipped drivers followed a driver equipped with a traffic light assistance system. The study shows the need for system developers and researchers to take effects on non-equipped drivers into account for the development and evaluation of ITS.

Another study based on a **multi-driver simulation** which consists of several driving stations that are used by the participants to drive through the same virtual and controlled environment is described in Chap. 21. Using empirical data this chapter shows the additional value of the multi-driver simulation compared to the traditional simulations.

A new approach for investigating motorized two wheelers' interactions with passenger car drivers is illustrated in Chap. 22. Within the project UR:BAN, a **Motorcycle-Car Multi Driver Simulator** was developed that enables a motorcyclist and a car driver to interact in the same virtual environment. This allows deeper insights into interactions and mutual behaviour adaptation. The simulator set up will be described and advantages, potential use cases and challenges of the new tool are addressed.

Chap. 23 summarizes insights on **study methodology** that are needed for connected driving simulators to investigate social interactions in virtual study environments. Within the UR:BAN project, several studies were conducted using a variety of connected driving simulations: A connected driver-driver simulation, a connected multi-driver simulation including four participants, a connected driver-pedestrian-simulation and a connected driver-motorcyclist simulation were used. This chapter summarizes the most important methodological conclusions concerning study design, study conduction and data analysis.

Methodology and Results for the Investigation of Interactions Between Pedestrians and Vehicles in Real and Controlled Traffic Conditions

16

Jens Kotte and Andreas Pütz

16.1 Research Questions and Overall Methodology

One of the goals of the UR:BAN subproject SIM was the development and parameterization of motion models for vulnerable road users. As one part of this goal the interaction between vehicle drivers and pedestrians was investigated in scenarios where a pedestrian intends to cross the driving path of an approaching vehicle. The main research question of this chapter can therefore be summarized to:

In which conditions does a pedestrian cross the driving path of an approaching vehicle and in which cases will the pedestrian let the vehicle pass by first?

The results of this research question are used to model the pedestrian behaviour in the described interaction situation with different purposes: During the development of driver assistance functions that support the driver in critical situations with pedestrians a deeper understanding and precise motion models on the common behaviour of the interaction partners can help to avoid misinterpretation of specific situations [1] and may therefore e. g. reduce the number of warnings or interventions of the technical assistance system that are perceived as unnecessary by the driver. In addition, test scenarios can be designed more realistically by rebuilding critical situations that were recorded during the data collection and by implementing the modelled behaviour into the motion trajectories of pedestrian dummies that can be used for critical test scenarios. A second purpose is the parameterization of motion models for the virtual simulation of interaction events, e. g. for traffic simulation tools. To that end, distributions of crossing decisions depending on different boundary conditions are important to incorporate realistic interaction behaviour

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into simulation tools. Hence, the previously mentioned research question is broken down into pedestrian and driver related research questions:

Pedestrian related research questions:

1) Which situational variables have an influence on the crossing decision of the pedestrian?
2) Which differences can be seen for directed and undirected crossing events?
3) How does the interaction depend on the vehicle type (passenger car and truck)?

Driver related research questions:

1) How does the driver reaction differ between directed (e. g. at crossing aids) and undirected crossing events?

Similar work on the pedestrian decision to cross the path of an approaching vehicle has also been carried out with other empirical approaches (see [2–5]). The underlying assumption of the discussed research questions is that the crossing decision of the pedestrian is based on the necessary deceleration of the approaching vehicle to avoid a critical situation. An associated evaluation parameter is the Deceleration to Safety Time (DST) which is described in [6].

To answer the research questions three different approaches for data collection were chosen, compare Fig. 16.1. In a first clinical study, described in Sect. 16.2, subjects drove

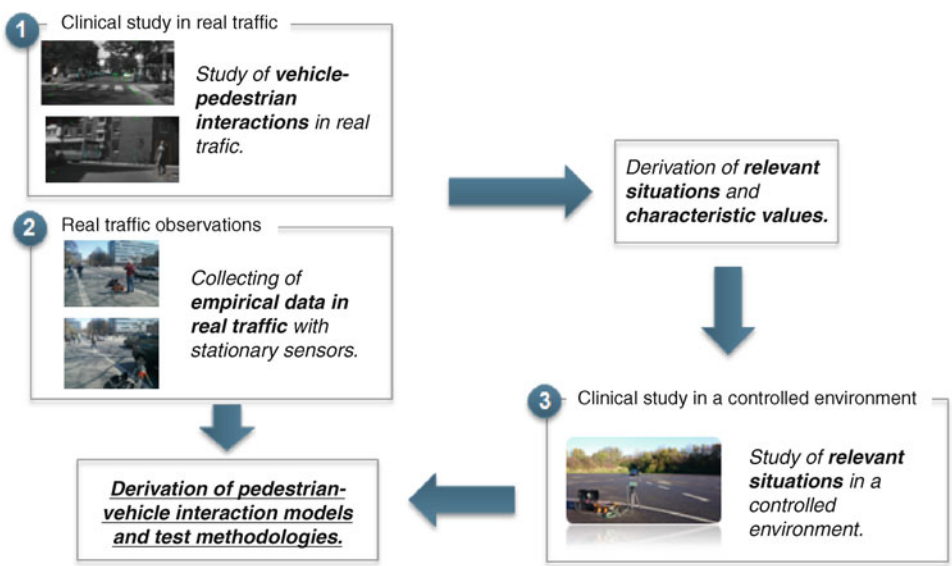


Fig. 16.1 Overall methodology

an equipped vehicle in real traffic conditions without knowing the actual object of study on a route which is highly frequented by pedestrians. In a second experiment, real traffic observations were conducted at different locations with stationary sensors, see Sect. 16.3. The results of both experiments were used to derive relevant situations and values for the third data collection. The third experiment was again a clinical study, but this time in a controlled test field to investigate relevant situations in controlled test conditions (see Sect. 16.4). Finally, all results are used to derive interaction models and test methodologies for the considered scenarios and to answer the initially formulated research questions.

16.2 Interaction Study Under Real Traffic Conditions

The conducted clinical interaction study under real traffic conditions aimed to improve the description of the movement behaviour of the pedestrians. In addition, it serves as reference data of the natural interaction between pedestrians and vehicle drivers for the evaluation of driver assistance systems for the protection of vulnerable road users. Hence, the study did not only focus on the pedestrians in interaction situations, but considered also the driver reaction in these situations. The chosen experimental setup enabled to record interaction scenarios in which both interaction partners did not know that their mutual behaviour was the actual object of study. The evaluated data provides therefore a high external validity and may serve for the parameterization of simulation models as well as driver assistance functions that incorporate the prediction of pedestrian movements.

16.2.1 Methodology

Central scenario of the interaction investigation was the crossing of pedestrians in situations of approaching vehicles and the noticeable crossing intention of the pedestrian. As situational variables the existence of crossing aids, such as zebra crossing or crosswalks were considered subdividing observed interactions into directed crossing (with crossing aids) and undirected crossing (also called j-walking in the US). To be able to investigate interaction scenarios as uninfluenced as possible and to consider also the driver reactions at the same time the study was designed to be conducted in real traffic conditions and with naïve test subjects as vehicle drivers.

30 test subjects drove the test vehicle (see Fig. 16.2) which was equipped with different sensors to record the vehicle surrounding as well as the driver reaction and input. For the environment detection an image processing system was used to detect pedestrians in the driving environment. A short-range radar system served as additional information resource for environment objects such as other vehicles. In addition, cameras were integrated in the rear side and back windows to widen the observable vehicle surrounding and to facilitate the interpretation of situations in which the pedestrians decided to cross behind the vehicle (and therefore outside of the detection field of the image processing and radar systems).

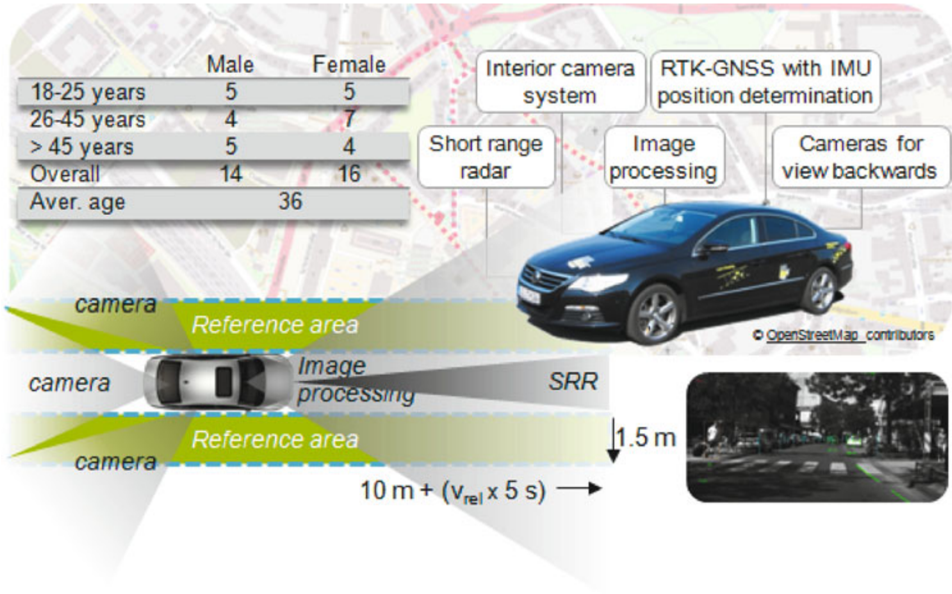


Fig. 16.2 Methodology Study 1

Driver reactions (steering or pedal input) during interaction events were recorded at the CAN-interface supported by an interior camera system whereby driver distraction could be considered. To allow a context based interpretation of the data a RTK-GNSS position determination was used which allowed combining recorded data with additional information from a digital map.

The driver collective consisted of 16 female and 14 male participants with an average age of 36 years and was subdivided into different age groups to assure a representative test sample (see Fig. 16.2). To avoid behavioural adaptations the test subjects were not informed about the real study case, but were told to participate in a study on the effects of repeating driving context on driver fatigue. Drivers were asked to drive on the predefined route as they would usually do and to verbally annotate specific events that they perceived as critical (without mentioning pedestrian interaction events). After approximately 30 min the test drive was paused for 5 min motivated to the test subjects with a second questionnaire on the driver's fatigue state and the necessary data transmission. Afterwards, the test drive was continued as before. All drivers were monetarily rewarded for their participation to attract not only drivers who enjoy driving. Nevertheless, the subjective self-reflection that was combined with the first questionnaire revealed that most drivers are well trained and enjoy driving which has to be considered in the interpretation of the results.

A driving route in the inner-city area of Aachen was defined that guaranteed a high frequency of interactions with pedestrians due to the vicinity to the university and the good weather during the data collection. The driving route had a length of 1.4 km which was repeatedly driven by the test subjects for approximately 60 min. Due to this repetition of the driving route influences of different local knowledge between the test subjects could be mainly avoided since drivers that were unfamiliar with the driving route could get used to the local circumstances. Additionally, the number of comparable situations could be increased by the repetition. In total, in 30 h a distance of ca. 600 km was driven. The route incorporated five intersections with traffic lights, ten (smaller) junctions without traffic lights, three crosswalks and two zebra crossings. Approximately 50% of the route was unidirectional which allowed a simple and fast overview on approaching vehicles for the pedestrians and avoided uncertainty about the relevant case vehicle for the decision of the pedestrians. These boundary conditions led to various undirected pedestrian crossing events in these areas.

16.2.2 Results

During the data collection about 5000 pedestrians were detected in the defined reference area of the image processing sensor detection field (compare Fig. 16.2) of which ca. 1900 events were classified as interactions between pedestrians and the vehicle. An event was classified as interaction event if the pedestrian was detected in the reference area and intended to cross the driving path of the vehicle. The crossing intention was evaluated based on the occurrence of an actual crossing event either in front or behind the test vehicle. Due to the sensor setup of the test vehicle and the fact that all considered pedestrians had to be detected in the reference area approx. 90% of the detected pedestrians crossed the vehicle path in front of the vehicle. Most of the detected interaction events (ca. 68%) were undirected crossing scenarios, 12% took place at crossing aids and 20% at traffic lights. The latter are not considered in the following. Sample sizes for the hereafter presented results may differ from these numbers (percentages) due to specific filter criteria for the evaluated aspect (e. g. that pedestrians had to be continuously tracked from the left to the right reference area, see. Fig. 16.2).

The following description of results differentiates between directed and undirected driving. As a first step descriptive parameters for the pedestrian and driver behaviour as well as their mutual interaction behaviour are evaluated. These parameters are afterwards used in the modelling of the crossing behaviour.

Motion Behaviour of the Pedestrian

For the description of the motion behaviour of the pedestrians Fig. 16.3 shows the distribution of the crossing velocity. It has been evaluated as the mean value of the velocity component orthogonal to the direction of the vehicle motion while being in the driving path. Hence, the figure shows the average crossing velocity of the pedestrian while being in the conflict zone. The velocity is in the range between 1 and 2 m/s and therefore comparable to crossing velocities as they can be commonly found in literature, e. g. [4, 7]. For both, the directed and the undirected crossing the median is approx. 1.5 m/s.

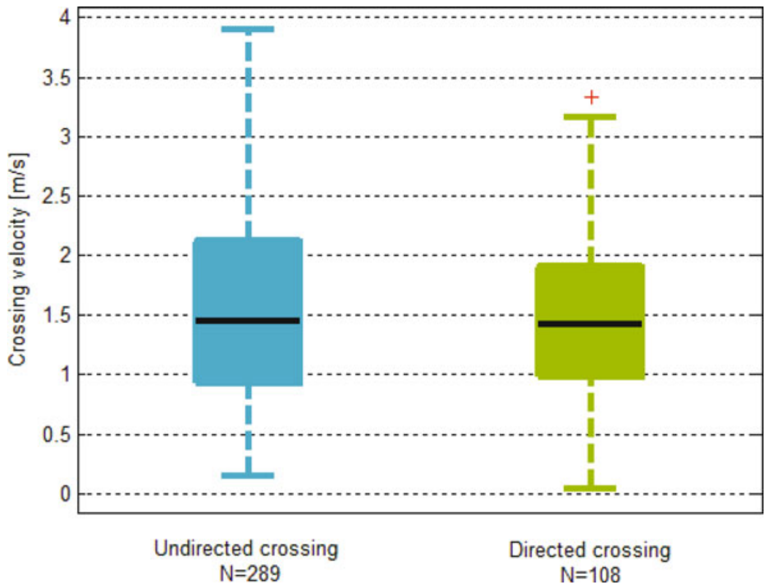


Fig. 16.3 Distribution of average crossing velocity during crossing events

Driver Behaviour

An interesting parameter for the evaluation of the driver behaviour during the interaction with crossing intended pedestrians is the longitudinal acceleration. To that end, the maximum decelerations during the interaction process can be seen in Fig. 16.4. In addition to generally applied filter criteria, only those interaction events are considered in which the pedestrian required the highest deceleration in comparison to other objects within the vehicle's driving path. In doing so, it can be assured that the pedestrian was the reason for the driver's reaction to decelerate and not any object further away (e. g. a pedestrian crossing behind the last vehicle of congestion).

In comparison, slightly higher decelerations were observed for the directed crossing which was expected since the pedestrian have the right of way at zebra crossing. On average, the measured decelerations are between 0.5 and 1 m/s^2 for the undirected crossing. All registered decelerations are within the range of comfort decelerations according to [8].

Interaction Behaviour

A parameter for the description of the interaction behaviour is the Post Encroachment Time (PET) since it consists of the motion behaviour of both interaction partners. The PET was evaluated based on the path driven by the test vehicle. Since the point in time of the pedestrian leaving the driving path could not be determined for all interaction events, the sample size is reduced in comparison with the previous results. PET values below one second, which are an indicator for critical situations (see [9]), were registered quite

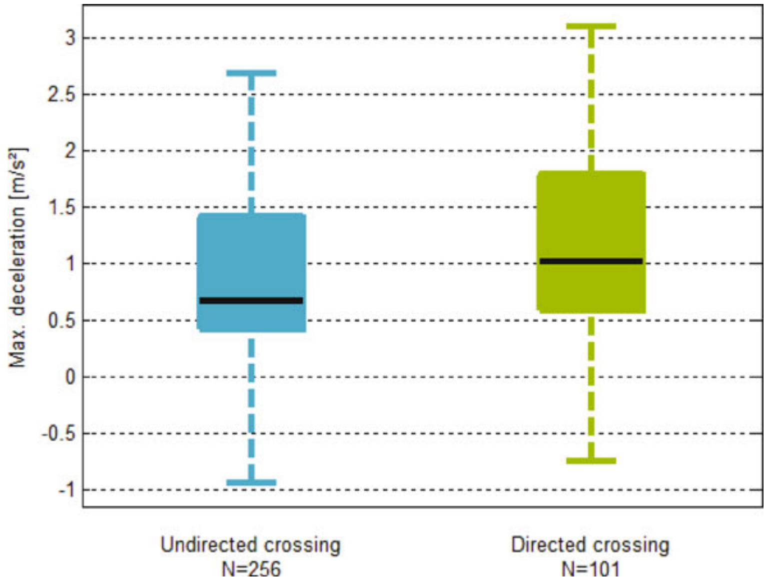


Fig. 16.4 Distribution of maximum deceleration by driver (positive: deceleration, negative: acceleration)

rarely and only for the undirected crossing. In general, the mean values for directed and undirected crossing lie close to three seconds with the mean value of the directed crossing being slightly lower than the one of the undirected. Notice that the sample size in Fig. 16.5 is relatively low in comparison to the overall number of interaction events. This is due to the fact that the pedestrian had to be continuously tracked from the reference area on the one side of the vehicle to the reference area on the other side.

Determination of Crossing Frequency

In addition to the descriptive evaluation of the interaction behaviour of the pedestrians and the vehicle drivers the dependency of the crossing frequency on the interaction parameters is determined. Based on this dependency the crossing probability will be modelled afterwards. To that end, the so-called Deceleration to Safety Time (DST) was calculated for all interactions. This parameter describes the necessary deceleration to implement a specific safety buffer (time) between leaving the conflict zone by the first interaction partner and entering the conflict zone by the second partner. In the following, the DST is calculated for the vehicle driver according to the assumption that the pedestrian takes the crossing decision based on the related influence for the approaching vehicle. For the determination of the DST the previously assessed crossing velocity (compare Fig. 16.3) is assumed to be constant at 1.5 m/s. The distance to be covered by the pedestrian to leave the conflict zone was calculated as the shortest distance from the current position of the pedestrian to the exit point of the conflict zone due to the actually driven vehicle path. The previously as-

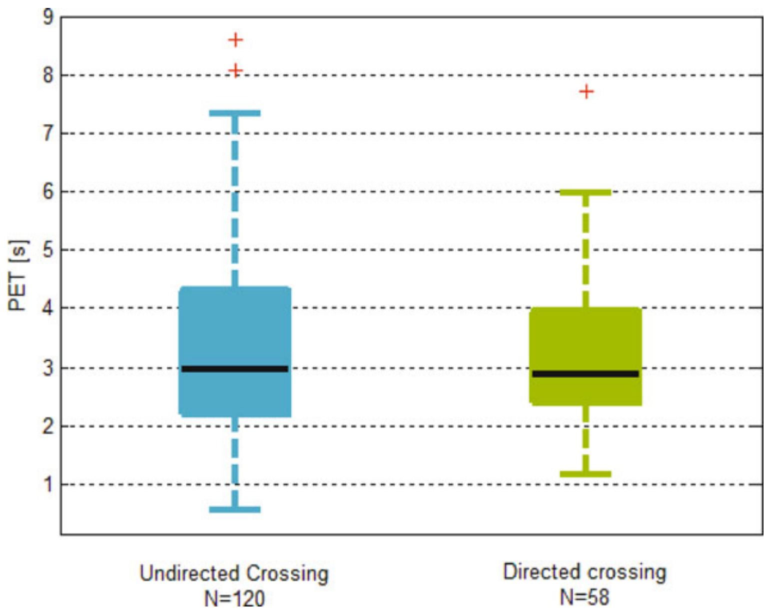


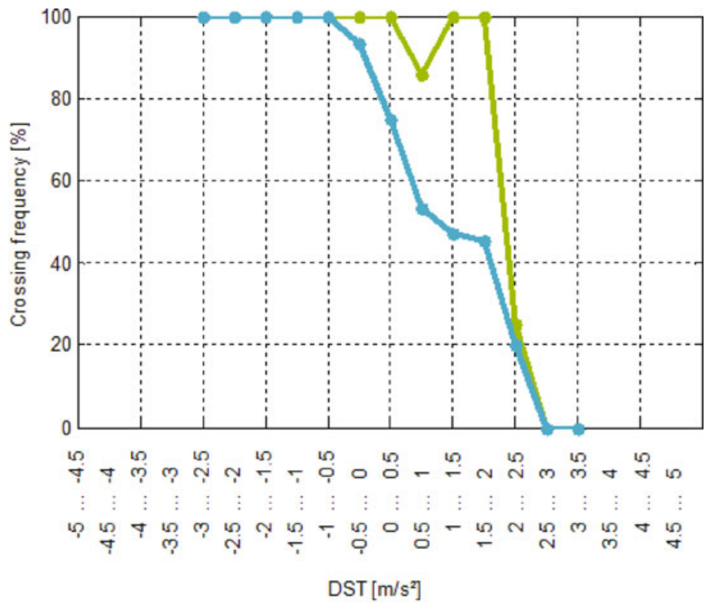
Fig. 16.5 Distribution of Post Encroachment Time (PET) during crossing events

sessed PET of three seconds was used as safety time. Due to the underlying assumptions the previously assessed average crossing behaviour is used as the decision base for the pedestrian. This assumption is necessary to create a common evaluation basis for actual crossing events as well as situations in which the pedestrians do not cross the vehicle path.

The interaction events were assigned to DST classes according to the maximum DST during the interaction events. For each class the proportion of pedestrians crossing the driving path to the overall number of interactions in this class is calculated as the crossing frequency for this class. The crossing frequency shows the decreasing frequency with increasing required vehicle deceleration (see Fig. 16.6). Comparing directed and undirected crossing situations results in an occurrence of higher crossing frequencies for higher necessary decelerations during directed crossing events in which pedestrians have the right of way (e. g. at zebra crossings). Due to the small sample size for the directed crossing (because of strict filter criteria) an unsteady characteristic has to be registered. Higher overall crossing frequencies at higher required decelerations can be observed for the directed crossing.

16.2.3 Modelling for Crossing Probability

By means of the analysis of the aforementioned crossing frequencies a model for the crossing probability is deduced. To that end, it is assumed that the crossing frequencies of



$N_{combined}$	0	0	0	0	3	2	1	3	12	18	31	22	19	23	19	6	2	0	0	0
$N_{undirected}$	0	0	0	0	0	0	0	0	2	3	7	7	2	1	4	1	0	0	0	0
$N_{directed}$	0	0	0	0	3	2	1	3	10	15	24	15	17	22	15	5	2	0	0	0

Fig. 16.6 Crossing frequency in dependency of DST

the described data collection can also be transferred to other situations. On that condition the developed model could be used to predict the crossing probability of a pedestrian that is detected by the environment detection of an assistance system. The crossing probability in return could be used for parameterisation of a warning or intervening strategy.

For modelling purposes of the crossing probability it is assumed, that pedestrians base their decision whether to cross the driving path or not in front of the approaching vehicle on the necessary deceleration for a safety margin of three seconds. In addition, it is assumed that the crossing probability is normally distributed and can be modelled like that. The crossing probability can therefore be formulated as:

$$p_{\text{crossing}} = \frac{1}{2}\left[1 + \text{erf}\left(\frac{\mu - \text{DST}}{\sqrt{2\sigma^2}}\right)\right]$$

The decision base of the pedestrian consists therefore of the following situation parameters which are incorporated in the definition of the DST:

$$\text{DST} = \frac{2\left[s_{\text{veh}} - v_{\text{veh}}\left(\frac{s_{\text{ped}}}{v_{\text{ped}}} + t_{\text{safe}}\right)\right]}{\left(\frac{s_{\text{ped}}}{v_{\text{ped}}} + t_{\text{safe}}\right)^2}$$

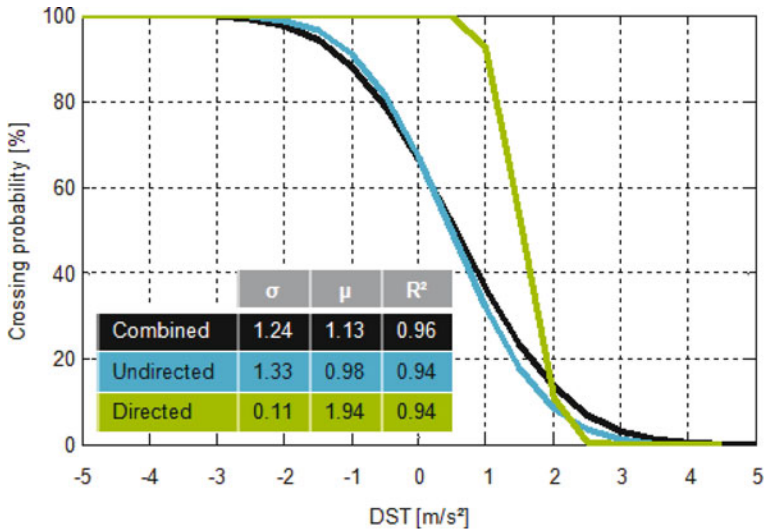


Fig. 16.7 Modelled crossing probabilities for directed and undirected crossing events

The following situation are incorporated in the definition of the DST:

s_{Veh}: Current distance of the approaching vehicle to the conflict zone,
s_{Ped}: (Minimum) distance to be covered by the pedestrian for the crossing,
v_{Veh}: Vehicle velocity (as estimated by the pedestrian),
v_{Ped}: Crossing velocity of the pedestrian (as intended),
t_{Safe}: Time gap between leaving of the conflict zone and the entering by the vehicle.

Only the intended crossing velocity and the accepted safety time gap can be directly influenced by the pedestrian and might therefore be moderating parameters for the deduced model. Fig. 16.7 shows the modelled crossing probabilities for the directed and undirected crossing. The offset of the crossing probability to higher necessary decelerations for the directed crossing is depicted in the difference in the mean μ of approx. 1 m/s^2. The higher variance σ^2 for the undirected crossing may be influenced by the sample size (compared to the one of the directed crossing).

16.3 Static Traffic Observation Under Real Traffic Conditions

Based on the results of the clinical interaction study under real traffic conditions and additionally in order to complement the gathered data, real traffic observations with a stationary sensor were conducted. Since the vehicle sensors of the interaction study mainly focused on situations that occur in front of the test vehicle, a stationary sensor is able to additionally gather data about situations and behaviours of pedestrians that are not in the field of view of the vehicle sensors and e. g. cross the street behind the vehicle.

16.3.1 Methodology

As basis of the traffic observations a mobile measurement system was developed that consists of an IBEO LUX laser scanner, a camera, a mobile computer and a battery. The configuration is shown in Fig. 16.8. To record and synchronise all data the software ADTF (Elektrobit) was used. This configuration enables a quick start-up and operation of the system in different environments. Since the focus of the observations is the pedestrian behaviour and not the driver behaviour a hidden deployment of the sensor is not necessary.

The measurement system was used on two different locations in the inner city of Aachen (Wüllnerstraße, Templergraben) and on one location in the inner city of Vaals (Maastrichterlaan) to complement the measurements of the clinical interaction study. On the first location, Wüllnerstraße, the system was used to observe the pedestrian behaviour on a crossing aid. This location was also part of the route of the clinical interaction study so that the results are comparable. The second measurement location, Templergraben, is close by (approx. 260 m) the first location and in front of the RWTH Aachen University so that it can be assumed that the collective of the observed pedestrians is similar to the one of the clinical study. Since this location is between two university buildings the frequency of crossing events is high. A crossing aid does not exist. As third measurement location a crossing aid in the city of Vaals, Netherlands, right behind the border to Germany was chosen. The configuration of the situation is comparable to the configuration of the Wüllnerstraße but since it is not close to the university and located in the border region the collective of the observed pedestrians is assumed to be different. Instead of a majority of

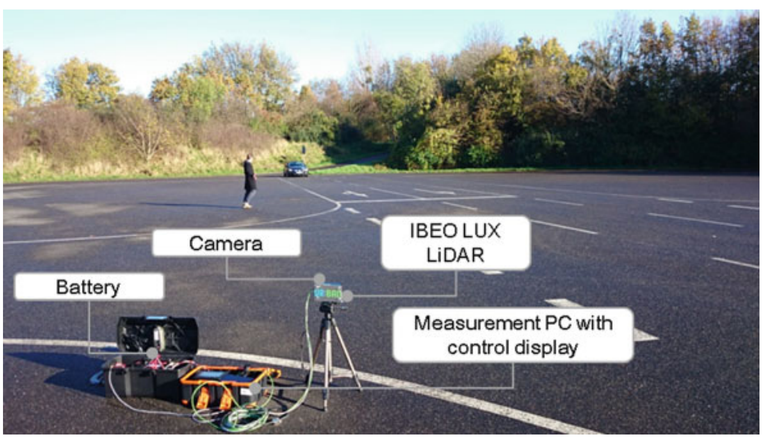


Fig. 16.8 Configuration of stationary measurement system

German students, observed at the first two locations, here a mix of German and Dutch people were observed. All three locations have in common that the traffic to be considered for a crossing decision is unidirectional. The speed limit at the location Wüllnerstraße and Maastrichterlaan is 50 km/h and 30 km/h at Templergraben. A map with the three different locations is shown in Fig. 16.9.

All measurements (one for each location) were performed at lunch time and on sunny days. Overall around 3.5 h (approx. equally distributed for the three locations) of recordings could be evaluated with in total 3339 detected pedestrians by the LiDAR sensor. Detected pedestrians with an observation period of less than 2 s or without interacting with a vehicle were excluded from the evaluation, so that depending on the evaluation data from around 59 to 258 pedestrians were evaluated.

Fig. 16.9 Measurement locations traffic observations

16.3.2 Results

The recorded data were filtered and analysed regarding the dependency of the interaction behaviour on the environment (crossing aid, collective, speed limit ...) as well as regarding the dependency of parameters for describing the interaction on those factors. For this purpose different interaction and situation parameters, like time gap, distance to interaction partner, PET, TTC (Time to Collision) and DST were calculated based on the recorded data and compared to each other. Since the TTC is only defined if the pedestrian and the vehicle are on a collision course with each other the evaluable data set for this parameter was small compared to the other interaction parameters.

The evaluation shows a relation between the situation and most of the interaction parameters, but also that the relation between the interaction parameter DST_0 and the crossing frequency seems to be almost independent from the situation. The crossing frequency depending on the DST_0 for all three locations is shown in Fig. 16.10 individually as well as combined. Due to the fact that the DST_0 is defined as the necessary deceleration of the second interaction partner (vehicle), so that the first partner (pedestrian) can leave the conflict zone before the second partner enters, especially values of $DST_0 > -1.5\,m/s^2$ are interesting. In this case these values describe interaction events in that the vehicle has to accelerate with a maximum of $1.5\,m/s^2$ to arrive at the entrance of the conflict zone at the time the pedestrian leaves the zone. As shown in Sect. 16.2.3, the DST_0 depends on the parameters s_{Veh}, s_{Ped}, v_{Veh} and v_{Ped} so that it is also possible to compare locations with

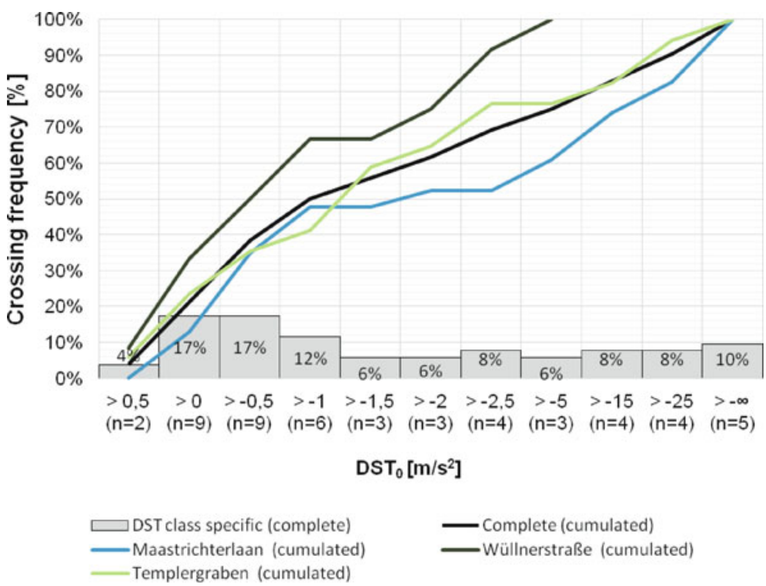


Fig. 16.10 Crossing frequency over DST for traffic observations

different speed limits. An assignment of different DST_0 values and conflict categories can be found in [6].

The analysis also shows that only a small percentage of the pedestrians (4%) crosses the street at positive DST_0 values, which means that these pedestrians assume that the vehicles decelerate to let them cross the street and to avoid a collision. Hence the majority of the pedestrians only cross, when no further deceleration of the vehicle is necessary.

16.4 Interaction Study Under Controlled Traffic Conditions

The clinical study in real traffic in combination with the real traffic observations served as basis for a common crossing behaviour analysis of pedestrians. Since some specific situations occur rarely in real traffic, but have to be considered for pedestrian behaviour analysis, a clinical study in a controlled environment was designed. The requirements were derived from the experiences and results of the previous experiments.

16.4.1 Requirement Definition from Tests Under Real Traffic Conditions

The aim of the interaction study under controlled traffic conditions is to gather sufficient data in specific situations for that the conducted studies and observations under real traffic conditions did not provide enough information. Based on the results of the first two experiments essential statements about two of the three defined pedestrian related research questions and the one driver related research question (see Sect. 16.1) can be derived (see Sect. 16.2.2, 16.2.3 and 16.3.2). For a sufficient evaluation of the third pedestrian related research question,

How does the interaction depend on the vehicle type (passenger car and truck)?

the analysis of the first two experiments shows that the database is not wide enough, since interactions between trucks and pedestrians occur rarely. Nevertheless, this type of interaction is important to be analysed due to the high number of truck-pedestrian accidents and their high severity [10]. A specific analysis of this type of interaction shall be feasible based on the study under controlled traffic conditions.

The previous conducted experiments showed a relation between interaction parameters, like DST, and the crossing behaviour. As shown before, most of them mainly depend on vehicle or situation parameters like speed, distance, deceleration and time gap. For a statistical investigation of this relation a wide range of variations of these parameters in relation to vehicle-pedestrian interactions have to be evaluated. Since this is only feasible in real traffic with many measurements on different locations, it was investigated as part of the study under controlled traffic conditions.

In addition, real traffic observations often have the problem, that the sensor view on interesting elements of the scenarios is concealed by various objects (e. g. infrastructure elements or other road users). This problem led to a high number of interactions that had to be filtered out in the conducted traffic observations. Since the effect can be controlled in a study under controlled traffic conditions, an additional close to the body sensor set-up can be integrated, tested and compared to a ground truth sensor output as part of the study. Thus the measurements served also as basis for analysis of a close to the body sensor set-up.

16.4.2 Methodology

Based on the requirements defined in Sect. 16.4.1 a study under controlled traffic conditions was designed and conducted to investigate the interaction between pedestrians and vehicles. Central scene of the study was a crossing aid (zebra crossing) that had to be used by pedestrians (test subjects) to cross a marked road on the closed test track of the Institute for Automotive Engineering (ika). The road was used by a passenger car and a truck (drivers were confidents), that performed pre-defined manoeuvres which were synchronised with the position of the pedestrian. Fourteen variations per vehicle type were defined so that overall twenty eight different interaction scenarios could be investigated. Each variation consisted of a defined approaching speed, a start position of the deceleration manoeuvre and an average deceleration rate. For each approaching speed also one variation without a deceleration manoeuvre was conducted. The average deceleration rates were controlled by the Adaptive Cruise Control (ACC) interface of the vehicles. The order of the different scenarios was varied. An overview of the scenario elements is shown in Fig. 16.11.

To observe the interactions between the pedestrians and the vehicles the same mobile measurement system for stationary observations as used in the traffic observations shown in Fig. 16.8 was used. In addition, the pedestrians were equipped with a smartphone in their trouser pocket, a tablet in a backpack and a smartwatch on their wrist to enable the

Vehicle type	Speed	Distance start deceleration maneuver	Deceleration rate *
▪ Passenger car ▪ Truck	▪ 30 m/s ▪ 50 m/s	▪ No deceleration ▪ 50 m ▪ 30 m	▪ 1.8 m/s² ▪ 2.5 m/s² ▪ 3 m/s²

* Average deceleration rate controlled by the ACC interface of the vehicles

Fig. 16.11 Elements of scenario variations investigation of the potential of this close-to-body-sensor set-up. Applications on these devices recorded all available sensor data, like acceleration, rotation, etc. together with a timestamp consisting of GPS time and device time. The same timestamp is used in the stationary sensor set-up so that both can be fused afterwards.

To avoid behavioural adaptations due to the knowledge of the test subjects about the actual study case, the subjects were introduced for a study about the accuracy of CE device (smartphone, tablet, smartwatch) sensors. For this purpose two courses, one of each side of the marked road, were installed that the subjects had to complete. Each course consisted of eight marked positions evenly distributed on a circle with a radius of 3 m. The pedestrians had to start on position 1 and had to walk over the centre of the circle to one of the marked positions and then back to position 1. This was repeated for all marked positions per cycle. After each completion of the walking course the subjects had to answer some questions and proceed to the other course by crossing the road. The subjects were told that the courses are installed on each side of the road due to specific GPS effects that have to be investigated. In addition, they were told that due to an overbooking of the test track an additional study for vision systems is performed simultaneously on the marked road. To manage the overbooking a zebra crossing was installed and both parties were introduced to respect traffic regulations. Furthermore, the test subjects were told that they have to be as careful as they would cross a zebra aid in real traffic since it is always possible, like in real traffic, that the driver has not seen the pedestrian.

After each completion of the walking course the number of questions asked by the questioner was regulated to synchronise the crossing intention with the approaching vehicle. When the questioners saw that the vehicles reached marked positions they told the subjects that it is now time to proceed to the next course. To avoid an influence of the questioners' behaviour on the subjects, the questioners always followed the subjects with a distance of around one meter and the subjects were told that this is due to a clear view of the LiDAR sensor on the subjects so that the accuracy of the CE device sensors can be evaluated. Both vehicles used the road also randomised when the pedestrian were still completing the course to avoid that the pedestrians recognise that the vehicles are part of the study.

Pictures of the conducted study are shown in Fig. 16.12. On the left side of the figure a subject crosses the street while interacting with the passenger car. On the right side of the figure the subject is completing one of the courses and the truck performs a random manoeuvre to avoid that the test subjects establish a link between the occurrence of the vehicles and their crossing intention.

Prior to the start of the study, the subjects had to fill out a questionnaire about their demographic background, driving experience and the positions of the CE devices on their bodies related to the ground were measured. The pedestrian collective consisted of 6 female and 24 male participants with an average age of 24.6 years ($\sigma = 4.09$; $\min = 19$; $\max = 41$). Two spare crossing events per test subject were initiated by the questioner to complement the twenty-eight pre-defined manoeuvres of the vehicles. In total, nine hundred crossings were recorded. Since the synchronisation between the crossing intention

Fig. 16.12 Pictures of the conducted study under controlled traffic conditions

and the approaching vehicle is not trivial not all crossings included an interaction with a vehicle.

16.4.3 Results

The recorded interactions were analysed automatically regarding the relation between crossing frequency and interaction parameters like DST based on the LiDAR data. For gaze behaviour the data was analysed visually and the safety distance was assessed by a combination of a visual and LiDAR information analysis.

The evaluation of the relation between crossing frequency and DST_0 is shown in Fig. 16.13. It can be seen, that 50% of the pedestrians in the study crossed the street at a DST_0 of $-2.5\,m/s^2$, whereas 50% of the pedestrians observed in real traffic crossed at DST_0 values of around $-1\,m/s^2$. This fact shows that the pedestrians in this study crossed the street with a higher safety buffer than the pedestrians in the traffic observations (Sect. 16.3). In addition, the evaluation shows that pedestrians use a higher safety buffer while interacting with the truck than with the passenger car. This can be derived by the fact that no pedestrian crossed the street at DST_0 values higher than $0\,m/s^2$ while interacting with the truck. The evaluation of the vehicle speed while the pedestrian decided to cross the street in the cases the vehicle is already close by (distance <15 m) also supports this thesis. In interactions with trucks the pedestrians decided to cross the street at an average speed of the truck of 1.24 m/s while in interactions with the passenger car of 2.77 m/s ($p = 0.0304$). An evaluation of the distance between road marking and waiting position of the pedestrian shows in addition hints for the higher safety buffer, but the effect is not significant. On average, the participants waited at a distance of 1.28 m while interacting with the passenger car and 1.46 m while interacting with the truck ($p = 0.2185$). For the evaluation of the speed and the waiting distance the mean values per subject were evaluated. Further effects were observed, but not considered in this evaluation, due to high requirements on the measured values.

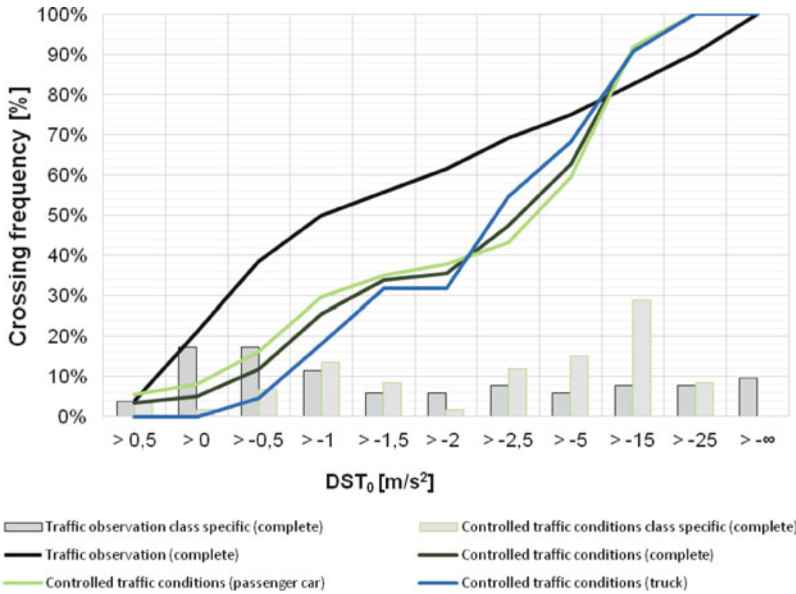


Fig. 16.13 Crossing frequency over DST for traffic observation and study under controlled traffic conditions

The evaluation of the gaze behaviour supports the hypothesis, also investigated in many previous studies (e. g. [11]), that the eye contact between pedestrian and driver are an important part of the interaction process. On average, the participants make eye contact 1.61 (passenger car: 1.58; truck: 1.65) times with the vehicle before they cross the street. No significant difference between truck and passenger car ($p = 0.5311$) can be observed.

16.5 Summary

As one part of subproject SIM vehicle-pedestrian interactions were investigated based on an overall methodology consisting of three different experiments. The goal was to evaluate influences on the crossing decision of pedestrians and to analyse the differences in the driver behaviour between pedestrian interactions on directed and undirected crossings.

As first component of the overall methodology a clinical interaction study under real traffic conditions was conducted, in which $N = 30$ test subjects drove an equipped vehicle on a defined route through the city of Aachen. The study was designed in a way that it is possible to investigate the pedestrian as well as the driver behaviour during interaction events. To evaluate also events outside the field of view of the vehicle sensors, like e. g. the behaviour of the pedestrians several seconds before the crossing, an additional traffic observation on two different locations in Aachen and one in Vaals were conducted to complement the results of the clinical study as second component of the methodology. Based on an evaluation of the results of these two data acquisitions requirements for a third data acquisition approach, a study under controlled traffic conditions with $N = 30$ participants, was defined. This study was conducted on the closed test track of the Institute for Automotive Engineering (ika).

Overall a high number of interaction events was recorded ($N > 3000$). Due to the fact that for a complete description of a vehicle-pedestrian interaction event a large field of view and a sufficient object detection over a specific time range is necessary, the usable sample for a statistical evaluation is much smaller. Nevertheless, an automatic situation analysis for pedestrians that crossed in front of the approaching vehicle showed sufficient results. For pedestrians, that crossed behind the vehicle, the results of the automatic situation analysis was not usable without further manual analysis, since not all parts of the interaction event could be recorded by the vehicle mounted sensors. A first evaluation of additional body close sensors, like the CE devices used in the study under controlled traffic conditions, showed promising opportunities in combination with the used stationary sensor set-up for future evaluations, although they come along with the disadvantage that their data is not accessible during traffic observations.

The evaluation of the studies/observations showed that interaction parameters like PET or DST are useful for interaction analysis. Especially the parameter DST showed its advantages as an almost situation independent description of the interactions. Regarding the question, which kinematic conditions have to be fulfilled so that pedestrians decide to cross the road in front of an approaching vehicle no distinct limits can be derived. In addition, it could be shown that pedestrians cross the road on crossing aids at higher DST values than on locations without crossing aids. This means that they expect higher decelerations (according to amount) from the interacting vehicle to avoid a collision. Therefore differences between directed and undirected crossing events could be observed.

The study under controlled traffic conditions showed the influence of the vehicle type on the pedestrian behaviour. Pedestrians use higher safety buffers while interacting with trucks compared to interactions with passenger cars. The participants of the study crossed the road at lower vehicle speeds and higher DST values while interacting with trucks.

The video analysis of the conducted studies/observations confirms the hypothesis, that eye contact between pedestrians and drivers is an important part of the interaction process. Hence, a pedestrian dummy for testing interactive pedestrian safety systems was developed, that is able to cross the street depending on different interaction parameters and to move the head simulating eye contact with the approaching vehicle.

In summary regarding the formulated research questions an influence of the situational variables directed (with crossing aid) and undirected crossings was shown. In directed compared to undirected crossing events pedestrians expected higher decelerations (according to amount) from the interacting vehicle and a different driver reaction (slightly higher decelerations in crossing aid events) was observed. Regarding the research question, if the vehicle type (passenger car, truck) has an influence on the interaction behaviour of the pedestrian, it could be observed that pedestrians cross the street while interacting with a truck with higher safety buffers compared to interactions with passenger cars.

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Understanding Interactions Between Bicyclists and Motorists in Intersections

17

Mandy Dotzauer, Sascha Knake-Langhorst, and Frank Köster

17.1 Introduction

17.1.1 Background on Cyclists and Crashes

Cycling is a cheap, convenient, healthy, and environmental-friendly mode of transportation that has reached new popularity [1]. The increase of number of cyclists and the change of mode of transport is noticeable. More persons switch from motor vehicles to bicycles, especially in urban areas. For example, in Germany, the number of bicycle owners has increased from 67 million to 72 million between the years of 2005 and 2014 [2]. In addition, 30% of households in urban areas (cities with a population equal to or greater than 500,000 inhabitants) own only a bicycle for mobility purposes. Compared to the year 2003, this is an increase by eight percent [3]. On average, bicyclist travel distances of about 5 kilometers [4]. Not only does cycling affect health positively [5], health benefits outweigh risks such as higher exposure to air pollution or being involved in a crash [6, 7].

On the downside, an accurate estimation of incidences involving cyclists seems impossible. Often, cyclists are involved in single crashes. Injuries are slight, so that the incident is not reported to the police and no medical care is required. Even though the number of

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crashes resulting in slight injuries is underrepresented in crash statistics, the number of fatalities involving a cyclist is well documented. The number of crashes with motorists is comparably small, but they often result in severe consequences for bicyclists. The likelihood of being killed in such a crash is significant [8]. Even though the total number of fatalities of bicyclists decreased over the past decade, the rate of fatalities increased [8]. According to a report of Münster, 51% of all fatalities involving a bicyclist occurred at junctions. Out of these fatalities, 85% occurred at intersections. Based on a thoroughly analysis of incidences in the city of Münster, Germany (rated number 1 bicyclist-friendly city of Germany), key factors contributing to crashes in intersections have been identified. According to the report, motorists as well as cyclists contribute to crashes equally. The main contributing factors of motorists are failing to yield to bicyclists, followed by making an error when turning. Bicyclists on the other hand make errors such as riding on the wrong side of the road/bicyclist path and tend to violate the right-of-way. The authors of the report concluded that these behaviours are the manifestation of a lack of cooperation of the road users [8].

17.1.2 Concept of Cooperation

Per definition, cooperation is a joint action meaning that two or more parties work or act together for a common benefit or purpose. Being cooperative means being able to work together with common intentions towards a common goal. Cooperation requires trust, trust that the other parties involved will also behave cooperatively [9]. The so-called prisoner's dilemma illustrates how the degree of cooperation affects the outcome. The prisoner's dilemma was originally framed by Flood and Dresher in 1950. Tucker built a story around the theoretical game theory and named it prisoner's dilemma. This dilemma arises every time a conflict of interest exists [10].

The story illustrating the dilemma involves two criminals that have been arrested and imprisoned. They are not able to communicate with each other. The prosecutor has only enough evidence to get the criminals convicted for a year. At the same time, the prosecutor offers both criminals a bargain. If they betray each other, they both will be imprisoned for two years. If one confesses and the other remains silent, the later will be sentenced for three years while the other goes free. If both criminals do not betray each other, they will be imprisoned for one year [11].

The dilemma as illustrated in Fig. 17.1 is that each criminal is better of confessing than being silent. On the other hand, the outcome is worse when both confess instead of remaining silent. The common view on this dilemma is the existing conflict between individual and group rationality. Acting upon self-interest instead of seeing the bigger common good (meaning the most benefit for all parties involved) might lead to a worse outcome. In the example of the prisoner's dilemma, acting solely based on self-interest would mean that one decides to confess hoping to go free. If the other decides to do the same, they both will be imprisoned for three years instead of being set free. Both criminals

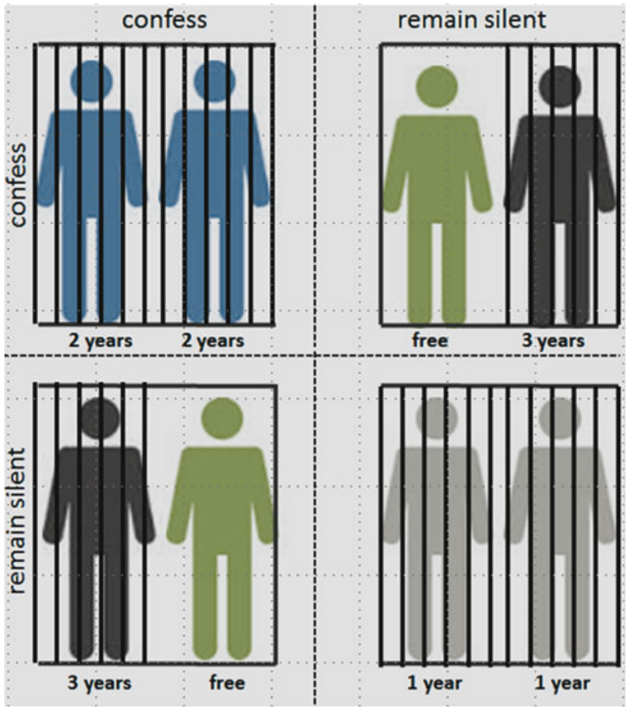

Fig. 17.1 Illustration of the Prisoner's Dilemma including possible outcomes

would have the greatest benefit if they would remain silent. Not betraying each other will result in being imprisoned for one year (i. e. common good, [11]).

Even though the prisoner's dilemma originated as a game theory, the construct has, for example, also been applied to psychology. Recently, the focus has been on cooperative behaviour and under what circumstances/conditions persons are willing to act for the common good and not only for the individual good. Cooperative behaviour requires trust as well as willingness to compromise with regard to inter- and intrapersonal conflicts. In a situation, motives are mixed. Each interaction partner has its own agenda comprised of egocentric, social, and cooperative motives. Based on this agenda, each interaction partner makes a cost-benefit analysis leading to a behaviour that could be either cooperative or uncooperative. But cooperation is only constructive when each interaction partner gives up the individual good for the common good [9].

The willingness to give up the individual good for the common good is also influenced by situational factors. Those factors include the possible individual gain compared to the possible loss, but also the distribution of power amongst the interaction partners. If power is distributed asymmetrically, the more powerful partner is less willing to cooperate. In addition, the more powerful partner may be more successful in persuading the less powerful partner to cooperate [9].

How do the prisoner's dilemma and the idea of cooperation apply to the motorist-bicyclist interaction in intersections? The relationship with regard to power distribution can be described as asymmetrical. The person in the vehicle is protected by its chassis as well as a number of active and passive safety systems. Cyclists, on the other hand, are vulnerable road users. In the worst case, they are not protected at all. In the best case, cyclists wear a helmet to prevent severe head injuries in case of a crash. According to the traffic sociologist Alfred Fuhr, being in a vehicle protected by the chassis, the driver does not feel the need to be very cautious as the driver's life is not at stake. As a result, as a motorist, one might tend to neglect to check the blind spot. The motorist is safer and more protected than the bicyclist in case of a crash. Bicyclists, on the other hand, try to use all the available space as efficiently as possible taking shortcuts where they can, tending to ignore traffic rules that apply to them as they do to any other road user. The motorist is compared to the bicyclist rather inflexible. If, for example, traffic stocks, so does the motorist while the cyclist can wiggle its way through traffic. In terms of flexibility, the cyclist seems to be more agile than the motorist also leading to an asymmetrical distribution. If cyclist and motorist do not adjust their behaviour for the common good, crashes are unavoidable [12] as the increase in the fatality rate already shows [8]. Cooperating (i. e. making a decision based on the common good instead of self-interest) may increase road traffic safety significantly and should be the primary goal of all road users. Conflicts may be avoided when every road user is a bit more considerate giving some room for the interacting partner. Driving a bit slower for a moment and sacrificing a bit of time might affect the overall road traffic safety positively. This would mean that after perceiving and assessing a situation, every road user makes an assessment of the potential danger and then makes a decision based on the common good and not on the individual good [13].

17.1.3 Research Questions and Research Goal

Lack of cooperation has been identified as one of the underlying mechanism leading to fatal crashes of bicyclists [8]. At the same time, significant amount of encounters between bicyclist and motorist do not end up in a near crash or crash. Yet, it is not well understood how bicyclist and motorist get by without being involved in a crash or how conflicts between them evolve: whether they emerge slowly over time or abruptly. The behaviour of motorists and bicyclists as well as the interaction between them needs to be investigated and better understood. Based on the literature [8, 9, 13], different scenarios of why conflicts emerge are thinkable:

1. **Lack of cooperation**: It suggests that conflicts emerge over time because of insufficient cooperation of bicyclists and motorists and the need to push one's interest and to demonstrate power and dominance. Studies also show unfair behaviour of others during several occasions leads to stopping corporation based on several past negative experiences. This might also lead to the lack of cooperation between bicyclists and motorists.

2. **Motorist does not see cyclist**: In this situation, a conflict emerges abruptly and can only be acted upon after its occurrence. This can lead to uncooperative behaviour of the cyclist because the cyclist might assume a deliberate act.
3. **Cyclist sees motorist**: In this situation, it is thinkable that the cyclist insists on its right-of-way and assumes that the motorist will cooperatively yield. It might be a demonstration of the bicyclist's power and dominance.

In order to better understand the interaction between motorists and bicyclists, their encounters in an intersection were recorded and their behaviour analysed aiming to answer the following questions:

1. How and why do conflicts between bicyclists and motorist occur?
2. Where and when (in intersections) do conflicts emerge? Do they emerge abruptly or build up over time?
3. How are conflicts resolved?
4. How do conflicts differ from encounters?
5. Is it possible to detect conflicts before they escalate?
6. Is it possible to quantify behavioural patterns? If so, what parameters are suitable?

As of now, protection of vulnerable road users, such as bicyclists, is of a passive rather than an active nature. Assistance such as warnings and alarms are provided to motorists, but not to bicyclists. The idea of cooperation is that each interaction partner makes a sacrifice for the common good. Neither bicyclists nor motorists are superior to one another meaning they are equally responsible for avoiding situations such as collisions in intersections. If the postulated goal is to develop cooperative assistant systems preventing, for example, crashes in intersection, the interaction between motorists and bicyclist needs to be understood. In turn, tailored warnings can be provided to the involved parties. This way, interaction partners can act upon recommendations that serve the common good: preventing safety-critical situations or even (fatal) crashes.

17.2 AIM Research Intersection

Test field AIM (Application Platform for Intelligent Mobility) was built-up by German Aerospace Center to serve as a test bed for multiple research and development activities in the field of urban mobility [14]. The test field follows a toolbox approach and is composed of several services covering simulation environments, test tracks and field instruments. One of these services is the AIM Research Intersection [15]. It is an instrument allowing detecting, tracking, and classifying motorized and vulnerable road users under real-time conditions in the vicinity of a complex urban intersection.

The AIM Research Intersection is located on the northeastern corner of the Braunschweig inner city circle, marked red in the left part of Fig. 17.2. The illustration on the

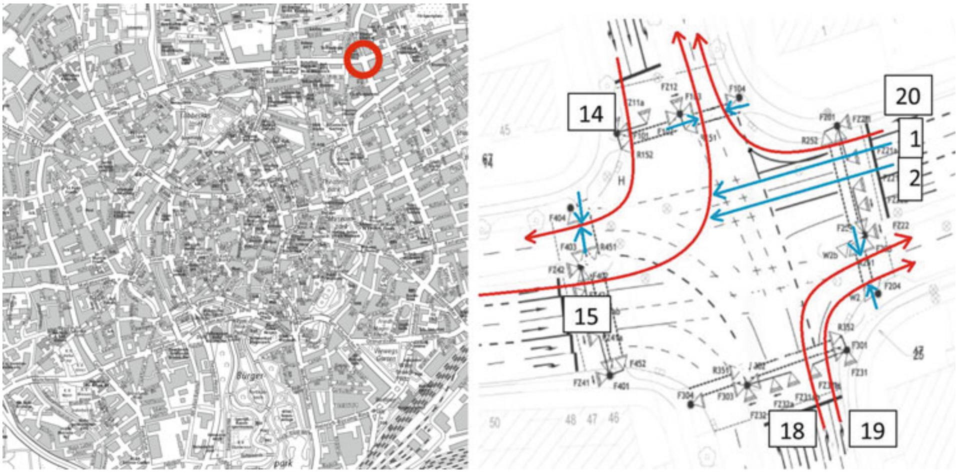

Fig. 17.2 Map of the of inner city of Brunswick and representation of crossing traffic flows at AIM Research Intersection

right shows the topology of the intersection enriched with a depiction of the traffic flows on this multi-lane intersection. Therefore, road users need to directly interact with each other.

This specific intersection was chosen because of its complexity and traffic load making it unique in the city's road network. A wide range of traffic situations can be observed here ranging from free roads to high peaks in rush-hour traffic with typical congestion problems.

17.2.1 Technical Set-up

In order to detect, track, and analyse a high variety of traffic situations as well as motorized and non-motorized road users in the intersections several technical components needed to be implemented across all intersections arms. The sensor set-up of the research intersection is displayed in Fig. 17.3. A more detailed view can be found in [16] and [17].

In the left hand figure, the outline of the intersection is displayed with the field of views of all sensors. Blue segments depict the sensor areas of the MSS (Multi Sensor System). This sub-system is used to detect motorized traffic participants in the inner part of the intersection and adjacent areas. The sensors are installed on four different poles as shown in the upper right part of Fig. 17.3. All pole installations consist of two mono cameras as well as a 24 GHz multi-range radar system and an infrared flashlight for artificial scene illumination. Thus, the sensor set-up of MMS shows a high grade of redundancy in order to ensure an optimal view of every part of the junction while minimizing loss of information due to coverage effects. The IR-flash helps to ensure and maintain an appropriate service level of the optical systems even under bad weather conditions and at night.

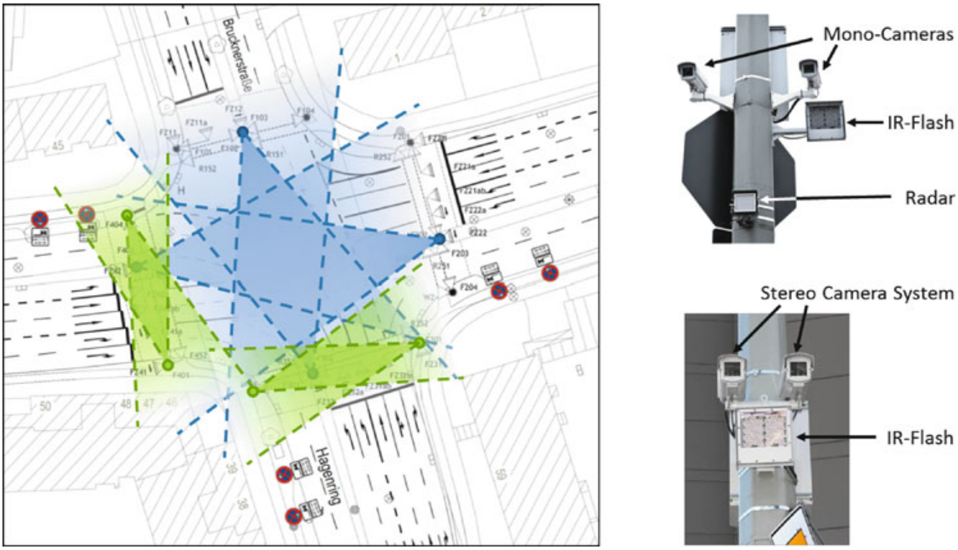

Fig. 17.3 Sensors' fields of view and display of the sensor set-up of the pole installations

In addition to the MSS, the western and southern crossings are instrumented with a subsystem called SENV (System zur Erfassung nicht motorisierter Verkehrsteilnehmer, engl: system to detect non-motorized road users) allowing detecting traffic participants in the respective areas of the intersection. Primarily, the sub-system is used to investigate cross road behaviour of pedestrians and bicyclists. In addition to its primary usage, SENV related data can also be used for enhancing the MSS data base. The SENV installations are shown in the lower right part of Fig. 17.3 and consist of a stereo camera system with the already mentioned infrared flash. The pole installations are placed in an opposing layout to guarantee a good line of sight for every given situation.

All of the given sensor data are fused and processed automatically in a concrete station holding an air-conditioned server rack. The main output of the research intersection is trajectory data with a data rate of 25 Hz as well as corresponding scene videos. These trajectories contain the objects' position, velocity, and acceleration as well as other relevant state information such as physical dimensions or classification, distinguishing five different classes of traffic participants (truck, van, car, bicycle, and pedestrian). Fig. 17.4 shows a screenshot of a four-segment video stream with augmented object wireframe models.

Different traffic participants are depicted with different coloring schemes (e. g. cars are represented with green boxes around them while pedestrians are shown with red boxes). In addition, the traffic light status is retrieved from another component of the AIM test field: the AIM reference track [18]. This information can be used to enrich the collected data and retrieve more information such as red light violations.

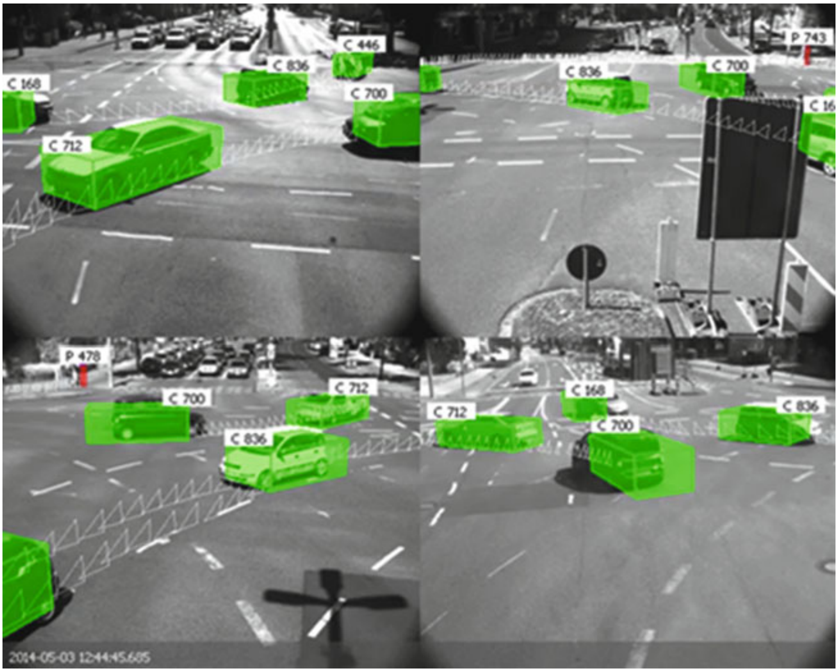

Fig. 17.4 Video screenshot of a traffic scene from four different directions with augmented object information

17.2.2 General Features and Objectives

The intersection can be used as an instrument for measuring natural traffic behaviour for the given complex urban intersection scenario. The presented technical set-up allows a 24/7 mode of operation; therefore, many relevant factors influencing traffic behaviour can be considered for analyses (e. g. time of day, week or year as well as different environmental conditions such as weather or temperature effects). Therefore, particular cases of interest can be studied in more detail. On the other hand, the situation as a whole can be studied and data can be collected over a longer period of time up to several weeks and months. Collection of continuous data of the traffic scene allows studying long-term effects. Fundamental questions are:

1. What are relevant processes and interactions in such a scenario?
2. What kind of effect mechanisms can be found?
3. What kind of interrelations can be found between different factors and modes of traffic?

Thus, the AIM Research Intersection is a tool serving as a basis for research questions given in Sect. 17.1. In order to tackle the incoming data, approaches enabling automatic scene interpretation need to be in place. Surrogate safety measures, such as PET (post encroachment time) have been implemented to extract situations for further analyses. This approach will be explained in more detail in Sect. 17.3 and a detailed overview of new and well-known surrogate safety measures is given in [19].

17.3 Observation of Bicyclist-Motorist Interactions in Intersections

17.3.1 Use Case: Bicyclist-Motorist

The above described research intersection was used to observe encounters between bicyclists and motorists. The pedestrian/bicyclist crossing coming from North (Brucknerstraße) leading South (Hagenring) on the west side of the intersection (Rebenring) served as observation point (see Fig. 17.5). Situations of interest were encounters of bicyclists and motorists at the crossing. While both types of road users approached the intersection from North, bicyclists went straight ahead going further south, while motorists turned right at the intersection going west. Bicyclist and motorists had the green phase simultaneously. This crossing scenario was used as it carries the most potential to be safety-critical and fatal for bicyclist in case of a collision with a motorist. Motorists and bicyclists are structurally separated in this scenario. Bicyclists have a designated path on the sidewalk.

In order to document and analyse interactions between bicyclists and motorists, video recordings of five consecutive working days between 8 am and 6 pm of September 2014 were used. In order to not view all the video material, potential encounters between bicyclists and motorists were extracted based on a PET (post encroachment time) value of 3 s. The PET value serves as a safety surrogate measure used to detect and analyse safety critical situations. The PET value can be used in situations when one road user crosses the

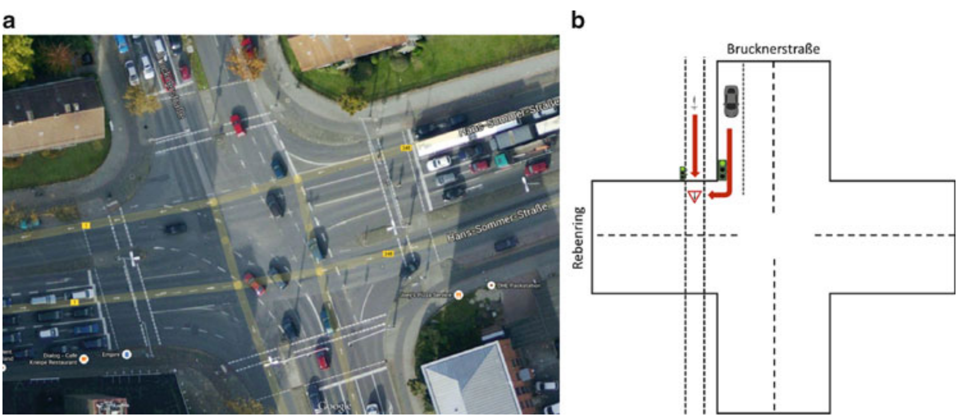

Fig. 17.5 **a** Bird's eye view onto the intersection (Source: Google). **b** Schematic drawing of the observed situation

path of another road user. The metric quantifies the time gap between the road users [20]. Low PET values indicate a high probability of safety-critical situations. A PET value of zero indicates an actual crash. Situations extracted based on the PET value were viewed in at least two iterations. During the first iteration, the extracted situations were viewed and labeled as either encounter or conflict. In the following iteration, the situation and interaction between bicyclist and motorist were described based on an observation protocol.

17.3.2 Traffic Conflict Technique

Based on video recordings, the interaction between bicyclist and motorist was documented by means of an observation protocol loosely based on the traffic conflict technique [20]. With the help of the protocol, it was possible to describe the interaction between bicyclist and motorist based on observable changes in speed over time. In addition, other variables such as vehicle type, running a red light, causing and resolving a conflict, as well as observing an encounter or a conflict, were documented in the protocol.

For the purpose of this observational study, the observed area of interest was divided into two segments: (1) the turning area and (2) the pedestrian/bicyclist crossing (see Fig. 17.5). As understanding encounters and emergence of conflicts was of central interest, motorists and bicyclists were observed and their behaviour reported while approaching the intersection (first segment) and meeting at the pedestrian/bicyclist crossing (second segment). For each segment several variables were reported. For each interaction partner the speed (fast, medium, slow) as well as noticeable changes in speed (e. g. strong deceleration) were documented. In addition, it was reported whether motorists or bicyclists caused a conflict, whether they made any driving errors, such as not yielding, or resolved a conflict. The descriptive behaviour was quantified as each item was coded in order to run chi-square analyses. In the end, a matrix was developed showing how and to what extent motorists and bicyclists cooperate.

17.4 Findings and Implications

Altogether, 144 encounters including nine red light violations and twelve conflicts were found and analysed during the observation period of five working days. Those situations were described based on the protocol and chi-square analyses were used for statistical analyses in order to gain more insight in the interaction between motorists and bicyclists.

As shown in Table 17.1, analyses of conflicts showed that each conflict was caused by motorists. Half of them were caused by passenger vehicles the other half by vans. In all cases, motorists did not yield to the bicyclists. Bicyclists had to abruptly decrease their speed in order to avoid a collision with motorists. Therefore, bicyclists resolved the conflict. In addition, in nine occasions bicyclists ran a red light. Out of these nine occasions, four can be classified as “simple” violations (i. e. the light was red for up to

Table 17.1 Cooperation matrix based on the results obtained during the observation study at an intersection. The numbers ($n = 109$) in the matrix correspond with the number of observed cooperation strategies. Conflicts as well as situations in which one of the interaction partners did not pass the stop line when the light was green were excluded

	Area of pedestrian/cyclist crossing				
Area of turning		Same-same	Same-adjusted	Adjusted-same	Adjusted-adjusted
	Same-same	*9*		*15*	3
	Same-adjusted		2		
	Adjusted-same	*27*	1	*39*	3
	Adjusted-adjusted	3	1	1	5

one second); the remaining five were "qualified" violations (i. e. the light was red for more than one second). Running the red light, did not result in any conflicts. On those occasions, motorists gave right-of-way to bicyclists.

Next to describing and analyzing conflicts and red light violations, it is also crucial to look at the encounters that were neither conflicts nor red light violations. In our study, eight percent of the encounters resulted in a conflict showing that conflicts are rather rare. If the goal is to design safety systems detecting and preventing collisions, it is important to understand how bicyclists and motorists interact without creating safety-critical situations. Understanding the ordinary behaviour might help identifying behaviour deviating from the norm. Therefore, encounters between bicyclists and motorists were analysed and based on the results, a cooperation matrix created describing motorists' and bicyclists' encounters in the observed situations. For the creation of the matrix, changes in speed as documented in the protocol were used. Those changes were protocoled for bicyclists and motorists in two segments: (1) the turning area and (2) the pedestrian/bicyclist crossing. Possible combinations are:

1. Bicyclist and motorist do not change their speed (referred to as same-same).
2. Motorist keeps speed, bicyclist changes speed (referred to as same-adjusted).
3. Motorist changes speed, bicyclist keeps speed (referred to as adjusted-same).
4. Bicyclist and motorist change their speed (referred to as adjusted-adjusted).

Accordingly, the following matrix was created visualizing the interaction patterns:

Four different patterns of interaction were identified, but the frequency of occurrence differed. In 39 cases, motorists adjusted their speed across both observation areas, bicyclists kept their speed constant while approaching and crossing the intersection. The interaction between motorists and bicyclists looked different in another 27 cases. Motorists adjusted their speed in the turning area and continued with constant speed across the pedestrian/bicyclist crossing. Here again, bicyclist approached and crossed the intersection with constant speed. In addition, it was also observed that bicyclist and motorists approached the intersection with constant speed. While bicyclists continued across the intersection with constant speed, motorists adjusted their speed shortly before crossing the pedestrian/bicyclist path. This pattern of interaction was observed 15 times. Nine times, bicyclists and motorists approached and passed through the intersection with constant speed.

Results show that most of the interactions between motorists and bicyclists are encounters and not conflicts. Only twelve situations were categorized as conflicts. In order to better understand how motorists and bicyclists encounter each other in one of the most safety-critical traffic situations (i. e. right turn at intersections while bicyclists go straight) without crashing, those encounters were used to gain better insight. Overall, it was found that in most of the situations, motorists adjusted their speed, while bicyclist continued through the intersection with constant speed. These results were expected as motorists needed to yield-right-of-way to bicyclists. In addition, it was found that when one of the interaction partners made an error (i. e. running the red light or not yielding) the other interaction partner resolved the conflict by not insisting on the right-of-way.

Better and early adjustments in speed on the part of the motorists were also observed. They reduced speed in the turning area, so that they could pass over the pedestrian/bicyclist crossing with constant speed, while bicyclists did not have to adjust their speed. Here, first signs of cooperation can be seen. Cooperation was also found. According to the results of the observation, in nine cases neither bicyclist nor motorists had to adjust their speed. They crossed the intersection with constant speed without creating a safety-critical event. Those nine cases show that cooperation in traffic, especially between bicyclists and motorists, is possible.

17.5 Further Research

Based on the results, first impressions are gained on how motorists and bicyclist encounter each other without creating critical situations in most cases. They need to be better understood in order to identify potential situations deviating from encounters as described above as those situations may lead to conflicts. Therefore, it is necessary to not only analyse encounters and /or conflicts directly (i. e. using safety indicators such as TTC or PET), but go back in time and analyse how these situations arise. Parameters such as speed and changes in speed appear to be valid candidates for such an analysis. Based on changes and variance in speed, travel pattern might be identified. In addition, interactions of speed while approaching the intersection might be mapped.

The AIM research intersection offers this opportunity. As mentioned above, motorists as well as vulnerable road users can be detected and tracked while crossing the intersection. At the moment, the detection range is limited to the area of the intersection starting at the stop line, but additional components will be implemented extending the detection area. With the extension, it will be possible to detect road users for more than 30 meters before reaching the stop line. Therefore, data recording road users while approaching the intersection will be available for analyses.

Based on this data, it will be possible to gain more knowledge about encounters and conflicts; if and how they differ and whether speed patterns differ from each other while approaching the intersection. It is thinkable to apply methods such as coherence analysis to investigate whether and how similar bicyclists and motorists approach the intersection, in cases when they meet in the intersection. Those results may deliver significant insight that can be implemented in algorithms aiming at preventing crashes from occurring while providing recommendations to motorists as well as bicyclists.

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Analysis and Modelling of the Operational and Tactical Behaviour of Bicyclists

18

Heather Twaddle

Life is like riding a bicycle, to keep your balance you must keep moving (Albert Einstein).

18.1 Motivation

The bicycle offers urban travellers an inexpensive, non-polluting transport alternative, which requires little space while moving or parking, can be manoeuvred quickly through congested road networks and offers health benefits to the user. Municipalities throughout the world are taking notice of the personal and societal benefits of utilitarian bicycling and are implementing policies and developing infrastructure to support current bicyclists and encourage potential bicyclists to start cycling. As a result, the modal share of bicycling is growing in many cities [1]. In turn, the effect of bicycle traffic on overall traffic efficiency in urban areas is becoming more important to consider in the design and assessment of road infrastructure. Unfortunately, as the volumes of bicycle traffic increase, so do concerns about bicyclist safety. Although traffic safety in general has improved greatly in many European countries in the last decades, the rates of bicyclist injury and death have stagnated [2–6]. In Germany, while the modal share of bicycling is about 3% when measured by distance and 10% when measured by trips [7], bicyclists account for 19.9% of all injuries and 11.7% of fatalities on German roads [5]. At urban intersections in Germany, a startling 39.1% of collisions involve at least one bicyclist [8]. In light of the significant impact of bicyclists on the overall traffic efficiency in urban areas as well as the excessive burden on bicyclists with regard to traffic safety, it is crucial to consider bicyclists explicitly in the evaluation of traffic engineering and control measures. This is particularly true

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at intersections, where bicycle traffic has a pronounced influence on traffic flow [9] and bicyclist safety is a pressing concern [8].

Microscopic traffic simulation is a frequently used tool for analysing traffic and forecasting the effects of road infrastructure design, signal control, intelligent transportation systems (ITS) and advanced driver assistance systems (ADAS). However, in order to validly simulate urban intersections with bicycle traffic, the models used to describe bicyclist behaviour within the simulation must be detailed and realistic. This is a complicated task when one considers the unique behaviour of bicyclists, which is characterised by the following features.

- **Flexibility**: Bicyclists can choose between using different parts of the road infrastructure. They can use a bicycle facility, if provided, or instead ride on the roadway with motor vehicles. Alternatively, bicyclists can decide to ride or dismount and push their bicycles on the sidewalk. It is possible for bicyclists to change sporadically between different parts of the infrastructure to best suit their tactical goals and to apply their flexibility with regard to traffic rules and regulations. An in-depth study of the rule acceptance of bicyclists in six cities in Germany showed that 36% of bicyclists violate a traffic regulation at some point during each trip [10]. The most common violations are riding against the designated direction of travel, not using a mandatory bicycle lane and running red lights.
- **Diversity**: Bicyclist behaviour is strongly influenced by the personal characteristics of the bicyclists. Observable aspects, such as age, gender and physical fitness, as well as non-observable traits, including bicycling experience, personality and mood, greatly influence both the tactical and operational behaviour of bicyclists [10–13]. Individuals within a population of bicyclists have differing desired riding speeds and acceleration profiles, respond differently to other road users and obstacles and make different tactical decisions.
- **Variability**: Not only do differences exist between bicyclists in a population, but the behaviour of one bicyclist fluctuates as he or she encounters different situations. Speed, acceleration and deceleration, rule compliance, infrastructure use and other facets of the operational and tactical behaviour are continuously adjusted depending on external (e. g. behaviour of other road users, infrastructure design) and internal (e. g. mood) factors [11].

However, currently available microscopic traffic simulation tools are limited in their capacity to simulate the flexible, diverse and dynamic behaviour of bicyclists. The first step in UR:BAN was to identify shortcomings in the state-of-the-art in modelling and simulating bicycle traffic with regard to behaviour at the tactical and operational level. The review of current modelling and simulation approaches was published in the paper *Bicycles in Urban Areas: Review of Existing Methods for Modeling Behaviour* [14]. In summary, bicyclists are typically simulated in currently available simulation tools using models that were developed for vehicular traffic. In some cases, these models have been extended to allow for increased flexibility in lateral movement [15]. While this extension greatly improves the simulation of bicycle traffic, many other aspects of bicyclist behaviour, such as the tactical choice between riding on a bicycle lane, the roadway or the sidewalk, and riding against the given direction of travel, continue to be difficult with currently available tools.

Following the identification of shortcomings in the state-of-the-art, the data necessary for closing these gaps was specified. In order to gain an understanding of the relationships between situational factors and the operational and tactical behaviour of bicyclists, it was imperative to collect data that provide a comprehensive overview of the entire situation at the intersection. Microscopic data that includes the position and speed of each road user at regular time intervals as they cross the intersection were necessary. To meet this requirement, video data was collected and trajectories were extracted using automated computer vision methods. Additionally, information describing the phase transitions of the signal control as well as maps detailing the geometry of the intersection were added to the trajectory database. The resulting database was quantitatively analysed to gain an understanding of the operational behaviour and tactical choices of bicyclists at signalised intersections. As a final step, the findings of the behavioural analyses were used to calibrate and extend existing models and develop new methods for modelling the operational and tactical behaviour of bicyclists.

In order to formulate the analysis and modelling tasks within UR:BAN, the hierarchical framework proposed by Michon [16] was used to classify road user behaviour based on the time scale of the choice and the type of action. According to this framework, tactical behaviour takes place on a timescale of seconds to minutes and includes controlled action patterns and conscious decisions made by a road user to cope with the immediate situation. Tactical behaviour is governed by decisions made at the strategic level, such as route choice, and is influenced by environmental factors, including the actions of other road users and the phase of the traffic signal. Operational behaviour is defined as automatic action patterns that take place on a timescale of milliseconds to seconds and includes such behaviours as acceleration, deceleration and obstacle avoidance. Behaviour at the operational level is directed by conscious choices made at the tactical level, such as the desired path and the desired speed, and is influenced by environmental factors, such as the condition of the pavement, the weather and infrastructure design. There are feedback loops between the operational level and tactical level in which the operational state restricts and influences the tactical behaviour, while choices at the tactical level activate and supervise behaviour at the operational level. The hierarchy defined by Michon [16] was used in UR:BAN to guide behavioural analyses and model development.

This chapter is organised using the following structure. The methods used for data collection and processing are presented in Sect. 18.2 and the behavioural analyses carried out using the resulting database are presented in Sect. 18.3. In Sect. 18.4, the modelling approaches developed based on the findings of the behavioural analyses are introduced. The outcomes of the project are discussed and concluded in Sect. 18.5.

18.2 Data Collection and Processing

The behavioural analyses and model development to be carried out in UR:BAN were identified through a thorough review of the literature and two meetings with a group of experts. As a second step, the observational data necessary to complete these tasks were specified. Both the behavioural analyses and model development necessitated trajectory data from bicyclists as well as an exhaustive description of the situation in which the bicyclists find themselves at each point along their trajectories. Aerial video data was selected for data collection and processing because trajectories could be traced from all road users within a given area and situational data could be extracted using automated methods or added manually.

The entire road network is relevant for the analysis of road safety and efficiency using microscopic traffic simulation. The scope of the research in UR:BAN, however, was confined to signalised intersections. This focus was justified by the disproportionately high safety risk to bicyclists at intersections in comparison to road segments [8]. In addition, many measures for improving the safety and efficiency of bicycle traffic are deployed at signalised intersections, including ITS and ADAS measures developed within UR:BAN. The research intersections were selected with the goal of maximising the variety of situations with which the observed bicyclists were faced. The type of bicycle infrastructure was used a key selection criterion for research intersections because this variable has been found to have a significant effect on the behaviour of bicyclists [10, 11]. Twelve types of bicycle infrastructure used in Germany were identified and clustered into four groups based on the separation from motorized vehicle traffic; (I) roadways with no specific bicycle facility (bicyclists move with motorised traffic), (II) roadways with an on-road bicycle facility, (III) physically separated bicycle facilities and (IV) miscellaneous bicycle facilities. Four signalised intersections were selected for data collection with varying types of bicycle infrastructure and traffic volumes. Research sites in Munich, Germany were selected because of the relatively high modal split of bicycle traffic of 17% in the city [17]. Basic four arm intersections were chosen to facilitate comparability between data collection sites. Of the eleven approaches at the four research intersections (one intersection includes a one-way street), four approaches belong to type I, four belong to type II and seven belong to type III. Type IV facilities, which include bicycle paths in green areas, contraflow bicycle lanes, two-way bicycle lanes and bicycle roads, were not investigated within this project.

Raw video data were collected at each research intersection for two to four days from before the morning peak traffic hour (ca. 7:00 am) until after the evening peak hour (ca. 8:00 pm). Each of the collection days was a weekday during the spring and summer months of 2013 and 2014. A GoPro Hero 3 Black Edition camera was used for data collection with a full HD resolution (1920 × 1080 pixels) and a frame rate of 25 fps. The wide angle lens made it possible to observe the behaviour of road users on all approaches of the intersections. Camera views of the four research intersections are shown in Fig. 18.1.

Two hours of video data from the morning peak hour at each of the four research intersections was selected for detailed analysis. This selection was made based on the

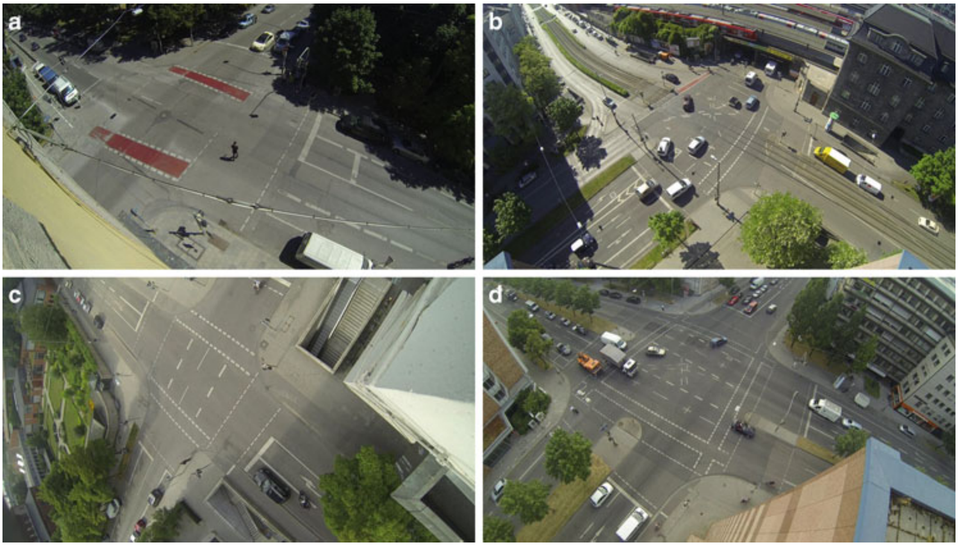

Fig. 18.1 Camera views from the research intersections Arcisstraße/Theresienstraße (**a**), Arnulfstraße/Seidlstraße (**b**), Karlstraße/Luisenstraße (**c**) and Marsstraße/Seidlstraße (**d**)

number of bicyclists, the stability of the camera (no wind disturbance) and the absence of shadows that can cause problems in extracting trajectories (overcast weather was found to produce the best results). The eight hours of selected video data was processed using the open source software *Traffic Intelligence* [18], which uses automated computer vision methods to extract the trajectories of moving road users. A trajectory database with the position and velocity vectors (x-y coordinates) of all the road users in each video frame was generated by *Traffic Intelligence*. An example of one of the research intersections, Marsstraße-Seidlstraße, with the extracted trajectories from a five minute video segment superimposed over a video frame is shown in Fig. 18.2.

An approach was developed in UR:BAN to classify the road users as pedestrians, bicyclists or motor vehicles based on their position in the video frame and their dynamic characteristics. The approach was presented and evaluated in the paper *Use of automated video analysis for the evaluation of bicycle movement and interaction* by H. Twaddle, T. Schendzielorz, O. Fakler and S. Amini [19]. The accuracy of the methodology used to track and classify cars, bicycles and pedestrians varied widely between the research intersections. The percentage of tracked road users ranges from 72–93%, while the percentage of correctly classified road users ranges from 28–97%. A method was also developed in this project to rectify the distortion in the trajectory data caused by the wide angle lens. The approach is based on functionalities provided in the open source computer vision library *OpenCV* [20].

The resulting trajectory database was manually corrected to reclassify mislabelled road users, delete erroneous or superfluous trajectories and merge trajectories that were dis-

Fig. 18.2 Trajectory data extracted from a five minute video segment using *Traffic Intelligence* [18]

jointed due to an occluding object or a stop (only moving objects are tracked with *Traffic Intelligence* [18]). The database was controlled to ensure that trajectories with discontinuities or jumps were not used for the behavioural analyses. Qualitative parameters describing the situation and the behaviour of the bicyclists that could not be collected using automated processes were manually added to the trajectory database. Precise information about the traffic signal phase and timing was obtained from the City of Munich for the specific data collection dates. This data was integrated with the trajectory database using a corrected time stamp from the video data. As a result, a corrected and verified database of trajectories from 5146 bicyclists was created, complete with signal timing information and qualitative descriptive variables.

18.3 Data Analysis

An analysis of the resulting database of trajectories, signal timing information and qualitative variables describing the situation and bicyclist behaviour is presented in this chapter. The intention of the analysis is to provide quantitative information concerning the operational and tactical behaviour of bicyclists that has not yet been provided by previous studies. The operational behaviour is analysed in Sect. 18.3.1 followed by a brief overview of the tactical analysis in Sect. 18.3.2.

18.3.1 Operational Behaviour

Three aspects of the operational behaviour of bicyclists were examined in UR:BAN using the trajectory data extracted from the videos: speed, acceleration and spacing between bi-

Table 18.1 Division of observed bicyclists into Group A, Group B and Group C

		Interaction with other bicyclists	
		time gap ≥ 2 s	time gap < 2 s
Signal phase upon approach	Green	Group A (N = 704)	–
	Red	Group B (N = 326)	Group C (N = 630)

cyclists while stopped. In order to isolate the behavioural aspects of interest, the observed bicyclists were divided into four groups based on their interaction with other bicyclists and the signal phase upon arrival at the intersection. The division criteria and the number of bicyclists in each group is shown in Table 18.1. The group of bicyclists that arrived while the signal was green and interacted with other road users (time gap < 2 s) are not included in the analyses presented in this chapter.

Group A includes bicyclists that arrived at a green signal and did not interact with other bicyclists. The trajectories from this group were used to analyse speed. Bicyclists in Group B arrived while the signal was red and had no interaction with other bicyclists. The acceleration and deceleration profiles were studied using trajectories from this group. Finally, trajectories from bicyclists who arrived while the signal was red and interacted with other bicyclists (Group C) were used to investigate the spacing behaviour while queuing. The analyses and results for each of the three selected aspects are summarised in the following sections.

18.3.1.1 Speed

Speed is an important parameter to consider in the design of road infrastructure and traffic signal control. Most of the research that has been done to date concerning bicyclist speed has been motivated by the need to consider bicycle traffic in signal control design at intersections. Intergreen times, the length of which has a strong influence on the capacity of signalised intersections, must be set to ensure that all road users can cross the intersection before conflicting streams are allowed to enter. The maximum crossing time is determined from the distribution of speed and acceleration rates among bicyclists. The average speed has been thoroughly analysed by researchers, mainly in the USA, with results ranging between 3.2 and 7.5 m/s [21–24]. Most of the studies estimate the mean speed and do not elaborate on the distribution of the speed observations. The methodology used to estimate the Level of Service (LOS) in the Highway Capacity Manual assumes a normally distributed average speed of 5 m/s with a standard deviation of 0.8 m/s [25]. No information is given concerning how differing speed distributions can be considered. Nonetheless, speed distribution is a crucial parameter in estimating LOS for bicyclists, as large speed disparities are known to cause issues with traffic safety and efficiency. Within UR:BAN, the speed distributions at the four research intersections were studied to provide detailed information for use in simulations and in design guidelines. The effect of various tactical decisions on the speed of bicyclists was investigated in order to specify speeds for bicyclists carrying out different manoeuvres.

The average speed across the intersection, the range of speeds observed for one bicyclist and the minimum and maximum speeds were extracted from the trajectories of bicyclists in Group A. Histograms for each of the observed speed parameters are shown in Fig. 18.3. An initial hypothesis of normal distribution for the four speed parameters was used as a starting point for distribution analysis. The mean and standard deviation of the observed data for each parameter were calculated and the resulting probability density function (pdf) and cumulative density function (cdf) of the normal distribution were plotted. The suitability of the normal distribution for the four speed parameters was evaluated using the kurtosis and skew of the data and a visual inspection of the histograms of the observed data.

The normal distribution was found to provide an accurate representation of the mean speed of the bicyclists crossing the intersection as well as the minimum and maximum speeds. All three parameters were found to have a slight negative kurtosis, meaning that the observed distribution contains fewer extreme values than the normal distribution. This could be remedied by using another distribution with a negative excess kurtosis, such as the raised cosine distribution, although this adds complexity due to the number of parameters necessary to define the distribution without significantly improving the fit. This

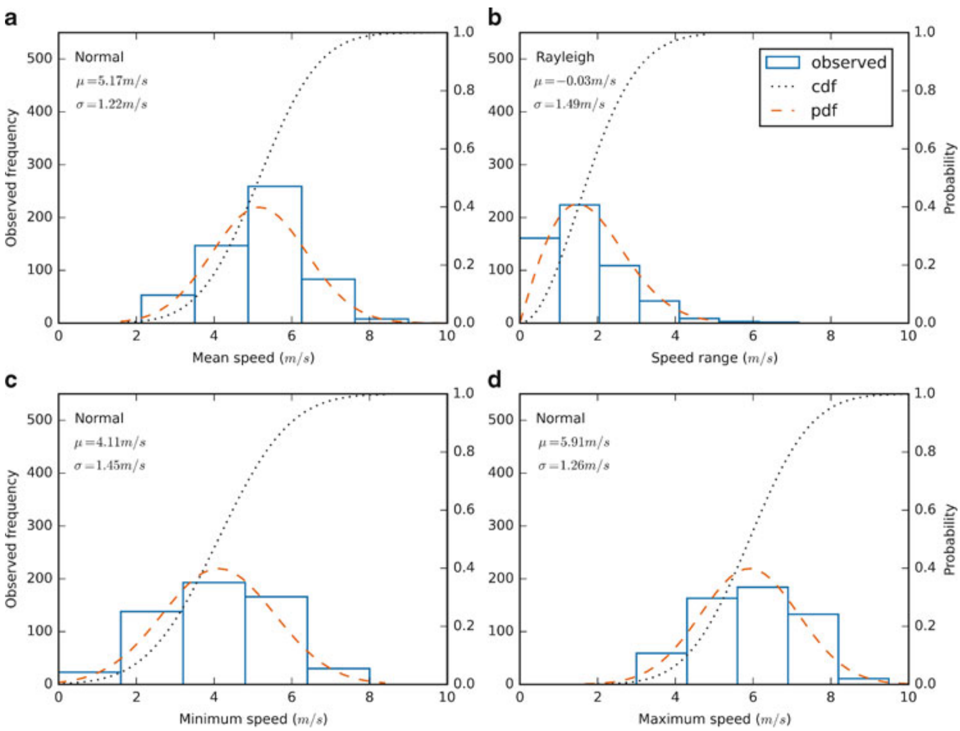

Fig. 18.3 Distribution of the mean speed (**a**), the range of speeds (**b**) and the minimum (**c**) and maximum (**d**) speeds of the observed bicyclists in Group A

problem can also be remedied by setting a minimum and maximum allowable speed. The slight skew in the observed mean, minimum and maximum speed distributions were not pronounced enough to reject the normal distribution. The range of speeds covered by the observed bicyclists, on the other hand, is positively skewed to the extent that the normal distribution does not provide an accurate representation of the observations. The Rayleigh distribution was selected in this case because it offers a good fit with the observed distribution and is characterised by only two parameters, a location (μ) and a scale (σ) parameter, analogous to the normal distribution. The final distributions with the fit location (μ) and a scale (σ) parameters are shown in Fig. 18.3.

The effects of selected tactical behaviours on the mean speed were quantified using the trajectories from bicyclists in Group A. To this aim, a multiple regression model was estimated with dummy variables representing three tactical choices; infrastructure selection (bicycle lane, roadway, sidewalk), direction of travel (with or against the mandatory direction) and type of manoeuvre (straight, left turn, right turn). The results of the regression are shown in Table 18.2. The base situation (constant) for the model is a bicyclist riding straight across the intersection on a bicycle lane, travelling in the mandatory direction of travel. A total of 704 observations were used to develop the multiple regression model.

The multiple regression model indicates that bicyclists travel slower when riding on the sidewalk or roadway in comparison to when riding on a bicycle lane (1.4 and 0.36 m/s slower average speed, respectively). Similarly, the average speed of bicyclists turning right and left is 1.20 and 0.54 m/s, respectively, slower than bicyclists travelling straight across the intersection. Bicyclists riding against the mandatory direction of travel ride 0.66 m/s slower on average than those moving in the mandatory direction of travel. However, the small number of bicyclists observed riding against the direction of travel limits the significance of this finding.

Results from the distribution analysis and the multiple regression model can be used in conjunction with the findings of previous research to model speed with more accuracy in microscopic traffic simulation tools. Other applications for the findings in this section include the calibration and extension of methods used in design and evaluation standards

Table 18.2 Multiple regression model of mean speed

Variable	Coefficient	t-statistic	Significance
Constant	5.22	94.142	0.000
Bicycle lane use (constant case)	–	–	–
Sidewalk use	−1.40	−3.527	0.000
Roadway use	−0.36	3.236	0.001
Straight (constant case)	–	–	–
Right turn	−1.20	−7.974	0.000
Left turn	−0.54	−1.609	0.108
Mandatory direction of travel (constant case)	–	–	–
Against mandatory direction of travel	−0.66	−1.279	0.201

such as the US American *Highway Capacity Manual* [26] and the German *Handbuch für die Bemessung von Straßenverkehrsanlagen* [27].

18.3.1.2 Acceleration and Deceleration

In a similar manner as speed, the acceleration and deceleration characteristics of bicyclists have a significant influence on bicyclist safety and traffic efficiency. For example, acceleration from a stopped position at a red light impacts the crossing time of bicyclists and therefore the necessary intergreen times. Maximum deceleration rates are important parameters in evaluating critical situations with regard to safety. However, few researchers to date have examined this aspect of the operational behaviour of bicyclists. Those researchers who have analysed acceleration and deceleration have typically assumed a constant rate of acceleration during an acceleration process and have found average acceleration rates ranging from 0.23 to 1.07 m/s^2 [21, 28–30]. No studies were identified that quantified the deceleration processes of bicyclists or the distribution curves of acceleration and deceleration rates amongst a population of bicyclists.

The trajectories from bicyclists in Group B were used to investigate the acceleration and deceleration[1] processes. In a first step, the distributions of the observed mean acceleration, the range of accelerations for each bicyclist, minimum and maximum acceleration were investigated. The method used for identifying and fitting a distribution model was the same as the approach used for the speed analysis (Sect. 18.3.1.1). An initial hypothesis of normal distribution was accepted or rejected for the four acceleration parameters based on a visual assessment of the histograms as well as an evaluation of kurtosis and skew. In cases where the normal distribution was rejected, a more suitable distribution was identified and parameterized based on the observed data.

For each of the acceleration parameters, mean acceleration, acceleration range, minimum and maximum acceleration, the normal distribution was rejected due to the skew of the data. The observed distributions for the mean acceleration, acceleration range and maximum acceleration are positively skewed. The Rayleigh distribution was selected to represent the observed distributions based on the shape of the observed data distribution and in consideration of the low number of parameters used to define the distribution (a location (μ) and a scale (σ) parameter, analogous to the normal distribution). The minimum acceleration (maximum deceleration) distribution is negatively skewed. The Gumbel distribution was found to provide the best fit with only two parameters describing the location and scale. The observed histograms and fit distributions are shown in Fig. 18.4. The minimum and maximum acceleration distributions are most relevant for the calibration and development of microscopic simulation tools.

The trajectories of bicyclists in Group B were investigated in more detail to determine how acceleration is controlled throughout an acceleration process. To enable this investigation, the speed ratio θ_s was introduced (Eq. 18.1) to indicate the degree to which

[1] The term acceleration is used in the remainder of this section to describe both positive acceleration and negative acceleration (deceleration) in order to simplify the text.

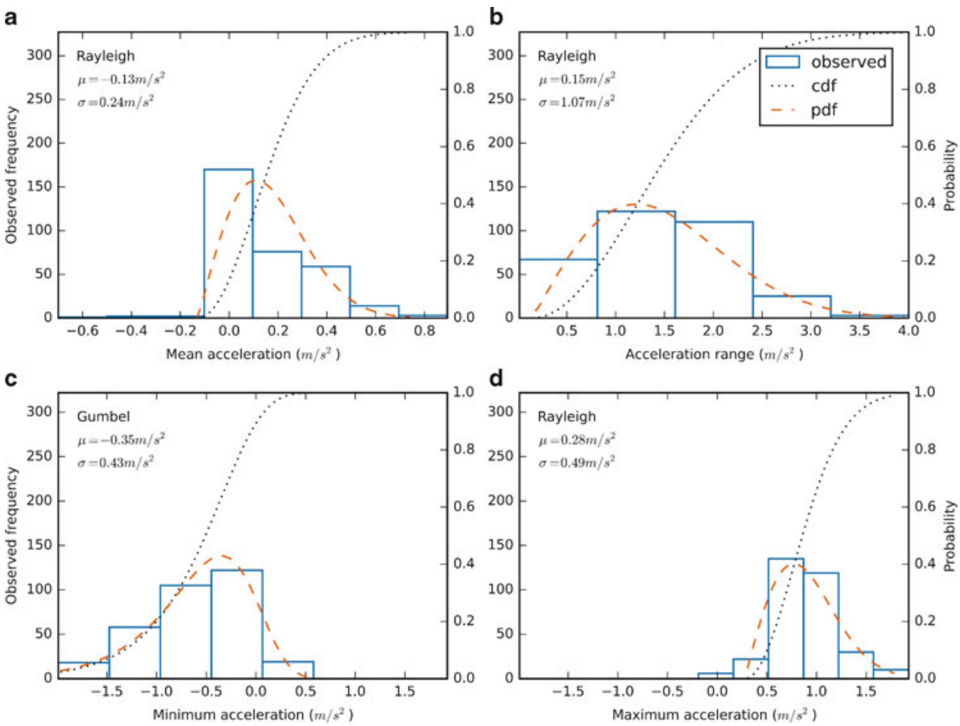

Fig. 18.4 Distribution of the mean acceleration (**a**), the range of accelerations (**b**) and the minimum (**c**) and maximum (**d**) acceleration of the observed bicyclists in Group B

a bicyclist has completed an acceleration or deceleration process.

$$\theta_s = \frac{s - s_i}{s_d - s_i} \tag{18.1}$$

In Eq. 18.1, s is the current speed (m/s), s_i is the initial speed (m/s) (e. g. 0 m/s when accelerating from a stopped position) and s_d is the desired speed upon completing the acceleration or deceleration process (m/s) (e. g. 0 m/s when deceleration to a stopped position).

Trajectories were identified that included a complete acceleration or deceleration processes in which the bicyclist either started or ended the process in a stopped position. For acceleration processes, the desired speed (s_d) was estimated by taking the average of the speed measured after the bicyclist first reached 85% of his or her maximum speed. Similarly, the initial speed (s_i) was estimated for deceleration processes by taking the average speed before the bicyclist first dropped below 85% of his or her maximum speed. An observation containing the θ_s value and the momentary acceleration was taken for each bicyclist at a frequency of five measurements per second. The trajectory data has a frequency of 25 measurements per second but the observations were aggregated to smooth

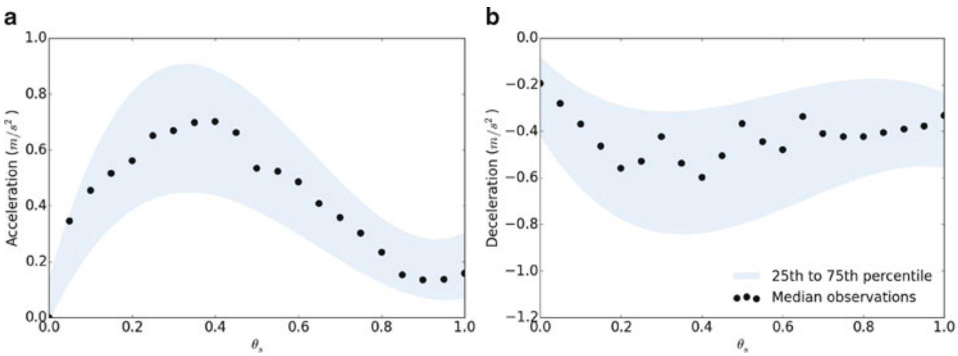

Fig. 18.5 Acceleration (**a**) and deceleration (**b**) profiles of the observed bicyclists in Group B

the acceleration profiles. The θ_s values were grouped in bins with a width of 0.05 and the median, 25th and 75th percentile of each bin are shown in Fig. 18.5 for accelerating (a) and decelerating (b) bicyclists in Group B. In total, 14,551 observations were collected from accelerating bicyclists and 1913 observations from decelerating bicyclists. The 25th and 75th percentile of the bins were smoothed using spline approximation with an order of spline fit of three.

The overall trend in the acceleration profile in Fig. 18.5a indicates that bicyclists do not accelerate constantly but rather accelerate most strongly during the first half of the acceleration process. The highest acceleration values, which range between 0.4 and 0.9 m/s^2, were observed at about $\vartheta_s = 1/3$ (one third of the acceleration process is complete). The acceleration drops to less than 0.2 m/s^2 when the bicycle has reached about 80% of his or her desired speed. The observed deceleration profiles indicate a more constant deceleration of between −0.8 and −0.2 m/s^2 throughout the deceleration process. The deceleration values were observed during normal deceleration processes and are not meant to be interpreted or used as maximum deceleration values.

The analysis of the acceleration and deceleration behaviour of bicyclists at intersections can be used to improve the accuracy of microscopic traffic simulation tools. Findings show that average acceleration, the range of acceleration and minimum and maximum acceleration amongst a population of bicyclists cannot be described using the normal distribution because of significant skewing. The Rayleigh and Gumbel distributions are suggested as alternatives. Similarly, the assumption of constant acceleration could not be confirmed by this data analysis for acceleration processes but seems to provide a good estimate of deceleration processes.

18.3.1.3 Spacing

The spacing maintained between bicyclists directly influences the density and flow of bicycle traffic. The minimum spacing accepted by a bicyclist also defines whether or not he or she can squeeze through a queue of motor vehicles at a red light, a behaviour that directly influences motor vehicle flow at intersections. For these reasons among others, this parameter plays a crucial role in bicycle and overall traffic efficiency, both on road segments and at intersections. Nonetheless, only two previous studies were found that examined the lateral spacing of bicyclists, both of which investigated spacing during overtaking manoeuvres. A German study found the average, minimum and maximum lateral spacing to be 0.60 m, 0.20 m and > 1.00 m, respectively [13]. A US American study estimated larger values for the average, minimum and maximum lateral spacing of 1.78 m, 1.35 m and 2.36 m, respectively [31]. No studies were found that quantified spacing while queuing.

Unlike motorised road traffic, which predominantly moves single-file in road lanes with intermittent lane changes, bicyclists have significantly more freedom of movement in the lateral direction and can pass one another in the same lane. The one-dimensional parameter that is used to measure motor vehicle traffic; the longitudinal following distance (spacing) between two vehicles in the same lane, is insufficient for describing bicyclist spacing. To measure the spacing between bicyclists, a two-dimensional vector was proposed that contains a longitudinal component, which is measured along the axis of the direction travel of the bicyclist, and a lateral component, which is measured perpendicular to the axis of the direction of travel. Both of these components are crucial for the calibration of microscopic traffic simulation tools because they directly influence the density and flow of bicycle traffic.

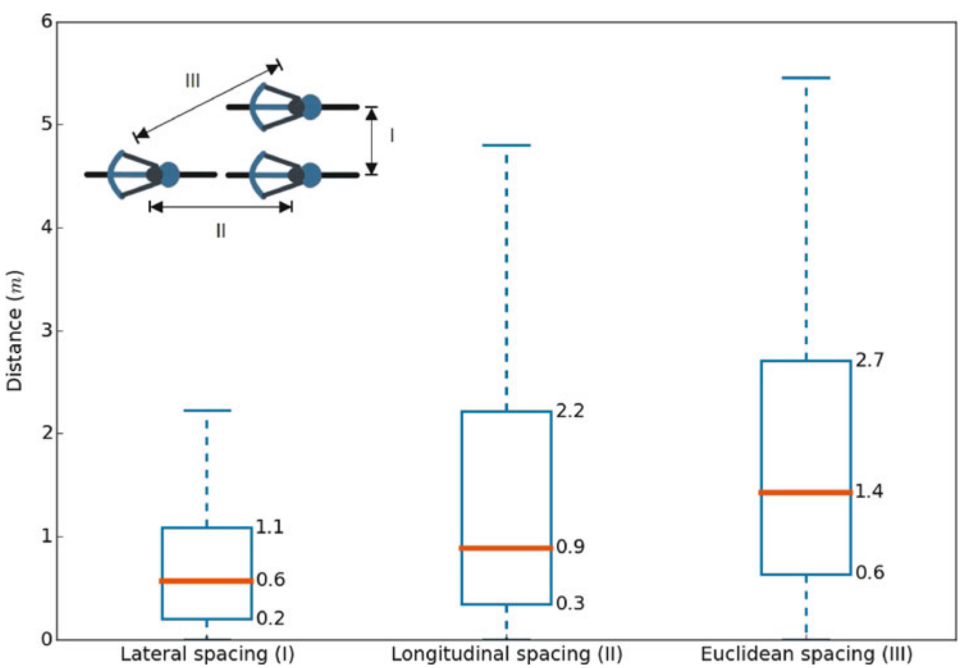

Fig. 18.6 Lateral, longitudinal and Euclidean spacing between stopped bicyclists in Group B

The spacing between stopped bicyclists was measured using the trajectory database. Platoons of bicyclists were identified by grouping bicyclists who stop (minimum speed <0.1 m/s) during the same signal phase on the same approach. The stopping positions of the platoon members were analysed to find the distance from each bicyclist to his or her nearest neighbour. The resulting lateral, longitudinal and Euclidean distances between the bicyclists are shown in the boxplots in Fig. 18.6. The measurements were taken from the centre of the bicyclists, which is typically near the head, as shown in the top left corner of the figure.

The findings shown in Fig. 18.6 are useful for calibrating microscopic simulation tools that require the minimum lateral spacing at a speed of zero. Furthermore, the spacing data can be used to quantify the density of bicycle traffic at different driving speeds. Density, along with the findings presented in Sect. 18.3.1.1 can be used to estimate the flow of bicycle traffic using the fundamental relationship between density (bicycles/m^2), speed (m/s) and flow (bicycles/h/m). This relationship has been confirmed by researchers to describe bicycle traffic in the same way as it has been used for decades for motorised traffic [9, 25].

18.3.2 Tactical Behaviour

Five aspects of the tactical behaviour of bicyclists at signalised intersections were selected for analysis in UR:BAN; the infrastructure selection upon approaching the intersection (bicycle lane, roadway or sidewalk), the response to a red traffic signal, the stop position when queuing, the type of left turn manoeuvre and the direction of travel. In the first step, a descriptive analysis of the tactical choices was carried out and the number and percentage of bicyclists observed executing the various behaviours was recorded. This information can be useful in creating tactical models based on the probability of a certain behaviour arising. For example, in the microscopic simulation tool VISSIM, it is currently possible to stipulate the percentage of road users that violate a red light [15]. Red light violations are then randomly simulated using this percentage. The observed frequency of bicyclists carrying of various options for the five investigated tactical behaviours are given in Table 18.3.

In order to gain an in-depth understanding of the factors which influence the tactical decisions of bicyclists, the relationships between situational variables and the observed tactical decisions were studied. A total of 43 independent variables belonging to four categories were investigated; the strategic choices of the bicyclist, the geometry of the intersection, the traffic situation and the traffic signal control. Each of the five tactical behaviours (dependent variables) and the independent variables was tested individually using null hypothesis testing ($\alpha = 0.05$) to determine if a statistically significant correlation exists. If a significant correlation was found, the effect size measures Cramer's V (V) for two categorical variables and squared canonical correlation (R_c^2) for a continuous independent variable and a categorical dependent variable were used to estimate the mag-

Table 18.3 Tactical behaviour, categories and observed frequencies

Tactical behaviour	Category 1	Category 2	Category 3
Infrastructure selection (bicycle lane available) N = 3927 bicyclists	Bicycle lane 94.6% (N = 3721)	Roadway 1.8% (N = 69)	Sidewalk 3.5% (N = 137)
Infrastructure selection (no bicycle lane available) N = 634 bicyclists	Roadway 90.5% (N = 574)	Sidewalk 9.5% (N = 60)	n. a. (dichotomous)
Response to red signal N = 2437 bicyclists	Stop 80.8% (N = 1968)	Violate 19.2% (N = 469)	n. a. (dichotomous)
Stop position N = 1648 bicyclists	Behind queue 83.9% (N = 1382)	In front of queue 16.1% (N = 266)	n. a. (dichotomous)
Left turn manoeuvre N = 531 bicyclists	Direct turn 17.9% (N = 95)	Indirect turn 35.8% (N = 190)	Indirect turn against direction of travel 46.3% (N = 246)
Direction of travel N = 5109 bicyclists	With direction of travel 97.9% (N = 5003)	Against direction of travel 2.1% (N = 106)	n. a. (dichotomous)

nitude of the effect. The independent situational variables that were found to have at least a small effect on the tactical choice were used to estimate a logistic regression model for each of the identified behaviours. These models are to be published in an upcoming paper *Tactical behaviour of bicyclists at signalised intersections* by H. Twaddle and F. Busch.

18.4 Behaviour Modelling

The outcomes of the behavioural analyses described in Sect. 18.3 were used to develop improved methods for modelling the operational and tactical behaviour of bicyclists for application in microscopic traffic simulation tools. A number of the findings, such as the distributions of the desired speed and the minimum and maximum acceleration, are useful for calibrating models that are currently implemented in simulation software such as VISSIM and SUMO. Other findings, such as those describing the acceleration and deceleration profiles of bicyclists, necessitate new modelling approaches.

18.4.1 Modelling the Operational Behaviour

The findings from the operational behaviour analysis described in Sect. 18.3.1 are applied in this chapter to refine and extend the model proposed by Falkenberg et al. [13]. In their model, bicyclists are represented using a diamond shape that is positioned with the vertices pointing along the lateral and longitudinal axes of the bicyclist. This shape supports staggered queuing as well as offset riding along links [14]. In this project, the Falkenberg et al. [13] approach was extended to include both a physical and a psychological boundary of the simulated bicyclists. The physical boundary defines the shape of the simulated bicyclist and acts as a hard barrier between the bicycle and other road users and objects in the simulation (shown in black in Fig. 18.7). Although different lengths and widths can be set for different types of bicyclists, the shape is static and does not change throughout the simulation. Generally, two or three types of bicycles with their corresponding length and width measurements are sufficient to describe a population of bicyclists (e. g. normal bicycles, cargo bicycles and bicycles with trailers). This static physical boundary is the extent of the model proposed by Falkenberg et al. [13], which is implemented in the microscopic simulation tool VISSIM.

The additional boundary proposed here is the psychological boundary, which defines the desired safety spacing of the bicyclist and is shown in blue in Fig. 18.7. This spacing is applied in addition to the physical boundary defined by the Falkenberg et al. [13] model. The desired lateral and longitudinal spacing of the bicyclists are set stochastically amongst a population of simulated bicyclists to recreate the variety in spacing preferences that exists in reality. The range of the spacing parameters measured in Sect. 18.3.1.3 is used to create a population of bicyclists with differing spacing preferences. There is no psychological spacing distance behind the modelled bicyclist to simulate the premise that bicyclists are not concerned with and only have limited control over the actions of road users travelling behind them.

The spacing values given in Table 18.4 are proposed based on the analysis of the observed trajectory data. The total lateral spacing of the bicyclist including the physical and psychological model range from a minimum of 0.6 m to a maximum of 1.1 m while stopped in a queue. The total longitudinal spacing while stopped in a queue ranges from 0.9 to 1.8 m. These values correspond with the median and 75th percentile of the observed values in both cases. The distances are measured from the centre of the bicyclist.

The safety spacing maintained by bicyclists does not remain constant but is rather adjusted continually based on the situation and the momentary preferences of the bicyclist. It is proposed here to include this intra-bicyclist variation by using a simple relationship

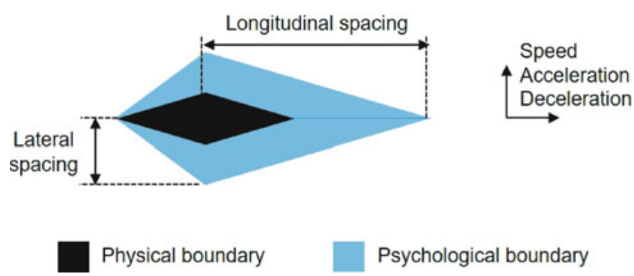

Fig. 18.7 Proposed approach for modelling the operational behaviour of bicyclists using a physical and psychological boundary

Table 18.4 Proposed values for lateral and longitudinal spacing parameters with a speed of 0 m/s

	Lateral spacing (m)	Longitudinal spacing (m)
Physical model	0.3	0.4
Psychological model minimum	0.3	0.5
Psychological model maximum	0.8	1.8

between the current speed, the desired speed and the spacing as shown in Eq. 18.2.

$$\left[Sp_{\mathrm{lat}}, Sp_{\mathrm{long}}\right] = \left(1 + \alpha \frac{s}{s_d}\right) \left[\mathrm{Sp}_{\mathrm{lat\ min}}, \mathrm{Sp}_{\mathrm{long\ min}}\right] \tag{18.2}$$

In Eq. 18.2 $\left[Sp_{\mathrm{lat}}, Sp_{\mathrm{long}}\right]$ is the current spacing vector (m), $\left[Sp_{\mathrm{lat\ min}}, Sp_{\mathrm{long\ min}}\right]$ is the minimum spacing vector (m), s is the current speed (m/s), s_d is the desired speed (m/s) and α is a constant that controls the magnitude of the spacing variation. This constant is not estimated here because the spacing variation could not be observed using the collected trajectory data at intersections.

The speed characteristics of the simulated bicyclists are randomly selected from the distributions shown in Fig. 18.3. The regression model coefficients given in Table 18.2 are implemented in the simulation by adjusting the desired speed of the simulated bicyclist by the respective speed difference (coefficient in the regression model). For example, if a simulated bicyclist that is randomly assigned a speed of 5.1 m/s from the distribution in the base scenario (bicycle lane use, travelling straight in the mandatory direction of travel) tactically decides to ride on the sidewalk, the desired speed will be reduced to 3.7 m/s.

Within the project UR:BAN, a new method for modelling the acceleration and deceleration profiles of bicyclists based on the observations presented in Fig. 18.5 was developed. A detailed description and evaluation of the developed modelling approach can be found in the paper *Modeling the speed, acceleration and deceleration of bicyclists for microscopic traffic simulation* by H. Twaddle and G. Grigoropoulos [32]. This modelling approach can be combined with the speed distributions, regression model and dynamic spacing model to improve the realism of microscopic traffic simulation of bicyclists.

18.4.2 Modelling the Tactical Behaviour

Two methods were developed and evaluated within UR:BAN for predicting the tactical behaviour of bicyclists based on the observed situational data; logistic regression modelling and machine learning using artificial neural networks. Modelling approaches were developed for the five tactical choices introduced in Sect. 18.3.2; infrastructure selection upon approaching the intersection (bicycle lane, roadway or sidewalk), response to a red traffic signal, stop position when queuing, type of left turn manoeuvre and the direction of travel. For both approaches, the dataset was broken into two subsets, one of which was used for estimating (training) the model while the other was used to validate (test) the resulting model. Depending on the size of the dataset for each tactical choice, 60 or 80% of the data was used for calibrating and the remainder was used for validating. The models were evaluated using confusion matrices and five evaluation measures; accuracy, positive prediction value, negative prediction value, true positive rate and true negative rate. The Receiver Operating Characteristic (ROC) curve was used to determine the optimal classification cut-off point for the binomial choice models.

Both methods were found to produce similar results based on an evaluation of the resulting confusion matrices, with accuracies that ranged from 76% to 92%. Machine learning approaches are known to produce exceptional predictions given a large training set and a large number of independent variables. This accuracy, however, comes at the cost of interpretability of the model. The resulting 'black box' may be useful in predicting outcomes, but the relationships between the input parameters describing the situation and the tactical choices are difficult to discern. The logistic regression models were deemed superior because of the possibility to understand the relationships between the observed situation and the choice outcome. The resulting choice models are to be published in an upcoming paper *Tactical behaviour of bicyclists at signalised intersections* by H. Twaddle and F. Busch.

18.5 Discussion and Conclusions

The realistic inclusion of bicycle traffic in microscopic traffic simulations is becoming increasingly important as the number of bicyclists in many urban areas continues to rise. Within the project UR:BAN, the operational and tactical behaviour of bicyclists was analysed using trajectory data extracted from videos collected at four intersections in Munich, Germany. One application for the findings from these studies is the calibration of existing models for bicycle traffic in simulation software. Shortfalls in the ability of currently available software to simulate bicycle traffic were identified and addressed in UR:BAN by extending existing models or developing new approaches for modelling the behaviour of bicyclists.

Three aspects of the operational behaviour of bicyclists were identified for analyses and model development; speed, acceleration and spacing. The use of trajectory data enabled the detailed investigation of the identified aspects. Data from 704 bicyclists who approached the intersection while the signal was green and did not interact with other bicyclists were used to select and fit distribution curves for the average speed, the range of speeds and maximum and minimum speed. A multiple regression model was estimated to quantify the effect of selected tactical behaviours on the average speed. The acceleration and deceleration behaviour of 326 bicyclists who stopped at a red light but were not influenced by other road users was investigated to select and fit distribution curves. Analogous to the speed analysis, mean acceleration, range of acceleration values and the minimum and maximum acceleration were investigated. An in-depth analysis of the acceleration profiles indicated that bicyclists do not accelerate at a constant rate, but rather begin an acceleration process with a relatively low acceleration, reach a maximum acceleration when approximately 1/3 of the process is completed and then decrease the rate of acceleration until the desired speed is reached. An investigation of the deceleration profiles revealed relatively constant rates of deceleration throughout the process. The lateral and longitudinal spacing of 630 bicyclists who stopped at a red traffic signal in a platoon of bicyclist were analysed to provide calibration data for existing models. An extension of the Falkenberg et al. [13] model is proposed based on the observed spacing behaviour that allows for the simulation of inter-bicyclist and intra-bicyclist variance in spacing behaviour. Together, the proposed methods for modelling the operational behaviour of bicyclists offer the potential to increase the realism of bicycle simulations.

The methods developed for predicting the tactical choices of bicyclists using independent variables describing the current situation were found to deliver accurate results (accuracies ranged from 76% to 92%). The inclusion of independent variables describing the personal characteristics of the bicyclists, such as gender, age, bicycling experience, bicycling preferences and aggressiveness, would likely further improve the predictive power. Data describing the personal characteristics of the observed bicyclists were not collected because of privacy laws and the high position of the video camera that was necessary for extracting accurate trajectories. Additionally, models including personal attributes would have limited application in microscopic traffic simulation because the agents in currently available tools are not equipped with such attributes. Therefore, as long as the variation in observed behaviour can be recreated within the simulation and the relationships between the different aspect of the operational and tactical behaviour can be maintained, it is unnecessary to associate these behaviours with personal attributes.

The operational model and tactical models can be combined in the simulation to reflect the feedback loops proposed by Michon [16] in his hierarchy of road user behaviour. This was realised in UR:BAN by determining the tactical behaviour using the developed logistic regression models. This behaviour was linked to the operational level through the speed multiple regression model. The resulting approach allows for a more realistic simulation of bicyclist behaviour at both the operational and tactical level.

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Urban Interaction – Getting Vulnerable Road Users into Driving Simulation

19

Christian Lehsing and Ilja T. Feldstein

19.1 Motivation and Goals – The Situation in 2012

Despite the increase of population by 4% registered-vehicles by 15% between 2007 and 2010, the number of road-traffic fatalities worldwide remained about the same at 1.24 million per year [1]. The stagnation of this still remarkable high number suggests that efforts being put into developing road safety measures are actually taking effect and preventing a higher number of road incidents and deaths. Furthermore, the rapid development of novel driver assistance systems, the rising implementation of intelligent traffic infrastructure, and the demographic change worldwide as well as individual performance abilities have had a remarkable effect on driving behaviour and habits. Hence, the classical regularities and models used for traffic research need to be updated. Actual driver and traffic models have a limited capacity to sufficiently illustrate the aforementioned aspects. Only the road users' reactive behaviour can be taken into consideration; the intervention of assistance systems, an increased amount of information, and the interaction or mutual behaviour adaption of partially assisted traffic participants remain unconsidered. This pushes simulation environments currently being used (driving and traffic simulation) to their limits. Performing efficacy- and safety-tests on future driving assistance or information systems in virtual environments under these conditions is more than questionable, especially in terms of validity. Testing new applications or systems in reality with dummies is costly and time consuming but will be necessary in the future. The interaction between the involved road users is also missing. Moreover, the performance of huge traffic data collections is associated with an immense planning and cost effort. The demand for an effective, efficient tool that supports the activities mentioned is therefore given [2].

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19.2 Social Interaction at a Glance

Humans adapt their behaviour towards each other in their various everyday roles – they interact. This is sometimes useful to achieve one's goals and under special circumstances is purely necessary to survive. The latter aspect is a feature of the traffic system, where human beings occupy one or more roles depending on the type of road user. Independently of this, the behaviour adaptation process (Fig. 19.1) consists mainly of interpreting:

- the environmental context,
- surrounding traffic, and
- responses to one's own behaviour [3].

One's behaviour is adapted as needed after interpreting the behaviour of other road users with whom one may come into contact while claiming the same infrastructure (e. g. road segment). This is supported by verbal or nonverbal communication, or both where applicable. Gestures, mimic, body posture, walking/driving speed, and auditive or visual signals serve as communication instruments and hints during encounters between human road users, for whom nonverbal communication plays a significant role [4, 5]. A system of common understanding is necessary to enable the mutual stimulus reaction scheme among them and to ensure an externally visible adaption of the participants' planned actions [6–8]. The common goal of interaction is behaviour coordination.

In driving simulators, various data can be recorded that allows a detailed analysis of the coordination procedure. Velocity, acceleration, position, and use of the horn or blinkers represent just some of this data. This data, together with sophisticated analysis methods and the underlying social-interaction theory introduced, forms the basis for investigations into interaction during multi-participant simulations. In particular, behaviour between cars and pedestrians and its quantification will be described in detail. Linear and nonlinear approaches are taken to analyse the "behavioural ping pong" unfolding between road users who meet in the same simulation. These analyses will help to understand processes occur-

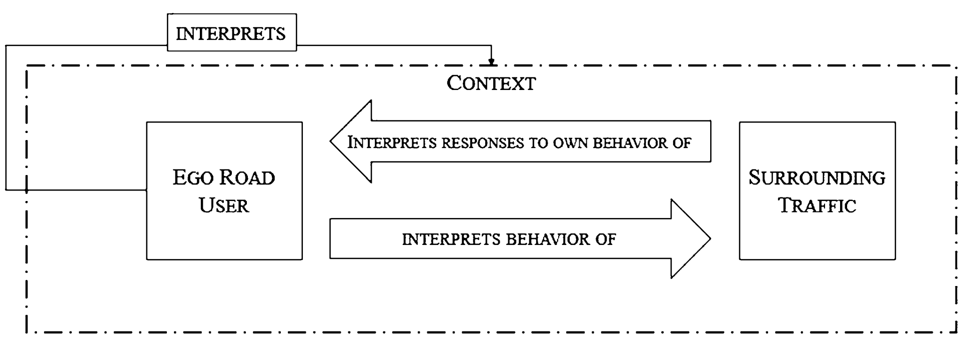

Fig. 19.1 Cooperation scheme. (Based on [3])

ring in traffic that might lead to critical situations and to identify the role of good or poor interaction/cooperation.

19.3 Pedestrian Simulators – A Global but Divergent Approach

For over 40 years now, traffic researchers have been putting effort into the investigation of pedestrian behaviour, often focusing on children and the elderly. They were mostly restricted to observational studies or accident-report analyses because experiments in real life that assured the participants' safety were difficult to set up and to conduct. For instance, researchers in the UK used the so-called "pretend road method" to investigate children's road-crossing behaviour [8–10]. Under this method, participants are placed in front of an artificial street parallel to an actual one (Fig. 19.2). The participants are then asked to cross the artificial street basing their decisions on the real street's car movements.

With the progress of technology, more and more possibilities in terms of virtual reality (VR) simulators are appearing and opening up new avenues for researchers. Most of these devices – often referred to as pedestrian simulators – can be classified into cave automatic virtual environment (CAVE) setups and head-mounted display (HMD) setups.

The French research institute IFSTTAR presented one of the first CAVE-based pedestrian simulators in 2003 and it has been constantly enhanced ever since [11, 12]. Other research institutes such as the Ben Gurion University of the Negev [13, 14], the University of Valenciennes [15], and the University of Iowa (Fig. 19.3; [16, 17]) followed suit.

Pedestrian simulators based on HMDs started emerging at about the same time as those based on CAVE technology. Among the first, Simpson et al. [18] presented a working setup about one and a half decades ago. Although the HMD used was capable of producing a stereoscopic image, the researchers initially displayed the same full-color image with a resolution of 640 × 480 for each eye. As the entertainment industry entered the market for HMDs, great technological leaps were achieved with new, more powerful devices being released almost every year now. New HMD-based pedestrian simulators such as those at

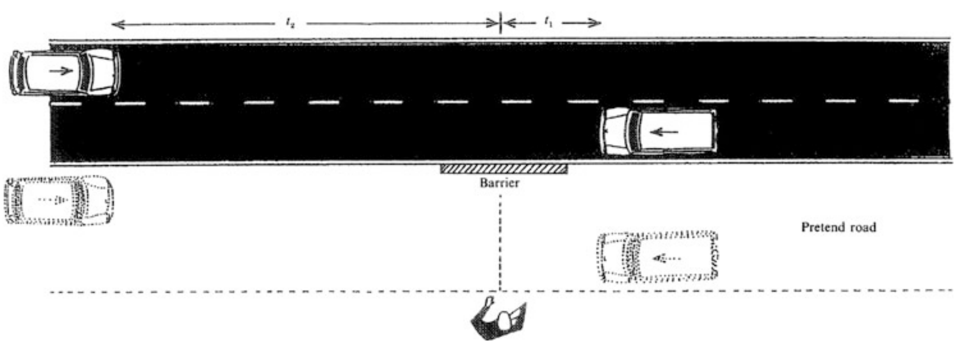

Fig. 19.2 Pretend road method [8]

Fig. 19.3 Pedestrian virtual environment at the University of Iowa [16]

the University of Guelph [19] or the Technical University of Munich [20] therefore began to appear during the past few years. The latter will be described thoroughly in the next section.

It should also be mentioned that some research institutes developed small-scale, less-immersive but more transportable setups displaying visual output on several screens [21].

19.4 Implementing the VRU – The UR:BAN Approach

The following section describes the components of the pedestrian simulator setup realised at the Technical University of Munich (Fig. 19.4).

19.4.1 Virtual Environment

The Silab software framework, which the Würzburg Institute of Traffic Sciences originally developed as driving simulator software, was chosen to represent the virtual environment. Software modifications were thus needed to implement a steerable human avatar in the virtual environment. This software was chosen because the university's driving simulators also use Silab. Connecting multiple simulators enables various road users to meet in the same virtual session thereby creating new possibilities for interaction investigations [22].

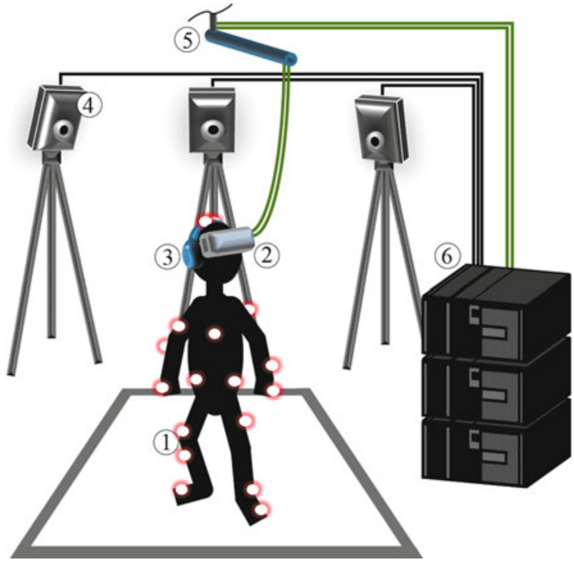

Fig. 19.4 Simplified concept of the current pedestrian simulator setup at the Technical University of Munich. (*1*) Motion suit, (*2*) Head-mounted display, (*3*) Headphones, (*4*) Motion capture system, (*5*) Dynamic cable mount, (*6*) Data processing and data control center

19.4.2 Motion Capture

A Vicon motion capture system was implemented and combined with a motion suit developed ad hoc to transfer the user's body movements and body language to the avatar in the virtual environment. The motion suit (Fig. 19.5) is a full body suit made of highly stretchable tissue and equipped with 39 infrared LED markers emitting 850 nm light through diffusers. These active markers ensure better tracking quality than the passive-reflective markers that Vicon provided. The motion-capture system uses trigonometric algorithms to recalculate each marker's exact 3D position followed by the creation of a human model according to the Vicon Plug-In-Gait model. The body segments' positions and orientations are transferred to Silab, which implements them in its avatar.

19.4.3 Visual Interface

The visual feedback for the user was realised using an HMD, initially the Oculus Rift Development Kit (DK) but later the successor model, Development Kit 2 (DK2). The device enables stereoscopic perception of the virtual environment with a resolution of 960 × 1080 per eye. Silab renders a different image for each eye, taking the distance in between the eyes into account and thereby enabling a realistic 3D view. With a field of view (FOV) of about 100° diagonally, the Oculus Rift DK2 is not far removed from human binocular vision, which is about 114° horizontally according to Howard [23]. The human horizontal far-peripheral vision, however, extends up to 200° [24] and cannot be accommodated

Fig. 19.5 Pedestrian simulator at the Technical University of Munich

using this head-mounted display. This needs to be taken into account when creating an experimental design to answer specific research questions.

19.4.4 Acoustic Interface

Acoustic perception is important for pedestrians in road crossing scenarios. Specifically in cases where vehicles are approaching from various sides, proper 3D sound perception of those vehicles helps the pedestrian to orient himself during his crossing task. However, implementing such an acoustic component is fairly challenging because an extensive sound library is needed covering different types of ambient sounds and specific objects' sounds such as a large variety of tire, engine, and airstream noises. These object sounds need to be adaptable depending on the object's position, velocity, and direction within the virtual environment as well as on the pedestrian's relative position and orientation with respect to the specific object. For this, a performant sound engine was implemented mixing basic sounds to generate realistic 3D stereo sounds. To isolate the user from the laboratory's noises, headphones were chosen over loudspeakers. This adds another difficulty as the headphones move together with the user's head and these tracked movements are used to constantly recalculate the representation of the acoustic environment in real-time.

19.4.5 Boundary Warning System

Since the virtual environment possess no boundaries except for those of the laboratory itself, the user must be prevented from colliding with walls and other objects in real life, which cannot be seen due to the HMD. A three stage boundary warning system was therefore implemented haptically, visually, and acoustically forewarning the user of imminent collisions. Software, to which information about authorized walking space is input, triggers the alert indicating the direction of the boundary that the user is approaching. The user wears a belt around the waist equipped with several vibrating motors that are activated in direction of the boundary. If the user continues walking in the direction of the boundary, a virtual fence appears visually in the virtual environment. If the user also ignores this warning, a 3D warning sound is added.

19.4.6 Dynamic Cable Mount

Data between the user and the control center is exchanged through cables. The control center transfers the visual and acoustic images to the HMD and the headphones, whereas the HMD sends motion data about the user's head captured by the integrated inertial-measurement units to the control center. Cables are necessary as a wireless transmission of that data volume is hardly realizable with acceptable latency at the current state of technology. The HDMI cable and the USB cable longer than 5 meters should be connected to amplifiers. Installing a cable mount above the laboratory's action space is advised to avoid interfering with the user. The cable amount should be dynamic and actively follow the user's movements. If the cable mount is dragged passively only, its inertia will create a drag on the HMD and therefore the user's head when accelerating or decelerating.

19.5 The Multiple-Simulator Setting – Enabling Social Interaction

Driving simulators have been used for decades to conduct studies under safe, standardised, repeatable conditions focusing on the driver's behaviour in certain scenarios and situations. These conditions highlight some of the advantages associated with the use of simulators in traffic research. In contrast, one of the main criticisms is the validity of the data gathered during the classical drive through an artificial environment with programmed, surrounding traffic. These surrounding road users obey traffic rules and engage in the scripted behaviour needed to produce the traffic constellation in which the researcher is interested. This worked well for highway scenarios with uniform traffic flow where interaction between drivers is seldom, but traffic in cities is different. Transient situations, heterogeneous participants, dynamic change of conditions, information overflow, and vital behaviour adaptations are just a few aspects characterizing urban traffic.

Fig. 19.6 Possible constellation of linked simulators

To conduct investigations that deal with traffic in urban areas, research has to enable the natural processes involved. One of these processes is the social interaction mentioned between traffic participants intended to coordinate behaviour and reduce the risk of accidents or worse. Therefore, the classical approach where one participant in one driving simulator is surrounded by programmed traffic that is only able to act within the limits of its script is insufficient. In the UR:BAN project, it is assumed that linking two or more simulators (Fig. 19.6) opens communication channels that allow behaviour adaption of the simulation participants. Depending on the research question, it is possible to link several driving simulators or a driving simulator to a pedestrian simulator as well as to a truck simulator or that of a powered two-wheeler.

These constellations allow deeper insight into the mutual reaction scheme that road user exhibit while they adapt to the situation, environment, and surrounding traffic.

Besides the advantages mentioned, some aspects of running an experiment with two or more participants need to be considered (see Chap. 23):

- Two or more simulators need to be synchronised.
- Participant supervision takes more time than it does in single-simulator studies.
- Test tracks containing the situations of interest might be more complex.
- Synchronizing participants in the simulation to build "interactive" situations is sometimes more complex.

19.6 Interaction in Numbers – A Methodological Overview

One of the goals in the "Simulation and Behaviour Modelling" subproject was to find tools and methods that on the one hand can enable human interaction in the synthetic environment of a driving simulation and on the other hand are apt to express this special interhuman process in numbers. This quantification should foster investigation into the basic patterns of human-related issues of urban traffic. This chapter introduces and summarizes promising classical and new approaches to data analysis such as safety measures, and linear and nonlinear analyses.

All these methods use the speed signals of the driver and the pedestrian in different urban encounters. It is assumed that the adaption of each individual's behaviour can be best detected via these signals.

The driver in a representative study encountered two types of pedestrians (programmed/bot vs. human-controlled) in three varying types of crossings (free lane vs. occlusion vs. zebra crossing). These independent variables served as a starting point for the following analysis of dependent variables such as time to arrival (TTA), deceleration-to-safety time (DST), braking pressure, and average speed.

19.6.1 Safety Measures

The classical way of analyzing human behaviour in traffic is to look at fundamental metrics such as speed, distance, and brake-reaction time or similar – all related to traffic-conflict severity. Further metrics can be computed based on this data, which the driving simulation software itself can easily record. The TTA (similar to time to collision (TTC) but intended for road-user trajectories that might intersect) employs both road users' speed and the distance at the moment of the driver's first brake reaction to calculate the time that the driver would need to reach the street segment that the pedestrian would also occupy if the driver had not braked. The DST, which is the driver's deceleration necessary to achieve a preselected safety time (time at which the pedestrian crossing zone is crossed after the pedestrian has crossed). Furthermore, braking pressure can reveal some information about the unexpectedness of crossing events (e. g. occlusion situations) [25, 26].

The differences in the yielding behaviour become obvious in the figure above (Fig. 19.7). The TTA's mean value varies remarkably in situations where the driver has the right of way and the pedestrian tries to cross the street with a focus on safe crossing. Whereas in the situation with zebra crossing, the driver behaves more uniformly, independently of the type of crossing pedestrian. This might result from the reversed right of way in this situation [27].

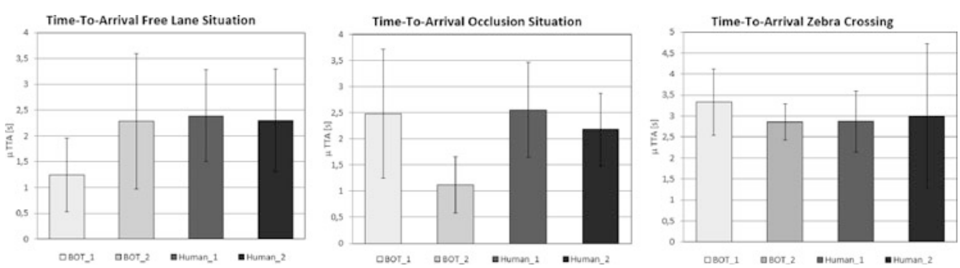

Fig. 19.7 Time to arrival in three different driver-pedestrian encounters

19.6.2 Time Series Analysis

As stated in Sect. 19.2, interaction takes time and is therefore a time-related construct. The safety measures mentioned in Sect. 19.6.1 account poorly for this and other methods need to be applied to consider the timing aspect of the driving data. A linear approach to this can be found in time series analysis and especially in the cross-correlation approach where similarities between two time-based signals (here speed signals) are calculated [28]. Both signals are time shifted against each other to find the maximum correlation between them. The following figures show examples of human-human and human-bot encounters in the free-lane situation.

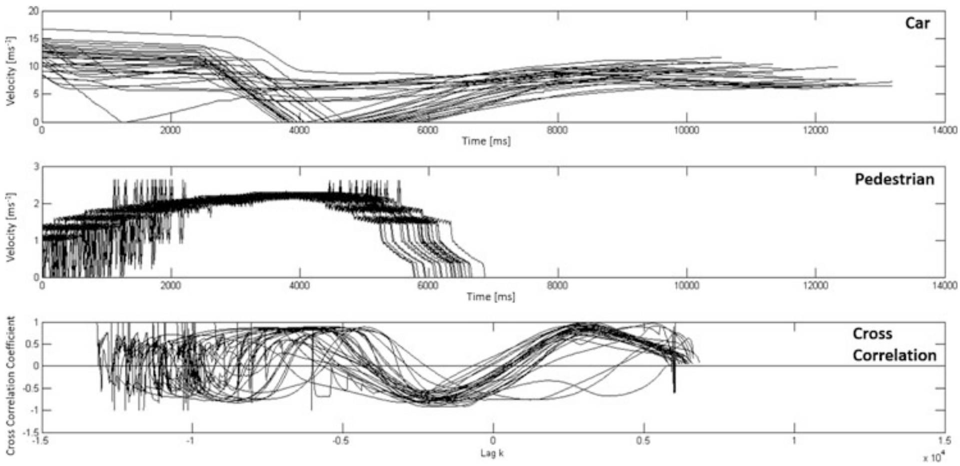

Fig. 19.8 Time series analysis for situation with programmed pedestrian

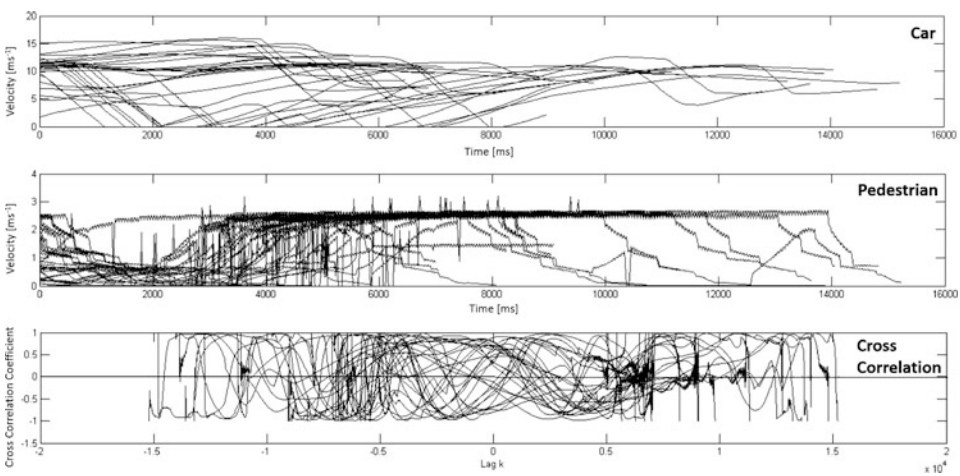

Fig. 19.9 Time series analysis for situation with human controlled pedestrian

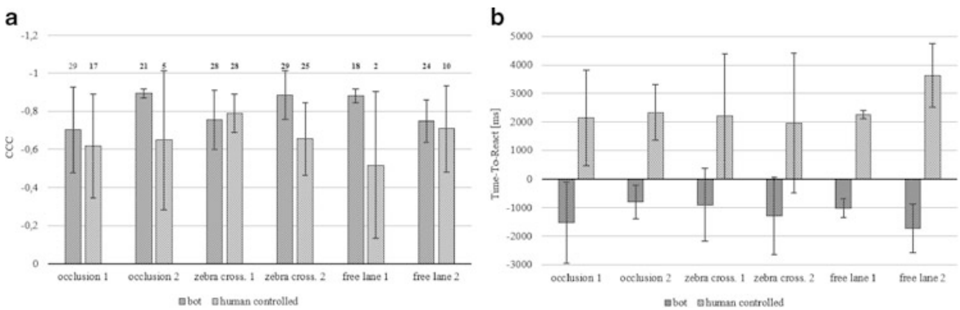

Fig. 19.10 Bar chart for cross correlation coefficients (**a**) and related time lags (**b**)

The diagrams show the speed signals of the car (upper graph) and the pedestrian (middle graph) and the resulting cross correlation curve (bottom graph; cross correlation coefficient over time lag k). The different speed behaviours of the two pedestrian types are clearly visible. In the situations with the programmed pedestrians (Fig. 19.8), only the driver could react whereas in the situations involving two humans (Fig. 19.9), both were able to adapt their behaviour cooperatively resulting in a fuzzier graph for the cross correlation coefficient. Another representation of time series analysis is shown in Figs. 19.10 and 19.11. Here, the maximum cross correlation coefficient with the necessary time shift (lag k) is displayed. The time shift of the signals is assumed to be the time the lagging time series needs to answer the behaviour of the leading time series and is therefore called time to react (TTR). In case of a negative TTR, the programmed pedestrian (bot) is the leading time series and in case of positive TTR the driver leads the behaviour adaption process in urban encounters.

Using cross correlation to analyse the signals shows conclusive results by means of the presented metrics. The TTR can detect differences in the type of crossing pedestrian as well as the cross correlation coefficient. The disparity can be visually supported by the given graphs [22].

19.6.3 Nonlinear Analysis of Driving Data

Within the scope of nonlinear approaches to quantifying and visualizing behaviour, the method of cross recurrence plots (CRPs) and subsequent analysis of these plots using cross recurrence quantification analysis (CRQA) show high potential supporting research on interaction in traffic.

The method, first established in 1987 was used to describe dynamic systems [29]. Climate and financial researchers applied it successfully (e. g. [30]) and recent approaches used it to describe behaviour in other disciplines such as traffic [31] or aviation [32]. In the UR:BAN experiments described here, the behaviour between a driver and a pedestrian

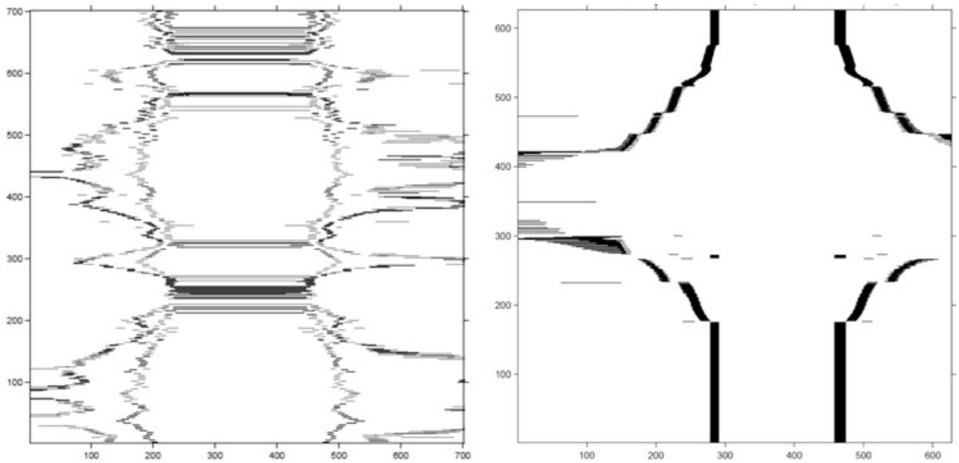

Fig. 19.11 Examples of cross recurrence plots

was of interest. Their speed and acceleration signals were analysed to reveal underlying processes that are related to interaction. The CRPs were able to distinguish between a programmed and a human-controlled pedestrian. The latter was able to interact with the car via speed reduction or vice versa. The following are two typical plots based on the aforementioned signals. The left plot visualises the encounter between the driver and a programmed vulnerable road user (VRU) and the right the human-human encounter (Fig. 19.11, axis indicate duration of encounter in ms).

Using CRQA, the structures and textures in these plots can be quantified and the behaviour of the (car-pedestrian) system can therefore be described (Figs. 19.12, 19.13 and 19.14).

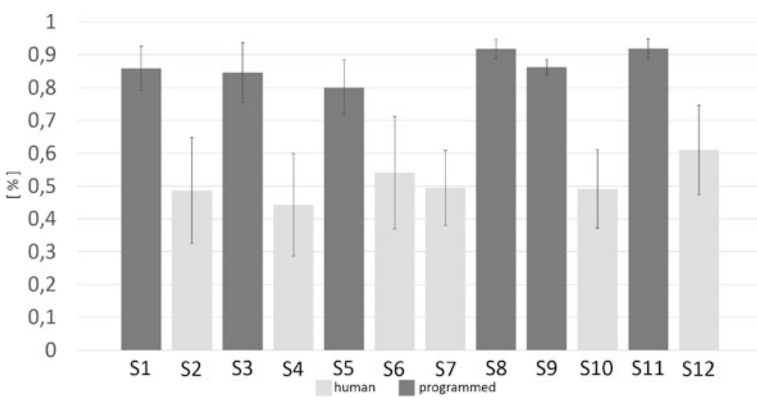

Fig. 19.12 Measure “determinism” of cross recurrence quantification analysis

Several complexity measures have been developed in the recent years, some of which are:

- *recurrence rate (RR)*: Counts the number of black dots in a CRP and is therefore a density measure for these points (and corresponds to the probability of recurrence states);
- *determinism (DET)*: Also predictability; takes diagonal lines into account and calculates the ratio of diagonally arranged points to all recurrence points in a CRP;
- *average diagonal line length (L)*: The diagonally arranged structures in a CRP represent the time intervals during which different parts of a trajectory are close to one another and thus describe the divergence of the trajectory segments in the phase space; and

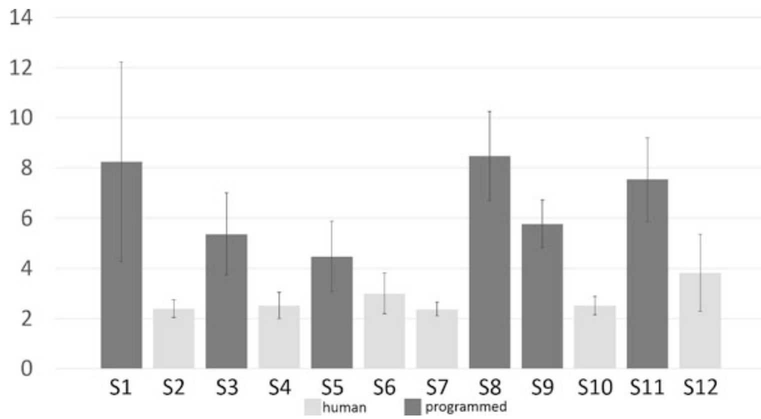

Fig. 19.13 Measure "average diagonal line length" of cross recurrence quantification analysis

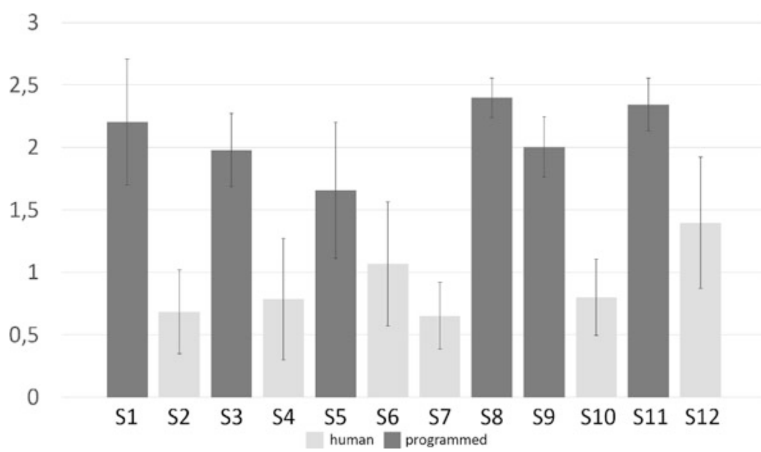

Fig. 19.14 Measure "entropy" of cross recurrence quantification analysis

- *entropy (ENT)*: Informs about deterministic structures and their complexity and is related to the Shannon entropy concerning the diagonal-line-length frequency distribution; can be computed for black and white area [33].

Applying CRQA to the plots, the following results show that the analysis is sensitive to differences in the constellation of road users.

These are just a few examples of measures. Not all have shown sufficient results and further analyses has to be performed to generalize the outcomes of the described experiments. Appropriate filtering of the data before applying CRQA is another aspect that has to be taken into account when looking at the underlying data of the signals.

19.7 Conclusions and Outlook

The goal of the activities in the Simulation subproject was the coupling of various simulators to enable social interaction in synthetic environments such as driving simulations. Detailed analyses with classical and novel methods has shown that it is possible to induce different behaviour when the experimental setting features two instead of one simulator and a human controls the surrounding traffic. Nevertheless, effort increases when the research question calls for multi-participant settings and two or more humans to meet in the same traffic scenario and react to each other. The gathered data seems to be more valid (compare [22] and [27]), but further analyses and especially comparison with naturalistic driving data would positively support the endeavors undertaken in the UR:BAN initiative. Ecological validity is a central aspect when it comes to the robustness of simulation data and the subproject Simulation tackled these issues with new technical and methodological approaches that seem promising.

For the future, the amount of technical equipment in the motion lab (which brings the pedestrian into the simulation) will be reduced and the calibration process simplified. Further investigations with driver-pedestrian encounters are planned, especially in the context of automated driving where the technological solutions of recent years open a new chapter in the pedestrian-driver conflict in urban areas. This constellation challenges the developers of the algorithms for environmental understanding of self-driving cars (independently from the level of automation) in unsuspected ways.

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Encounters Between Drivers with and Without Cooperative Intelligent Transport Systems 20

Katharina Preuk, Mandy Dotzauer, Frank Köster, and Meike Jipp

20.1 Cooperative Intelligent Transport Systems

Cooperative intelligent transport systems (C-ITS) appear to be a promising solution to increase road traffic safety in urban areas as today the vast majority of persons lives in urban areas or visits them frequently. In consequence, traffic increases and so do chances of fatalities and traffic congestion [1]. In Germany, the percentage of persons killed in urban areas increased by 5% from 2013 to 2014 [2]. Initiatives such as UR:BAN have formed focusing on the development of C-ITS in urban areas counteracting these issues [3]. Especially, traffic light-controlled intersections came into the focus of research. Traffic lights regulate traffic in complex intersections where different kinds of road users meet and interact. However, studies have shown that traffic lights trigger stop-and-go driving that is associated with increased fuel consumption, CO_2 emissions, congestion and driver frustration [4, 5]. Additionally, the switching of traffic light signals is difficult to anticipate. The inability to predict the switching is associated with a high degree of drivers' uncertainty, anxiety and increased workload [6–8]. Especially the so-called dilemma zone appears problematic while approaching traffic lights. Drivers may be too close to the intersection for stopping safely, but also too far away for passing through. An increased number of crashes has been reported in such zones. In addition, drivers' workload appears to be higher [9–11]. Another difficult situation at signalised intersection is the start-up at the onset of green. Drivers need some time to react to signal changes. This time is called start-up lost time. Especially in large urban cities, effects of start-up lost times are significant.

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Drivers often experience traffic jams, lose attention to signal changes and miss the onset of the green phase respectively. Consequently, traffic flow deteriorates at the signalised intersections [12].

Traffic light assistance systems can support drivers in these situations. Such systems can be understood as an umbrella term for various kinds of C-ITS applications for signalised intersections. Their development was the goal of several research projects such as eCoMove, INTERSAFE or UR:BAN focusing on different aspects such as traffic flow optimisation, eco driving or road traffic safety [13, 14]. Traffic light assistance systems are based on information exchange via either wireless communication between vehicle and traffic light or mobile communication networks (i. e. smartphones). Vehicle-to-infrastructure communication is based on communication standards (e. g. ETSI G5, IEEE 802.11p). The traffic light sends its current and upcoming traffic light state to so-called road site units (RSU). Road site units can be part of the infrastructure bundling incoming information of traffic lights and other sensors. They transmit the bundled information to the vehicles overcoming a distance of up to 700 m in urban areas [15]. Through in-vehicle applications drivers receive this information. How information is presented to drivers varies. The simplest way is to inform drivers about the current and upcoming signal and when it will switch (Fig. 20.1). More complex in-vehicle applications provide recommendations of how to efficiently approach traffic lights. For example, in the European project eCoMove, Ford developed an eco-driving system. This eco-driving system recommended the most efficient driving behaviour in terms of acceleration, deceleration, and gear-shift realised by a visual display and a haptic force feedback pedal [14].

The start-up assistance system developed by Volkswagen in UR:BAN aimed at reducing the start-up lost time after signal change. When drivers follow the advice, they are able to cross the stop line with a higher speed at the moment the traffic light switches to green (Poppe & Kranke, personal communication, April 11, 2013). Therefore, drivers cross the stop line earlier, and in turn, following traffic is able to do so as well. Various studies

Fig. 20.1 HMI draft of the currently developed urbanDRIVE at DLR. Drivers are advised to travel at a certain speed in order to cross the intersection on a green light [16]

have demonstrated the positive effects of traffic light assistance systems: More efficient driving behaviour and faster reactions to signal changes were found [14, 17]. Such systems have the potential to change the way we drive. C-ITS provide assisted drivers with information in anticipation of upcoming driving situations enabling more time and energy efficient driving. However, the penetration rate of such kind of systems will remain low for the next years. Nonetheless, the questions how such systems influence surrounding traffic should not remain unanswered.

20.2 Why Research Encounters Between Drivers with and Without C-ITS?

In 2013, the European Commission estimated an overall penetration rate of C-ITS of only 10% within the next two years, under the premises that all newly manufactured vehicles are equipped [18]. But as not all vehicles entering the market will be equipped with this technology, the percentage of the penetration rate may even be smaller than projected. Thus, only a minority will drive vehicles equipped with C-ITS. Drivers with an equipped vehicle will encounter unequipped vehicles' drivers (UVDs) most of the time. These UVDs will probably not be aware of C-ITS. However, UVDs may be affected by such systems. Different authors presume that drivers with C-ITS may show driving behaviour that may alter the encounters with UVDs [19–22]. Within the initiative ADVISORS, introducing adaptive cruise control (ACC), issues of encounters between drivers with and without systems were summarised based on results of six research projects [23]. One issue was that UVDs imitated the short following distances of equipped vehicles' drivers. In line with this result, Gouy (2013) found that UVDs' car-following behaviour was affected by automated vehicle platoons in neighbouring lanes [24]. It was found that UVDs also kept shorter headways when driving next to automated vehicle platoons with short headways. These studies show that behavioural adaptation of UVDs may be a consequence of encountering drivers with C-ITS. However, behavioural adaption of UVDs may have positive consequences: If UVDs adapt their driving behaviour to drivers with, for example, traffic light assistance system, they may also benefit from it. Consequently, the associated benefits of C-ITS may increase even without a high penetration rate. Katsaros (2011) calculated that in case of green light optimal speed advisory (GLOSA), a penetration rate of at least 50% is needed to find visible effects on fuel efficiency [25]. If UVDs imitate and adapt the behaviour of drivers with systems, significant benefits for the traffic flow and fuel efficiency may be found even with small penetration rates. This possible consequence of encounters between drivers with and without C-ITS has not been subject of research so far. Traffic simulation studies have considered different penetration rates of systems for calculating their benefits [26, 27]. However, most of the driver models in these traffic micro-simulations have constraints in terms of integrating human factors of driving [28, 29]. Thus, how UVDs may react to assisted driving behaviour of others and the consequences have not been evaluated properly.

First studies showed that drivers experiencing drivers with traffic light assistance systems feel bothered. Mühlbacher (2013) examined the influence of a traffic light assistance system on four drivers in a driving simulator study [30]. These four drivers were driving in a platoon approaching traffic lights. The penetration rate of traffic light assistance system was varied (0, 25, 50, 75 or 100% of the four drivers used a traffic light assistance system). Drivers were instructed to pull a lever when they felt irritated by the behaviour of the other drivers. It was found that with a penetration rate of 50%, drivers felt annoyed more often, especially in situations when they did not understand why drivers slowed down while approaching green traffic lights. In line with these results, Rittger, Muehlbacher, Maag and Kiesel (2015) found that UVDs felt more often irritated when drivers with systems were driving as lead vehicles in platoons and coasted for long distances in the approach to traffic lights [31]. UVDs may simply not expect or understand lower than usual speeds while approaching a green traffic light. However, understanding why others drive the way they do, is crucial for the individual driving behaviour. Drivers' behaviours and its regulation highly depends on what is anticipated of other drivers [32]. When drivers have difficulties understanding or expecting driving behaviour of others, two effects may arise: It is far more likely to perceive this driving behaviour as aversive and more difficult to adjust the driving behaviour accordingly. Frehse (2015) showed that understanding driving behaviour of others comes along with less anger, whereas not understanding the reason for, for example, a suddenly decelerating car in front increases anger [33]. The cognitive-motivational-relational theory of emotion explains why: When hindered in our goal (i. e. passing the traffic light within the green phase), we get frustrated [34]. Negative emotions, such as frustration, affect our intentions, cognition and behaviour. When being bothered, frustrated or irritated because of others, drivers tend to show more aggressive driving behaviour (e. g. tailgating, cutting off others; [35–37]). Moreover, when experiencing negative emotions, drivers are less likely to engage in adapting their driving behaviour (e. g. to assisted drivers; [38]). Drivers also tend to show unsafe driving behaviour, when having difficulties anticipating the behaviour of others. For example, most of the crashes at signalised intersections are attributed to deviating, not expected behaviour of other drivers [39]. The expected behaviour of others affects how appropriately and quickly drivers will react [40–46].

Thus, consequences of encounters between drivers with and without C-ITS may be, on the one hand, positive: UVDs may adapt their driving behaviour and show positive behavioural changes. Thus, benefits of such systems may be achieved even without a high penetration rate. However, on the other hand, encounters between drivers with and without C-ITS may also lead to safety-critical situations with UVDs. UVDs may also feel bothered by the behaviour of drivers with systems and react aggressively or less safely towards them. In turn, this might influence the acceptance of drivers with systems: Who would like to follow system recommendations when doing so leads to conflicts with others? Compliance with system recommendations, acceptance in general and willingness to use such kind of C-ITS may strongly depend on the experiences drivers with systems gain while encountering drivers without such systems. Thus, researchers and system developers should study these encounters more thoroughly in order to prevent safety and acceptance issues.

20.3 How to Research Encounters Between Drivers

Above mentioned results (Sect. 20.2) of past research illustrate the necessity to further investigate encounters between drivers with and without C-ITS. Different methods and tools have been developed to study how drivers interact with each other. Their advantages and disadvantages are discussed in detail [47–49].

Encounters between drivers may be studied in on-road studies such as naturalistic driving studies (NDS) and field operational tests (FOT). A naturalistic driving study is a study method to observe driving behaviour in real traffic. Naturalistic driving studies allow investigating everyday driving of participants in their vehicles equipped with data recorder, sensors, and cameras. Encounters with other drivers are not obstructed or biased by the presence of experimenters, instructions or the use of an unfamiliar study vehicle. Field operational tests aim to study the interaction of drivers with C-ITS on the road. Usually, FOTs are more controlled compared to NDS. Nonetheless, the recorded driving behaviour of participants is realistic and representative. Consequently, results of on-road studies (NDS and FOT) offer high external validity (i. e. degree to which study results can be generalised). However, they lack internal validity (i. e. degree to which study results can be attributed to manipulated factors and not to other confounding variables) as driving situations are not controlled. Therefore, a certain degree of experimental control may be necessary. On the one hand, participants have to meet so that encounters can be studied. Using NDS or FOT, it is unlikely to create those encounters at all – not to mention repeatedly to obtain robust data. On the other hand, even if participants meet, encounters may be biased by other confounding variables that are not controlled. Test track studies may be a solution to realise encounters between participants in a more controlled setting on closed or dedicated test roads. Here instructed participants drive instrumented vehicles in the presence of experimenters. Due to moral issues, test track studies may only focus on non-critical encounters between drivers. Studying critical encounters, driver simulation studies may be the solution. Driving simulators are a valid tool to assess driving behaviour [50–52]. In terms of research questions addressing C-ITS, driving simulators may also be the most efficient tool. The C-ITS does not really need to be implemented, but rather simulated. The necessary communication architecture and infrastructure (i. e. equipped infrastructure or vehicles) is not needed, as well. Especially research in an early stage of development of C-ITS may be realised with the help of driving simulators.

In conventional driving simulator studies participants interacted with simulated drivers (e. g. [14]). The behaviour of these simulated drivers was modelled based on driver models. However, most of the driver models are unrealistic [53]. For example, most of the car-following models describe driving behaviour as a stimulus-response function in terms of driving behaviour: Following drivers regulate their driving behaviour in accordance to the driving behaviour of leading vehicles. The Gazis-Herman-Rothery model (GHR), for instance, describes the acceleration behaviour of a following vehicle as proportional to the speed of a leading vehicle, their speed difference and headway [54]. The following driver reacts to even small changes in the relative speed even when the headway between these two vehicles is high. In contrast to this model, psycho-physical or action-point models such as the one proposed by Wiedemann and Reiter (1992) state that drivers only change their driving behaviour when certain thresholds are reached [55]. Although, the latter model integrated human factors characteristics such as safety needs and motivational factors, cognition in terms of emotions or of information processing is mostly neglected. Additionally, most of the existing driver models are not suitable for describing driving behaviour in more complex environments such as urban areas and in regard to safety research questions [29]. Hence, the human factors that may influence encounters between drivers with and without C-ITS in urban areas are neglected. However, such encounters may be studied replacing the simulated drivers with participants and coupling multiple driving simulators respectively. This concept of connected driving simulators had been realised in the MoSAIC (Modular Scalable Applications Platform for ITS Components) lab at the Institute of Transportation Systems at the German Aerospace Center (see Fig. 20.2).

In the MoSAIC simulation, multiple driving simulators are coupled. Thus, participants drive in the same virtual environment. However, the use of such a study method constitutes the need for a specifically tailored study methodology addressing the planning and conducting of the experiment as well as analysing data. Best-practices have addressed these issues [47–49]. In terms of planning studies, a major challenge is to design scenarios in a way that participants will actually meet. Another crucial point in terms of data

Fig. 20.2 Connected driving simulation realised in the MOSAIC lab at the Institute of Transportation Systems in Braunschweig at the German Aerospace Center (DLR)

analysis is that parameters are needed quantifying these encounters. Parameters have been developed describing the longitudinal driving behaviour of a platoon of drivers [30]. The length of a platoon of drivers and its variation have been used to describe car-following behaviour. In addition, another new developed parameter is used to describe the position of each driver in the platoon in relation to the other drivers [49]. In order to quantify how well drivers match their own driving behaviour to others, traditional use of statistical inference analyses may not be suitable [56]. Using spectral analysis, co-occurring rhythmic changes in the trajectories, the so-called coherence, can be applied to measure the degree of behavioural adaptation of drivers in car-following situations [57]. As described above, experiments in connected driving simulators require a tailored methodology, but also provide a tool, especially in early stages of C-ITS development, to investigate the effects of C-ITS on the behaviour of UVDs.

20.4 Encountering Drivers with Traffic Light Assistance Systems: Overview of a Study

Investigating the effects of the above mentioned traffic light assistance system is a use case best examined in a connected driving simulation. Traffic light assistance systems have the potential to enhance traffic flow and decrease environmental impact. At the same time, the traffic light assistance system leads to unusual driving behaviour. So what happens when drivers with such systems encounter other drivers? In a recent study, the effects of the driving behaviour of one driver with traffic light assistance system on two naïve UVDs were examined [57–59].

Three drivers completed the experiment in the same virtual environment simultaneously. The participants drove in a car-following scenario in an urban area. The lead driver was a confederate. The confederate's vehicle was equipped with two functionalities of a traffic light assistance system: The start-up assistance system and GLOSA. The start-up assistance system was developed by Volkswagen within the project UR:BAN (Poppe & Kranke, personal communication, April 11, 2013). The assisted confederate began accelerating before a traffic light turned green. Hence, the assisted confederate crossed the stop line with a higher velocity at the moment the traffic light switched to green. As a result, the traffic flow at signalised intersections might be optimised, especially when surrounding traffic adapts this driving behaviour. However, higher velocity in the moment of stop line crossing was only possible when the assisted confederate stopped several meters before the stop line. The parametrisation of the start-up assistance system was varied. The assisted confederate stopped either 4 m (moderate parametrisation) or 10 m (extreme parametrisation) from the stop line. The other functionality of the traffic light assistance system, GLOSA, helps preventing unnecessary deceleration behaviour in the approach to a traffic light that switched its signal from red to green. With GLOSA, the assisted confederate showed a higher velocity in the approach to a red traffic light that switched its signal during the approach.

Per experimental trial, two participants (UVDs) followed the confederate and experienced the above described system functionalities. Altogether, thirty experimental trials were executed, and therefore data of 60 drivers (40 male, 20 female) between the ages of 20 and 78 years (M = 30.6, SD = 10.8) collected. The study followed a mixed design. One factor manipulated within participants was the confederate's equipment with the two levels "with" or "without" traffic light assistance system and its two functionalities (GLOSA and start-up assistance system). The other factor manipulated within participants was the number of intersections as UVDs repeatedly drove through signalised intersections. The parametrisation of the start-up assistance system was varied as a factor between participants and nested within "with" level of the factor confederate's equipment. The parametrisation was either moderate (4 m) or extreme (10 m). The position of the UVDs (either 1st or 2nd UVD) was randomly assigned and another factor manipulated between participants. The true purpose of the study was disguised: UVDs were told that the study aimed to investigate different driver types in urban areas. UVDs experienced the scenario with and without the confederate's equipment in a randomised order. After each scenario, a questionnaire on how UVDs rate the confederate's behaviour was given. At the end, a post-questionnaire with open-ended questions was administered to determine whether UVDs noticed the assisted driving behaviour of the confederate.

The results of the study showed that UVDs benefited from the assisted confederate: They approached traffic lights without showing unnecessary changes in velocity and crossed the stop line earlier after signal change [58, 60]. Spectral-analysis was used to evaluate how well UVDs adapted their driving behaviour to the assisted confederate. In regard to the start-up assistance system, it was found that with the moderate parametrisation, the UVDs adapted their driving behaviour to the assisted confederate. However, in the extreme parametrisation, UVDs adapted their driving behaviour only over time. Additionally, the length of the platoon varied more and the 1st UVD kept a greater distance to the assisted confederate [57]. The results also provided initial evidence that safety issues may arise when UVDs encounter assisted driving behaviour: When the assisted confederate showed the unusual deceleration behaviour in the approach to a traffic light due to the extreme parametrisation of the start-up assistance system, shorter minimal time-to-collision and one rear-end crash were found [59]. Additionally, the assisted driving behaviour was rated as aversive. In general, only few UVDs guessed that the assisted confederate must have had a traffic light assistance system [60].

20.5 Encounters Between Drivers with and Without C-ITS: Open Questions

The results show that C-ITS such as GLOSA or a start-up assistance system of assisted drivers affect surrounding traffic. Positive behavioural adaptation was observed as UVDs adapted the efficient driving behaviour of assisted drivers. However, safety issues were also found for the extreme parametrisation of the start-up assistance system. Therefore, research should focus on three issues: (1) Taking UVDs into account when parametrising C-ITS, (2) understanding how behavioural adaptation of UVDs takes place and how positive behavioural changes of UVDs can be enhanced and (3) discussing whether informing UVDs may be a solution to enhance positive behavioural changes and reduce safety issues.

(1) Future research should focus on taking UVDs into account when parametrising C-ITS. The system's parametrisation appears to play an important role in encounters between drivers with and without C-ITS [58, 59]. As the results of the presented study suggest, moderate parametrisation of the start-up assistance system appears to be less aversive than the extreme one, caused no safety issues with UVDs, and led to a benefit in the driving behaviour of UVDs. It might indicate that the degree of deviation of assisted from normal driving behaviour affects acceptance and safety: The greater the deviation, the more likely are safety and acceptance issues of encounters with UVDs [59]. Researchers and system developers should keep this in mind when parametrising C-ITS. It may be necessary to find a trade-off between the parametrisation that leads to the best results in terms of traffic flow and emission and the negative consequences of encounters with UVDs. For example, from a technical point of view, the communication between RSU and equipped vehicles can be realised 700 m before reaching a traffic light. However, it may lead to severe negative consequences when drivers with systems start slowing down 700 m before reaching the green traffic light. In terms of speed choice, Mühlbacher (2013) found that the minimal velocity of drivers with GLOSA approaching traffic lights should not be below 30 km/h or differ more than 17.5 km/h from the desired speed [30]. Future research should focus on finding the thresholds of system's parametrisation that are acceptable for drivers and in turn diminish the mentioned negative consequences.
(2) Future research should focus on understanding how behavioural adaptation of UVDs takes place. Behavioural adaptation of UVDs may lead to positive effects such as UVDs adapting to the efficient driving behaviour of assisted drivers. To enhance these positive behavioural changes, the reasons why drivers adapt to others need to be clarified. Models and theories have been used to describe why drivers tend to change their driving behaviour when equipped with C-ITS. These models focus on negative behavioural changes of drivers as a response to system use. Motivational models such as the risk homeostasis theory state that behavioural adaptation of drivers with systems is a consequence of risk perception [61]. Drivers tend to be more careful when they perceive a driving situation as risky. But when feeling protected, for example, by antilock braking systems or airbags, drivers tend to behave riskier [62]. Additionally, trust models state that whether negative behavioural changes in driving behaviour occur depends on personality and the individual's level of trust, for example, in the assistance system [63, 64]. However, these models lack to explain why UVDs might adapt to the positive driving behaviour of drivers with systems. Social psychological models may be more suitable to explain positive behavioural changes

of UVDs to drivers with systems. These models focus on the influence of others on ones feelings or behaviour. For example, the extended theory of planned behaviour states that behaviour is shaped by what persons think others think of them (subjective norm), what one thinks is how others normally behave (normative norm) and what one actually experiences is how others behave in a specific situation (descriptive norm) [38, 65]. The descriptive norm may explain the speed choice of drivers in car-following situations: Drivers simply imitate the driving behaviour of the surrounding traffic [66, 67]. Whether this imitation of driving behaviour happens consciously needs to be researched. Motivational and trust models state that before drivers adapt their behaviour, they have to perceive, for example, the driving behaviour of drivers with systems and its benefit. Gouy (2013) also claimed that in order to research how UVDs adapt their driving behaviour to automated drivers, UVDs have to perceive and be conscious about the assisted driving behaviour [24]. If this is true, directing the attention of UVDs to assisted drivers may be necessary to study the mechanisms of why UVDs may adapt their driving behaviour. In the presented study, we found positive behavioural changes of UVDs, although most of them were not aware of the assisted confederate. Maybe behavioural adaptation occurs unconsciously as well. Skottke (2007) found that drivers adapt their current driving behaviour to their frame of reference (e. g. previous experienced driving situations or the environment) without noticing their behavioural changes [68]. This frame of reference might be a leading driver with C-ITS. Such kind of unconscious behavioural changes are discussed for driving behaviour requiring mostly perceptual-motor skills (e. g. fluent driving) [69]. Studies showed that leading drivers' acceleration patterns influence following drivers especially at signalised intersections [70]. However, that does not necessarily mean that positive behavioural adaptation may not be trigged top-down as well. Based on the SEEV model by Wickens (1992), top-down factors such as expectancy influence visual attention and perception [71]. The expectancy of encountering assisted driving behaviour and its value may be communicated to UVDs. These cues may be systematically addressed in future studies in order to extract factors affecting positive behavioural adaptation. Weller & Schlag (2004) also stated that behavioural adaptation depends on whether drivers perceive a benefit of it [72]. These assumptions are in line with the social learning theory [73]. Drivers observe consequences of the behaviour of others and tend to adapt this behaviour when the outcome adds positive value. Similar to that, Saad (2004) states that the readability of the driving behaviour of drivers with systems (i. e. how well UVDs understand assisted driving behaviour) might be a crucial factor influencing UVDs [22]. So, when the behaviour of drivers with systems and its positive consequences are salient and comprehensible for UVDs – will they adapt their behaviour? Future research should focus on this question to enhance positive behavioural changes of UVDs. Based on these results, it may be implicated whether and how UVDs be informed about the equipment of drivers with C-ITS.

(3) Moreover, informing UVDs about the equipment of assisted drivers may prevent safety-related issues such as these presented in Sect. 20.4. Drivers tend to react faster and more appropriately when the actions of others, such as slowing down, can be anticipated. Participants driving vehicles with GLOSA in a driving simulator study also suggested in forming surrounding traffic about their equipment [31]. They felt that they were bothering UVDs when they followed the system's recommendations. The study results also show another issue in terms of encounters between drivers with and without C-ITS: To what degree does the low penetration rate of C-ITS influence drivers with systems? To what extent do UVDs affect drivers with system? Two outcomes are thinkable. First, when drivers with systems experience or fear to experience issues with UVDs, their initial acceptance of the system may deteriorate. A field operational test administered in the Drive Car-2-X-project showed that drivers with GLOSA were worried that their driving behaviour may frustrate surrounding UVDs [74]. Otto (2011) found that drivers with GLOSA only followed system's recommendations when the recommended approach speed to a traffic light was greater than 20 km/h [75]. Second, drivers with systems may also not accept the technology because of missing communication partners: Drivers may not experience the benefit of their systems very often [49, 76]. However, the perceived benefit of a system is crucial for the overall acceptance and compliance [77]. Therefore, it seems system developers and researchers need to identify countermeasures to minimise or even prevent effects UVDs may have on drivers with systems and vice versa [58, 59]. However, research results have not yet confirmed that informing UVDs decreases the likelihood of safety and acceptance issues. If that is the case, it also needs to be investigated how information should be presented to UVDs. In the study of Rittger et al. (2015), participants proposed that stickers on the back of equipped vehicles may help understanding the behaviour of drivers with systems [31]. However, visual applications on equipped vehicles need to be designed in a way that UVDs intuitively understand the message. Otherwise, these applications may distract or irritate UVDs leading to an increased likelihood of safety and acceptance issues. Light signals have also been proposed for communicating drivers' intentions and behaviour [78]. In some cases of C-ITS, equipped vehicles may send light signals to communicate their driving behaviour and intentions respectively.

In conclusion, studies have given first insights in what happens when drivers with C-ITS encounter drivers without such systems. Results show that those systems affect the behaviour of UVDs. Safety-and acceptance-related issues have been identified, but the extent cannot be forecasted as wished. Questions of how, why, when these issues occur and how to counteract those remain unanswered. Their answers, however, are necessary for a successful deployment, in terms of road traffic safety, of C-ITS.

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The Multi-Driver Simulation: A Tool to Investigate Social Interactions Between Several Drivers 21

Dominik Muehlbacher

21.1 Need for Multi-Driver Simulation?

21.1.1 Driving Simulation and Traffic Simulation

Since a lot of years, traffic sciences have been using two popular tools of simulation: Driving simulation and traffic simulation.

In a driving simulation, a participant steers a virtual vehicle through a simulated environment. In most cases, the main focus of research is drivers' behaviour and perception. The popularity of driving simulation has several reasons: First, driving simulation allows creating sceneries tailored to the research question. Therefore, confounding variables like varying traffic or weather conditions can be controlled or eliminated. Additionally, the investigation of events which occur rarely in real traffic or might be safety-critical in real traffic is possible. However, driving simulation studies also have limitations: Effects like reactivity or demand effects may constrain the external validity of driving simulation studies. Furthermore, simulator sickness can influence the validity as symptoms like headache, sweating or eye strain might affect a driver's performance negatively [1].

In contrast, the traffic simulation gives the opportunity to investigate research questions concerning the whole traffic system, for example the development of congestions, effects of infrastructural measures like speed limits or the effect of driver assistance systems. For this purpose, it uses simulated driver models exclusively instead of real drivers in a virtual environment. A common model is, for instance, the Intelligent Driver Model [2]: This model is focused on car-following and considers the velocities of the own and the preceding vehicle, the headway and intelligent braking strategies with smooth transitions between acceleration and deceleration behaviour. Another important driver model

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is the psycho-physical perception threshold model [3] which uses – besides technical parameters similar to the Intelligent Driver Model – also psychological factors like drivers' motivation, headway estimations and need for safety to describe car-following.

However, a lot of different models exist and the results of an experiment may depend on the chosen modelling assumptions [4]. For some research questions, the traffic simulation has limitations because of the lack of understanding driver behaviour [5]. Validation studies using real driving data show that driver models do not fit perfectly because human driving behaviour is very variable, flexible and individual [6, 7].

21.1.2 Driver, Traffic, and Interactions

Between the poles "driver" and "traffic" exist further aspects which have not been considered in past research, namely groups of drivers and the social interactions within a group ([8, 9]; see Fig. 21.1). Social interactions are present whenever two or more drivers encounter each other. These events require that drivers take intentions and behaviour of the other road users into account and react correspondingly.

Social interactions in traffic are sometimes very short episodes (e. g. crossing at intersections) and sometimes longer term (e. g. car following on a rural road). They are crucial for driving safety (e. g. accidents between road users), traffic flow (e. g. development of congestions) and the atmosphere on the road (e. g. aggressive driving). Due to an increasing traffic volume, social interactions in traffic will have a more important role in the future.

It is not possible to investigate social interactions in a driving simulation. The problem of driving simulation is the presence of only one human driver. Of course, the driving simulation uses simulated surrounding traffic which is based on the models of the traffic simulation – however, these models are not so variable and flexible like human behaviour in traffic. Instead, most models used show predefined behaviour. Due to the same reason, traffic simulations do not enable the analysis of interactions.

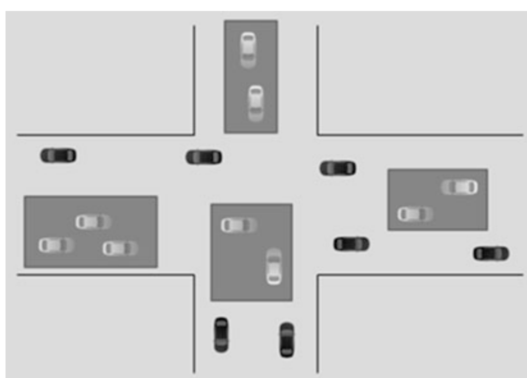

Fig. 21.1 Schematic representation of the whole traffic system (*light grey*) consisting of vehicles which interact temporarily (*dark grey*) and vehicles which are driving independent from each other (*black*). Taken from [9, p. 10]

21.1.3 Multi-Driver Simulation

It is not sufficiently possible to analyse social interactions in one of the established simulated environments (driver simulation and traffic simulation). The connection of several driving simulations could be the solution for this problem: In a so-called multi-driver simulation the participants drive through the same virtual environment and are able to see the other vehicles and can react to the other participants' behaviour which enables social interactions. Additionally, the most advantages of single-driver simulations (e. g. controllability and reproducibility of test situations, possibility to investigate safety critical situations) are given in a multi-driver simulation. Therefore, it can be seen as a link between driving simulation and traffic simulation [10].

A few research groups connected driving simulators and investigated issues such as driving behaviour at intersections [11], cooperative driving behaviour [12], as well as effects of a merging assistant [8], a hazard warning [10], or a traffic light assistant [13, 14]. Other studies dealt with methodological issues of the multi-driver simulation like developing new parameters to describe driving behaviour and interactions [9, 15, 16].

21.1.4 Aim of the UR:BAN Multi-Driver Simulator Studies

Although the previous chapter shows that several research studies were conducted with multi-driver simulator studies, a comparison of the multi-driver simulation with a single-driver simulation is missing up until now. This is important, as only when the differences are known it is possible to decide which kind of simulation has to be used for a specific research question. Therefore, one aim of the UR:BAN multi-driver simulation studies was to compare multi-driver simulation with a single-driver simulation. For this purpose, this chapter presents two studies investigating this issue:

1. In a first exploratory analysis, driving behaviour of simulated vehicles and real drivers was compared (see Sect. 21.3).
2. Afterwards, both kinds of simulations were compared using the example of the evaluation of a traffic light assistant (see Sect. 21.4).

21.2 The WIVW Multi-Driver Simulation

The multi-driver simulation laboratory of the Wuerzburg Institute for Traffic Sciences GmbH (WIVW) consists of four connected driving stations (see Fig. 21.2a). These can be used either as a single-driver simulation or as a multi-driver simulation:

- In the single-driver simulation, each participant drives through a separate but identical virtual environment. The surrounding traffic consists of simulated driver models only.

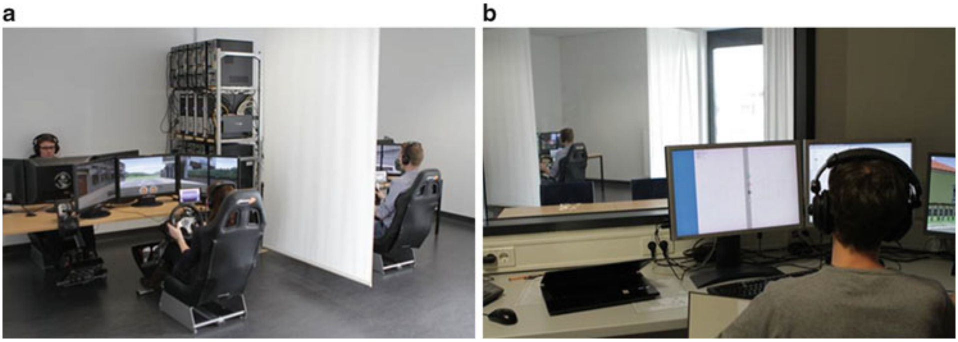

Fig. 21.2 Multi-driver simulation of the WIVW GmbH (**a**); working place of the operators (**b**)

- In the multi-driver simulation, four participants drive through the same virtual environment. Only the vehicles of the study participants make up the surrounding traffic.

Each mockup consists of a high-quality PC-game-steering wheel with force feedback and pedals. The visual system of each driving station provides a horizontal field of view of 150 degrees which is shown on three 22″ size LCD-displays with a pixel resolution of 1680×1050. The left, right and inside mirrors are embedded in the front view. A 10″ LCD-display with a pixel resolution of 800×480 is mounted near the steering wheel and can be used for secondary tasks, icons of driver assistance systems or touchpad-based questionnaires. Headsets provide the sound simulation and also enable the communication between the participants and the operators. In a WIVW multi-driver simulation study, two operators are controlling and monitoring a study with four participants. The working place of the operators is in an adjacent room which is separated by a window from the driving stations (see Fig. 21.2b).

The simulator is run by the software SILAB which was developed by WIVW. The network consists of 25 PCs connected via gigabit-Ethernet.

21.3 Study 1: Driver Models vs Human Drivers

21.3.1 Background and Methods

A comparison of driving behaviour of real drivers with driving behaviour of simulated driver models is necessary to test if simulated driver models show realistic behaviour. Larger differences would demonstrate the benefit of a multi-driver simulation.

For this purpose, four driver models completed a country road course with a length of 24.5 km in platoon formation (i.e., in line). The course contained various situations like different speed limits, overtaking of a slower car, or braking due to an unforeseeable obstacle (broken vehicle) after a curve. With minor changes, the driver models were based on the psycho-physical perception threshold model [3]. The desired velocity was different for the four positions within the platoon (position 1: 101.5 km/h, position 2: 108.7 km/h, position 3: 115.9 km/h, position 4: 125.8 km/h) so that the vehicles stayed in the platoon and did not lose contact. The desired time headway was set at 1.5 s.

Compared to this, four groups with four participants each negotiated the course. They were instructed to drive in platoon formation to ensure that each driver was influenced by the driving behaviour of the preceding vehicle. Additionally, they had to preserve their order in the platoon (i. e., they were not allowed to overtake the other drivers of the platoon).

The $N = 16$ participants (6 women and 10 men) were aged between 23 and 40 years of age (M = 30.8; SD = 5.3). Prior to the study, all participants were trained with the multi-driver simulation in order to introduce them to the simulator and reduce the probability of simulator sickness [9]. The participants were paid for taking part in the study.

The differences between the simulated platoon and the participants are shown using a course element of approx. 4 km. While speed limit was 100 km/h in the first two-thirds of this element, it was 70 km/h afterwards. After approximately half the way, the drivers had to overtake a slower car.

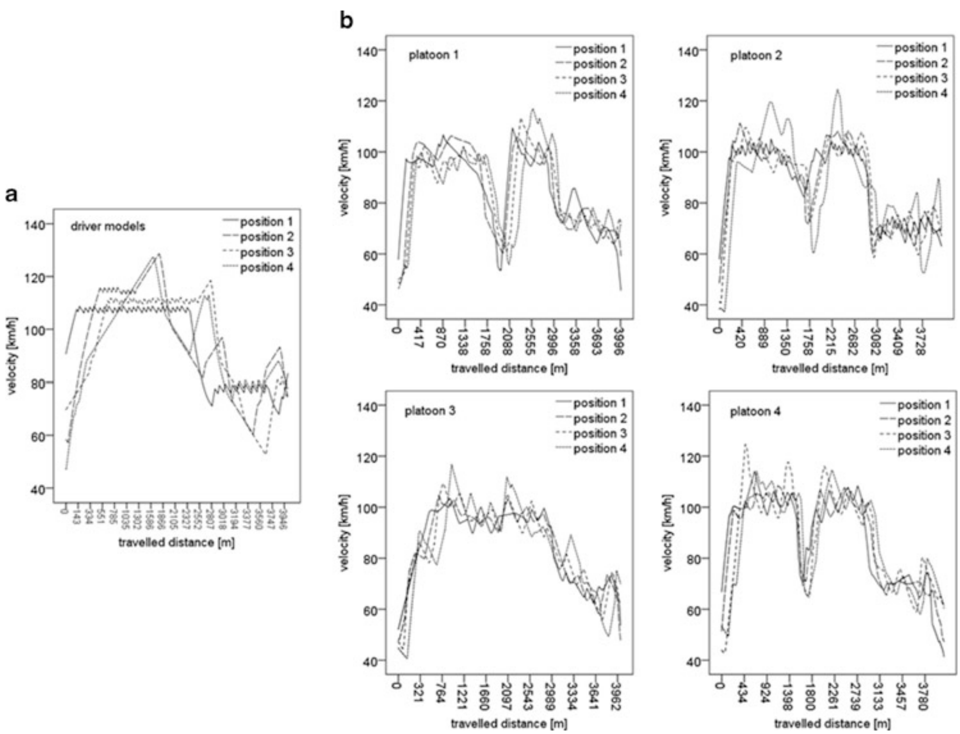

Fig. 21.3 Velocity of the platoons consisting of driver models (**a**) and consisting of human drivers (**b**)

21.3.2 Results and Discussion

Three of the four human platoons decelerate prior to overtaking from 100 km/h to approx. 60 km/h. In contrast, the simulated platoon and one human platoon (platoon no. 3) pass the slower car without reducing speed (see Fig. 21.3).

Most of the time, the velocities of the simulated vehicles oscillate around a value (see Fig. 21.3). This behaviour is typical for driver models using the psycho-physical perception threshold model. Due to the psychological factors which are considered in this model, the actual velocity differs from the predefined desired velocity. Compared to the human drivers, large variations of velocity do not occur in the run of driver models. Especially the driver models on the first position maintain velocity rather constantly.

The homogeneous driving style of the driver models affects longitudinal accelerations: These are 1.2 m/s^2 at maximum, while the decelerations exceed -1 m/s^2 only seldom (see Fig. 21.4). In contrast, human participants show an acceleration behaviour which is much more variable. Especially the decelerations are stronger. Sometimes, stronger braking events result in events of over-deceleration, i. e. the decelerations of following drivers

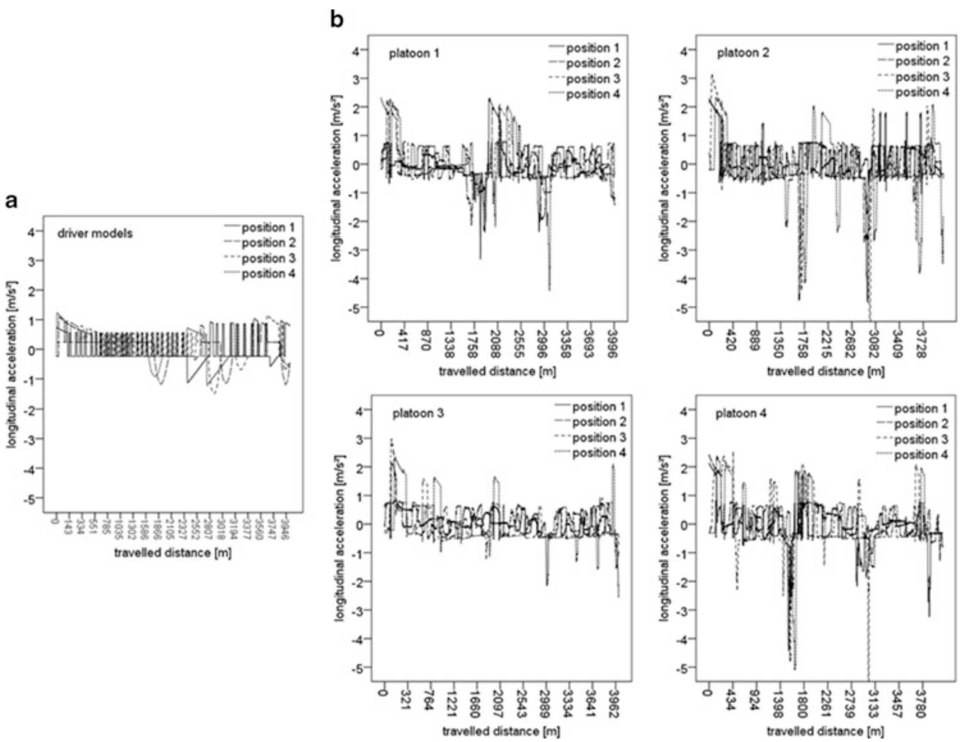

Fig. 21.4 Longitudinal acceleration of the platoons consisting of driver models (**a**) and consisting of human drivers (**b**)

are stronger than the decelerations of preceding drivers (e. g. platoon no. 4). The effect of over-deceleration is a well-known phenomenon which can be a reason for congestions [17]. However, this effect can't be seen in the run of the simulated platoon.

The comparison of human and virtual platoons demonstrates that driver models do not represent reality. Instead, the used driver models operate according to their programming which considers specific characteristics of human behaviour (e. g. over-decelerations) only insufficiently.

As a next step, it is important to check if these differences between driver models and human drivers affect behaviour of participants. Therefore, study 2 shows a comparison of single-driver simulation and multi-driver simulation.

21.4 Study 2: Single-Driver Simulation vs Multi-Driver Simulation

21.4.1 Background

The evaluation of driver assistance systems is a common use case of driving simulators. Traffic light assistance is a system which has been in the focus of much research using single-driving simulators in recent years [18, 19]. This system informs the driver about economic driving behaviour when approaching traffic lights. Therefore, the system might recommend to drive slowly or to brake at large distances in front of a traffic light. However, this driving behaviour could be annoying for following drivers without traffic light assistant [14]. Therefore, assisted drivers might worry about hindering the drivers following behind them. This could result in a weak compliance to the system recommendations.

Aim of the present study was to investigate if compliance to recommendations of a traffic light assistant depends on the presence and type of surrounding traffic. This was investigated by means of a multi-driver simulation as well as a single-driver simulation. It was expected that compliance is independent of surrounding traffic in the single-driver simulation setting, because here the driver is surrounded by simulated driver models which cannot be annoyed. In contrast, it was assumed that surrounding traffic modifies compliance in the multi-driver simulation as economic driving might bother following participants.

Besides this methodological research question, the evaluation of the traffic light assistant itself was another purpose of the conducted study. These results are published in separate papers [13, 20].

21.4.2 Methods

21.4.2.1 Traffic Light Assistant

During the approach of a traffic light, the traffic light assistant informed the driver visually about the optimal driving behaviour (e. g. "drive 20 km/h", "slow down to 30 km/h") to

Fig. 21.5 Driving recommendations of the traffic light assistant: coasting (**a**), driving (**b**), braking (**c**)

reach a green traffic light. To generate these recommendations, the traffic light assistant considered the current and next traffic light phase, participants' driving speed and distance to the traffic light. The driving recommendations were presented with distinctive colors (coasting = white; driving = green; braking = amber) in the HMI on the separate 10″ LCD-display. The speed recommendations for approaching the traffic light were between 20 and 50 km/h (see Fig. 21.5).

In the multi-driver simulation with four participants, the penetration rate of the traffic light assistant was 50%. While two drivers were assisted by the system, the other two drivers had no assistance.

In the single-driver simulation, the platoon consisted of one participant (who was either equipped or non-equipped with the traffic light assistant) and three driver models. These were based on the Intelligent Driver Model [2]. Two driver models followed the recommendations of the traffic light assistant, i. e. their desired velocity was the velocity which was recommended by the system. The third driver model was unequipped with a desired velocity of 54 km/h. 10″ LCD-display. The minimum time-headway of all simulated drivers was set on 1.5 s.

The participants were instructed that following the system recommendations is voluntary and not obligatory. In both runs, the participants were not informed if the other road users were equipped with the traffic light assistant or not.

21.4.2.2 Test Scenarios

The urban course consisted of eight identical segments: At the beginning of each segment, the four vehicles approached an intersection in platoon formation (i. e., in line). At the intersection, a traffic light was timed so that if the drivers travelled at the recommended speed they arrived at the intersection when the light turned green and avoided a stop. If the participant drove faster than recommended they arrived at a red light and had to stop. After crossing the intersection, the drivers had to stop at a "positioning sign" which was mounted at a gantry overhead (see Fig. 21.6). This sign pictured all four vehicles of the platoon (with their corresponding colors). Below each displayed vehicle was a parking space on the road. Each driver had to stop at the designated parking space. After all four drivers had stopped, the driver on the left parking space started to drive towards the next traffic light. The other drivers followed him/her in the prescribed sequence from left to

Fig. 21.6 Positioning sign

right. In each element, the vehicle order on the positioning sign was different. By means of this method the order within the platoon was controlled and balanced so that each driver experienced each position for an equal number of times.

21.4.2.3 Study Design

The type of driving simulation (single-driver simulation or multi-driver simulation) was the main independent variable. Each participant completed a session in both driving simulations (within-subjects factor). In the single-driver simulation, each platoon consisted of one human driver and three driver models. In the multi-driver simulation, each platoon consisted of four human drivers. Before each run, the experimenter informed the participants whether they would be using the single-driver or the multi-driver simulation, respectively. The two runs were conducted in counterbalanced order.

In both runs, the drivers were either assisted by the traffic light assistant or not assisted (between-subjects-factor).

Each run consisted of eight elements with one traffic light at an intersection. The drivers had to approach the traffic light in platoon formation. After each element, the drivers changed positions within the platoon and approached the next traffic light in another sequence. By means of this method, each driver was in 2 of 8 approaches each on first, second, third or fourth position in the platoon (within-subjects factor).

21.4.2.4 Dependent Variables

After each run, the drivers rated different aspects of the run (e. g. "The virtual world is realistic") on a 7-point scale from 1 = "disagree" to 7 = "agree". In a final inquiry at the end of the session, the drivers had to compare both runs in an open-question format.

To assess compliance to the traffic light assistant, the percentage of stops at intersections was calculated. A stop was defined as reaching a driving speed lower than 1 km/h.

The assisted drivers could only avoid a stop at the traffic light if they followed the system recommendations. Therefore, the percentage of segments without a stop at the traffic light is an indicator for the system compliance (so-called compliance rate).

21.4.2.5 Sample

Four test drivers participated in each session. In total, there were $N = 20$ participants (10 women and 10 men) between 20 and 65 years of age (M = 36.8; SD = 15.6). As in study 1, the participants were trained with the multi-driver simulation prior to the study [9] and were paid for taking part in the study.

21.4.3 Results

21.4.3.1 Drivers' Judgments

After each run, all drivers rated different aspects of the run in a questionnaire. Drivers with as well as without system note several differences between driving in a single-driver simulation and a multi-driver simulation: According to the participants, the virtual world of the multi-driver simulation is more realistic compared to the single-driver simulation ($t(19) = 2.27$; $p = 0.035$; see Fig. 21.7a). Additionally, the driving behaviour of the surrounding traffic is rated as more realistic in the multi-driver simulation ($t(19) = 4.24$; $p < 0.001$). Furthermore, the participants state that they felt observed by the other drivers in a higher degree in the multi-driver simulation ($t(19) = 4.53$; $p < 0.001$).

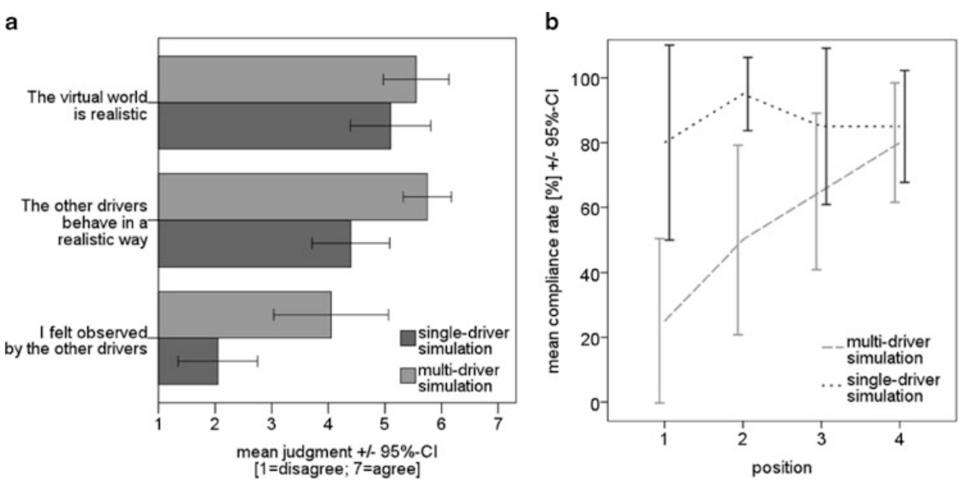

Fig. 21.7 Mean subjective judgments for items in the questionnaire for multi-driver and single-driver simulation (**a**); mean compliance rate for each position in the platoon in multi-driver and single-driver simulation (**b**)

21.4.3.2 System Compliance

In the single-driver simulation the drivers with system cross between 80 and 90% of the intersections without stopping. The position within the platoon does not affect the compliance ($F(3, 27) = 1.00$; $p = 0.864$; see Fig. 21.7b). In contrast, the position has an effect in the multi-driver simulation ($F(3, 27) = 5.21$; $p = 0.006$): While the compliance rate is approx. 20% in position 1, it increases gradually to 80% in position 4.

When comparing single-driver simulation and multi-driver simulation, drivers in the multi-driver simulation have a lower compliance rate in position 1 ($t(9) = 3.97$; $p = 0.003$) and position 2 ($t(9) = 2.86$; $p = 0.019$). However, there are no significant differences in position 3 ($t(9) = 1.50$; $p = 0.168$) and position 4 ($t(9) = 1.00$; $p = 0.343$).

21.4.4 Discussion

First, the participants notice several differences between the two runs: The run in the multi-driver simulation with human surrounding traffic is rated as more realistic compared to the run in the single-driver simulation with simulated surrounding traffic. This result underlines the external validity of the multi-driver simulation.

Additionally, the type of surrounding traffic affects the participants' compliance to the traffic light assistant. When driving in front of two or three human drivers, the participants do follow the system's recommendations to a lesser extent compared to driving in front of one or no human drivers. In contrast, when driving in front of simulated drivers there is no effect of the number of vehicles driving behind. The reason for this behaviour could be that assisted drivers might worry about hindering the drivers following behind them. This result shows the influence of knowledge the drivers have about surrounding traffic (simulated vs real).

21.5 Conclusion

Due to a lot of benefits, driving simulation and traffic simulation have been used successfully in traffic sciences. By means of these tools it is possible to answer research questions concerning driver behaviour and the whole traffic system. However, groups of drivers and the social interactions within these groups are aspects which lie between these poles "driver" and "traffic" and have not been considered in past research. It is not sufficiently possible to analyse social interactions via driving simulation or traffic simulation. However, the connection of several driving simulations could solve this problem. It results in a so-called multi-driver simulation which enables the investigation of social interactions.

One aim of the simulator studies in the UR:BAN project was to compare multi-driver simulation with single-driver simulation. This comparison is necessary for further studies – only if the differences and similarities between these tools are known, it is possible to decide which kind of simulation is appropriate for a specific research question. For this purpose, this chapter presented two studies investigating this issue.

In a first exploratory analysis, driving behaviour of simulated vehicles and real drivers was compared. The comparison of human and virtual platoons demonstrates that the driver models do not reflect the reality. Instead, the used driver models operate according to their programming which considers specific characteristics of human behaviour (e. g. over-decelerations) only insufficiently.

In a second study, single-driver simulation and multi-driver simulation were compared using the example of the evaluation of a traffic light assistant. The drivers' judgments underline the external validity of the multi-driver simulation. Drivers' compliance to the traffic light assistant was affected by the type of simulation. It seems that drivers consider the kind of surrounding traffic (real vs virtual) in their decision whether or not to follow the systems' recommendations.

Both studies demonstrate that there exist two main differences between the simulations which might affect participants' behaviour and perception:

1. Participants show *realistic driving behaviour when acting as the surrounding traffic* in the multi-driver simulation compared to the programmed behaviour of models in the single-driver simulation.
2. Like in real traffic, participants *know about the presence of other human drivers* in the multi-driver simulation. In contrast, participants in the single-driver simulation know that surrounding traffic is created by virtual drivers.

Prior to a study, researchers carefully have to take into account which kind of simulation is more appropriate for their research question. When deciding between single-driver simulation and multi-driver simulation, they need to consider the importance of the two aspects "realistic driving behaviour of surrounding traffic" and "knowledge about presence of other human drivers" for their research purpose.

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A New Approach to Investigate Powered Two Wheelers' Interactions with Passenger Car Drivers: the Motorcycle – Car Multi-Driver Simulation

22

Sebastian Will

22.1 Abstract

Motorcyclists are at high risk of getting involved in accidents that result in serious injury [1]. Especially interactions with cars bear a high risk potential, e. g. if motorcyclists are overlooked or if their potential to accelerate is underestimated. Up until now, little is known about motorcyclists' behaviour in general. Within the project UR:BAN, a Motorcycle-Car Multi-Driver Simulation was developed that enables a motorcyclist and a car driver to interact in the same virtual environment. This approach widens the set of research methods to investigate safety-relevant aspects of Powered Two Wheelers (PTW) and gains deeper insight into interactions and mutual behaviour adaptation. The following chapter describes the simulator setup as well as advantages and challenges. Furthermore, these topics will be supported by exemplary results of a study investigating Vehicle2X technology.

22.2 Introduction

In general, PTWs are an increasingly popular mode of transport. This holds especially true for urban areas, as more and more cities face problems with congestion, pollution or lack of parking space. For instance, the number of motorcycles in use within Germany has more than doubled in the last 20 years resulting in 4,054,946 registered motorcycles in January 2014 [2].

Unfortunately, PTWs are still among the most vulnerable road users and overrepresented in accident and injury statistics [1]. Accident analyses from different German and

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European data revealed that single-vehicle accidents account for up to one third of the registered accidents, while the rest involves more than one road user (e. g. [1, 3–5]). Especially interactions with other vehicles such as cars and trucks bear a high risk potential, e. g. if motorcycles' silhouettes are overlooked or if their acceleration is underestimated. In 2012, in Germany alone, 14,129 crashes between motorcycles and other road users were registered [6]. In about 80% of the crashes that involve another vehicle, the latter was a passenger car. The most common accident constellation is a front-side impact that primarily takes place at intersections ([1, 7]).

Driving simulators are a commonly used tool in the field of traffic sciences to investigate those critical scenarios and evaluate effects of potential countermeasures. Up until now, only a few motorcycle simulators which serve as research tools are available in the field of empirical traffic sciences [8]. Due to the fact that there is always one rider in a programmed virtual environment, motorcycle simulators allow the assessment of important research questions (e. g. [9, 10]), but always exclude real interaction and mutual behaviour adaptation between more vehicles. These facts reveal the need to investigate Powered Two Wheeler safety from a new point of view. Besides the important derived accident countermeasures like technical improvements of motorcycles (e. g. ABS, traction control) or adequate rider training, the next step towards improved PTW safety is to address interactions between PTWs and other road users. Therefore, the Motorcycle-Car Multi-Driver Simulation was implemented within the scope of the project UR:BAN.

22.3 Simulator Setup: The Motorcycle-Car Multi-Driver Simulation

The general idea of using connected driving simulators to assess interactions has already been established for cars (e. g. [11, 12]). The next step was to link a motorcycle simulator to a car simulator resulting in two subjects driving in the same virtual environment. This allows gaining a deeper insight into interactions and mutual behaviour adaptation of two real drivers in a safe and controlled environment.

Within the scope of the project UR:BAN a motorcycle riding and a car driving simulator were coupled. The static motorcycle simulator is equipped with a full-size BMW R 1200 RT motorcycle and prepared for intermountable mockups (see Fig. 22.1).

This enables the rider to use fully realistic controls such as usual handlebar, brake lever/pedal, clutch, gear selector, etc. Three 55 inch flat screens offer a 180° horizontal field of view. A 10 inch touch screen is used as cockpit showing speedometer and revolutions per minute. Additionally, different Human-Machine-Interfaces (HMI) e. g. for Advanced Rider Assistance Systems (ARAS) or On-Bike Information Systems (OBIS) can easily be displayed there. If necessary, riders can directly fill out questionnaires online or engage in secondary tasks displayed on the touchscreen (e. g. operating a board computer). Two 7 inch TFT-displays are installed as mirrors. An electrical actuator is used to produce a steering torque at the handlebar up to 50 Nm. Acoustic feedback including sounds of surrounding traffic is delivered by a 2.0 sound system. The speakers work

Fig. 22.1 Static motorcycle riding simulator

in combination with a shaker, installed under the rider seat, delivering engine vibrations to the rider. The simulator is running with the software SILAB riding scenario control.

The car driving simulator includes a generic car mockup with a real driving seat, steering wheel with force feedback and brake as well as accelerator pedal. It works with automatic gear shift. Five projectors produce a 300° horizontal field of view. A 15 inch flat screen works as an instrument cluster showing speedometer and revolutions per minute. A second 15 inch flat screen installed in the dashboard can be used to display a navigation system, secondary tasks or HMIs. Two 7 inch TFT-displays replace the rear-view and wing mirror (see Fig. 22.2). A 5.1 sound system is installed to deliver auditory cues from the ego vehicle and the surrounding traffic. Additionally, eye-tracking as well as physiological measures can be recorded. The simulator is also running with SILAB riding scenario control.

The motorcycle simulator and the passenger car simulator are connected to a multi-driver simulator via a 1GB Ethernet switch. A specific computer of the multi-driver simulation is configured with the SILAB software and works as the traffic main computer. At any point during operation the driving dynamics of the motorcycle as well as those of the car are both evaluated and the results are transferred to the traffic main computer. The traffic main computer is then used to evaluate the driving models for all SILAB simulated vehicles in order to create the appropriate scenarios for the two human drivers.

This setup requires two operators: one for each simulator in order to take care of the participant, to give instructions, to hand out questionnaires etc. Both operators can observe a variety of driving parameters like velocity, lateral position etc. in real time and monitor the positions of both participants from a bird's-eye view. However, one of them is the main operator who is responsible for running the scenarios. Furthermore, a multi-driver simulation has more extraordinary requirements that have to be dealt with. That is, for example, the synchronization ensuring that the two participants meet each other at

Fig. 22.2 Static car driving simulator

the relevant intersection or the corresponding road network with appropriate navigation systems to name just some of them. A detailed methodological review can be found in the Chap. 23.

22.4 Study Example: Intersection Support

Generally speaking, the Motorcycle-Car Multi-Driver Simulation can be useful for all scenarios including these two types of interacting vehicles. On the one hand, general knowledge on mutual behaviour adaptation can be gained. On the other hand, specific systems such as Advanced Driver/Rider Assistance Systems could be investigated in a safe and controlled environment. This was done for an intersection support using Vehicle2X technology within UR:BAN. Excerpts of this study will be described as one possible use case in the following section.

22.4.1 Background

As stated above, PTW riders suffer from a high vulnerability compared to other road users. Literature reveals that urban intersections are a special PTW-car accident hot spot. Vehicle2X technology could help minimize these critical situations. These technological inventions are already subject to passenger car research for years. In the motorcycle sector it is not really covered yet, as there is a smaller market, less space for implementations at the handlebar and more recent challenges to face, such as ABS implementation or traction control that are already covered in the automotive sector. Nevertheless, there lies huge potential in such systems so that the aim was to implement an informing advanced rider assistance system and to estimate the safety potential of this resulting intersection support for PTWs.

22.4.2 Methods

As special interest lies on the interaction and mutual behaviour adaptation between motorcyclist and car driver, the above-described Motorcycle-Car Multi-Driver Simulation was used for investigation. The course existed of an urban scenario with about 60 junctions. Eight of them were used to provoke critical situations. All junctions resembled each other in appearance in order to avoid participants from becoming suspicious and changing to unnatural behaviour due to environmental hints. $N = 24$ pairs of participants completed this course twice: once with and once without intersection support in a randomized order. A cover story was used in order to avoid overcautious behaviour: The participants did not know that they were driving in a multi driver simulation and they were told that the study aims at investigating an intersection support. The system used an unspecific information icon to inform the rider respectively driver about a potential conflict partner in cross traffic (see Fig. 22.3).

The information was emitted when the time-to-arrival of the first of the two orthogonal approaching vehicles fell below 2.87 s [13]. Both vehicles were synchronised by red traffic lights at a pedestrian crossing 100 m in front of the junction. At the eight relevant research intersections, the traffic lights were green for both vehicles. Participants did not realise this and perceived a surprising critical situation representing a typical error that leads to two vehicles entering a junction at the same point in time. As independent variable the availability of the intersection support was varied in four steps:

a b

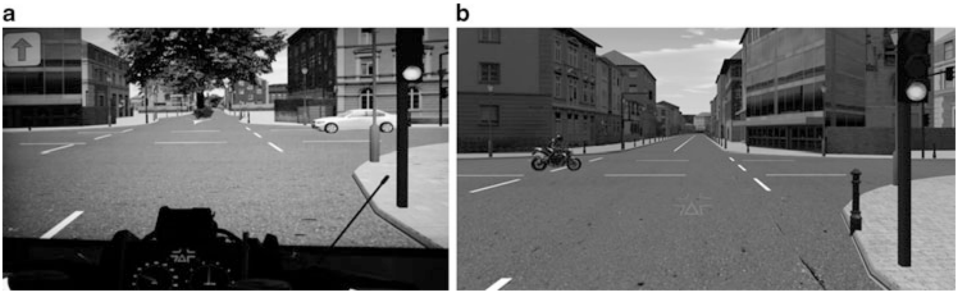

Fig. 22.3 Intersection support – information icon for PTW displayed in cockpit (**a**) and for passenger car driver in head-up display (**b**)

- None of the vehicles was equipped (none).
- Only the car was equipped with the intersection support (only car).
- Only the PTW was equipped with the intersection support (only PTW).
- Both vehicles were equipped with the intersection support (both).

As dependent variables objective and subjective parameters describing situation criticality were analysed. The following parameters are of special interest to the new methodology of connected motorcycle and car driving simulators. That is post encroachment time (PET) indicating the difference in time of two vehicles passing one common conflict zone. Shorter PETs are said to describe more critical situations whereas PETs < 2 sec are referred to as "critical interactions" and PETs < 1 sec are referred to as "very critical interactions" [14]. Moreover, the distance to intersection (DTI) is relevant given in interaction plots. These plots indicate a pair of subjects' approach to an intersection from orthogonal directions. Each axis displays the DTI of one of the vehicles (see also Chap. 23).

22.4.3 Results

Scenario control poses an inherent challenge to connected driving simulations. The gain of having more realistic interactions accounts for the loss in controllability due to two independently acting participants. Fig. 22.4a shows the distribution of PETs at the intersection when none of the vehicles is assisted. The dashed lines mark the critical interactions according to PET. Just about half of the planned critical interactions turn out to be critical (those between the dashed lines). In the other scenarios the two participants miss each other by up to twelve seconds. This could, for example, be the case because one vehicle accelerates faster than the other or one participant accelerates right away while the other one starts delayed. Therefore, study planning for a multi-driver experiment has to take this into account, including e. g. more situations of interest as not all of the planned critical scenarios might work as formerly intended.

The interaction plots in Figs. 22.5 and 22.6 clarify this. When none of the participants' vehicles is equipped with an intersection support almost all lines run in parallel to the diagonal line. This means neither drivers nor riders brake before entering the intersection. The lines farther away from the diagonal indicate a lag in the vehicle's intersection approach. The numbers of cases with the PTW rider or the passenger car driver being first are almost identical with motorcyclists being a bit more defensive. In 40% of the cases the PTW is the first to cross the junction. This is shown by almost the same amount of lines ending on the upper side respectively right side of the plot.

The effect of the intersection support can clearly be seen in Fig. 22.6. Even when facing a green traffic light, the vehicle equipped with an intersection support slows down before crossing the junction. The left plot shows lines turning to the right side of the graph. This indicates that the car gets closer to the intersection whereas the PTW does not approach significantly anymore. Accordingly, in 67% of the cases, the car enters the intersection

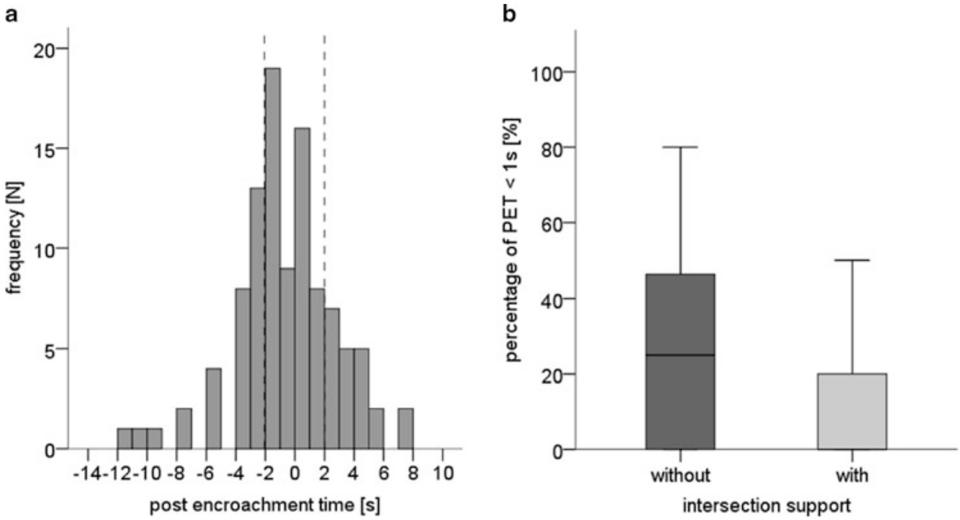

Fig. 22.4 Distribution of PETs at the intersection (**a**). Effect of at least one of the vehicles being equipped with the intersection support on the number of critical interactions (**b**)

first. Vice versa, the right graph shows lines turning to the upper end of the plot indicating that the PTW enters the junction while the passenger car driver decelerates. In 80% of these cases the PTW is the first vehicle to cross the intersection.

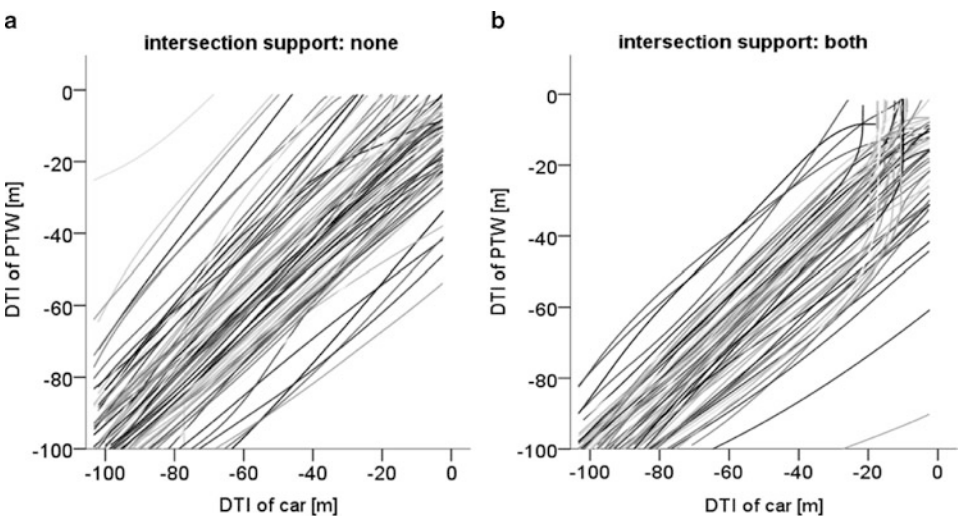

Fig. 22.5 Interaction plots when none (**a**) respectively both (**b**) of the vehicles are equipped with an intersection support

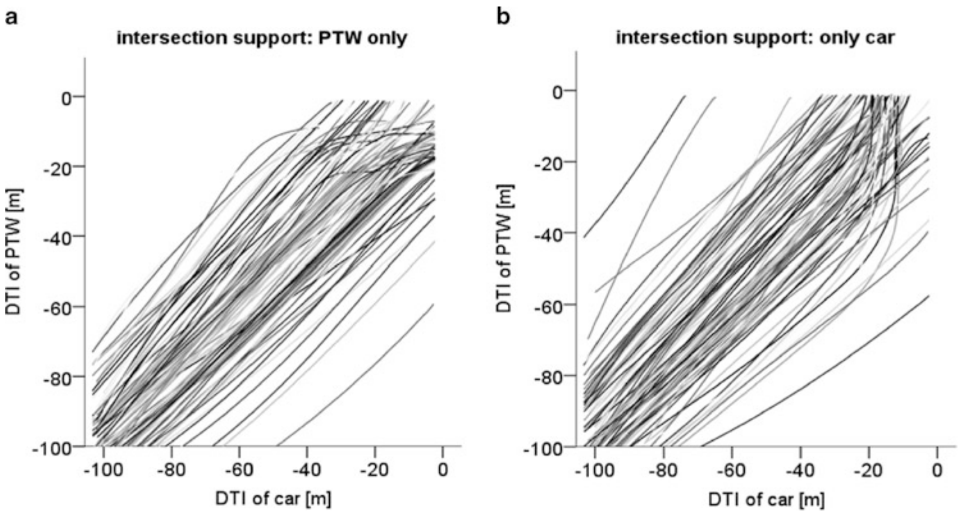

Fig. 22.6 Interaction plots when only the PTW (**a**) respectively the car (**b**) is equipped with an intersection support

Taking a closer look at the interactions in which both vehicles are assisted, lines turning to both sides of the graph can be seen (see Fig. 22.5b). Nevertheless, more lines turn to the right end revealing that PTWs tend to step back in ambiguous situations. PTWs only enter the intersections as the first vehicle in 28% of the situations.

In conclusion, Fig. 22.4b shows that the intersection support reduces the amount of very critical situations according to PET significantly ($F(1.92) = 2.22$; $p = .014$; $\eta^2 = 0.135$). This holds true as long as at least one of the vehicles is equipped with the intersection support.

22.4.4 Discussion

This study besides others within the scope of the project UR:BAN proved the Motorcycle-Car Multi-Driver Simulation to run stable. From a methodological point of view, the synchronization method using specific traffic light configurations can be seen as a promising way of provoking relevant critical scenarios. Nevertheless, the distribution of PETs at the intersection revealed the need for effective parametrization of the scenarios. Depending on the environmental conditions (speed limit, surrounding traffic, …), the synchronization point (the red traffic light 100 m in front of the junction) has to be chosen carefully. On the one hand, the participants need some time to reach the intended speed. On the other hand, the bigger the distance, the higher the chance is of both vehicles missing each other. Another consequence could be to plan the road network in a way that it is either built up iteratively until all relevant scenarios have worked or include a higher number of research scenarios allowing for some of them to fail.

Taking a closer look at the potential of Vehicle2X technology to reduce critical situations at intersections, one can state a positive effect: The intersection support seemed to increase PTWs' as well as car drivers' safety. The number of critical incidents was decreased independently from the fact which vehicle was equipped with the assistance system. An interesting finding was that PTW riders tend to give way in ambiguous situations in the connected simulation. This phenomenon is also known from real riding. Motorcyclists try to avoid harm as they are usually the ones being seriously injured in an accident with a passenger car.

22.5 Conclusion

The Vehicle2X study showed one potential use case of the newly invented Motorcycle-Car Multi-Driver Simulation. One the one side, challenges like synchronization in specific scenarios of interest were addressed. On the other side, advantages such as gaining knowledge about mutual behaviour adaptation (e. g. which participant enters the intersection first in ambiguous situations and how participants react to each other's behaviour such as approaching the junction slowly) were outlined. Insights into these questions cannot be gained in typical single-driver simulators as the participants react to scripted vehicles and bots. Getting back to the starting point of an increasing number of PTW riders and them being one of the most vulnerable road users, a lot of countermeasures have to be taken in the future. Surely, a lot of important things will be done on the technical side concerning active and passive rider safety, but actions beyond this will be needed. Actions that take a closer look at the rider, whose behaviour is not yet investigated sufficiently, will be of great importance in order to take the right measures. The Motorcycle-Car Multi-Driver Simulation can add one piece to the puzzle, leading the way to improved PTW safety.

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Multi-Road User Simulation: Methodological Considerations from Study Planning to Data Analysis

23

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23.1 Introduction

An aim of the UR:BAN project was to connect existing driving simulators in order to describe and analyse behaviour of several interacting road users. Multi-road user simulations allow investigating social interactions between these road users (i. e. influence on other drivers or influence of other drivers). In order to cover most of the urban road system consisting of various road users, the following multi-road user simulations were developed:

- connected driver-driver simulation (see Chap. 20),
- connected multi-driver simulation (see Chap. 21),
- connected driver-pedestrian-simulation (see Chap. 19),
- connected driver-motorcyclist simulation (see Chap. 22).

In the past few years, different research groups have already made first experiences with connected driving simulators. However, these experiences were made for a specific

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type, for example, connected driver-motorcyclist simulation [1], connected driver-driver simulation [2] or connected multi-driver simulation [3]. An encompassing methodological consideration of connected simulations, however, lacks and will be reflected thoroughly in this chapter. It is obvious that using multi-road user simulations has its special demands. These requirements have to be regarded during the whole process of a scientific study:

1. Considerations are necessary concerning study planning: If social interactions between participants are the scope of a study, test scenarios need to be designed ensuring social interactions at all. These aspects are discussed in Sect. 23.2.
2. Conducting studies in multi-road user simulations implies challenges which do not occur in a single-driver simulation. These challenges concern technical aspects as well as issues regarding experimenters and/or participants. Sect. 23.3 deals with these issues.
3. Numerous options for data analysis are possible due to the simultaneous participation of several persons. Besides the analysis of single drivers, parameters to describe and investigate driver groups are needed. This issue is highlighted in Sect. 23.4.

As a conclusion, in Sect. 23.5 appropriate possible applications of multi-road user simulations are discussed and also compared to single-driver simulations.

23.2 Planning Studies

23.2.1 Scenario Design

Particularly, the multi-road user simulation is a tool which is used to investigate social interactions while driving. To achieve social interactions in the multi-road user simulation, participants have to encounter each other or have to stay within a distance which forces the road users to react to each other. Social interactions can occur in situations in which road users cross at intersections, are following each other or in situations with oncoming traffic. However, the benefit of the multi-road user simulation would not be given when road users do not meet in the virtual environment.

According to [4], there exist three options to support encounters between drivers and thus to provoke social interactions in connected virtual environments:

- **Road design** supports encounters between road users at predefined locations on the road in crossing or merging scenarios as well as in situations with oncoming traffic. These locations could be intersections, roundabouts, narrow zones, or driveways. Participants have to start driving from different locations at the same time. A simultaneous start can be realised using traffic lights turning green at the same time or instructions of the experimenter via speaker or headset. Via routes of the same length and the same speed limit, they are led to the relevant locations of interest. If drivers travel according to the posted speed limit, they encounter each other at the location at the same time. Instead of a speed limit, preceding simulated vehicles with synchronised velocity profiles can also be used to lead participants to the location.

- **Surrounding traffic** may force participants to stay together on the road. Especially highway scenarios with high speed limits and several lanes pose a risk that drivers hold different velocities. If they lose connection, social interactions do not develop any more. By using slow driving simulated vehicles which precede the participants, fast driving participants can be decelerated so that the platoon of drivers is restored.
- **Instructions** can be used to keep participants within a platoon to investigate social interactions during car following. An example for such an instruction is the "two-second rule" (i. e. to stay at least two seconds behind the vehicle that is directly in front). However, following instructions might affect naturalistic driving behaviour and thus confound the results.

23.2.2 Confederates

In studies conducted with connected driving simulators, confederates can be used to provoke predefined situations that cannot be scripted authentically. A confederate shows natural driving behaviour adapting its behaviour, if necessary, in order to produce and control test scenarios. Nevertheless, it is of great importance to account for reproducibility as much as possible. This issue may, for example, be countered using augmented reality. Artificial elements such as real-time bar plots showing the distance to the vehicle ahead can be displayed in confederates' fields of view enabling them to adjust the following behaviour

Fig. 23.1 Confederate in the connected motorcycle-car multi-driver simulation. The projection includes augmented reality elements displaying the distance to the vehicle ahead in meters and seconds as well as recommended thresholds indicated by *arrows*

[1]. Depending on the research question, different longitudinal or lateral parameters can be applied (see Fig. 23.1).

In order to avoid the suspicion of participants, the confederate needs to be treated as everybody else (e. g. filling in questionnaires). Furthermore, it is of great importance to ensure that no other participant notices special treatments such as augmented reality elements, especially when all test drivers are in a common room.

23.2.3 Selection of Participants

The acquisition of participants for studies in connected driving simulators is more complex compared to conventional studies in single-driver simulators. The sample size usually needed for sufficiently high statistical power levels needs to be multiplied by the numbers of road users per experimental trial for studies in the multi-road user simulation. As a result, the acquisition of participants is more time-consuming. In addition, if a participant drops out either of simulator sickness or other reasons (e. g. does not show up), the experimental trial cannot be used for further analysis. Therefore, lists of possible back-up participants or confederates, who can fill in, are recommended.

When studying cooperative driving, the degree of social similarity or antipathy/sympathy between participants may influence the study's outcome. It may be advisable to separate participants while conducting an experiment to avoid undesired interactions between them. As a result, the influence of confounding variables may be minimized or even avoided [5]. Participants with a high degree of social similarity (i. e., same age, background) may be more inclined to cooperate [6]. Gender effects may also influence results: Female drivers tend to show more cooperative driving behaviour than male drivers [7]. While planning an experiment with multiple drivers, experimenter may take these effects into account when selecting participants for each trial.

23.3 Conducting Studies

23.3.1 Demands on Experimenters and Monitoring

During a test session in a driving simulation study, the experimenter is responsible for several tasks. Prior to the test run, the experimenter explains the procedure to the participants. During the test run, it is necessary to check whether the participants follow the instructions and all technical devices work properly. After the test run, the experimenter hands out questionnaires or conducts inquiries with the participants.

In a multi-road user simulation study, all these tasks are multiplied due to the larger number of participants. Therefore, it is recommended to use several experimenters in these studies. For example, two experimenters were required in the UR:BAN studies in the multi-driver simulation with four participants. Each experimenter took care of two participants. Also the studies in the connected driver-motorcycle simulation were conducted by two experimenters as the two mockups were located in different rooms. Here, each experimenter was responsible for a participant.

Comparable a to single-driver simulation study, problems (e. g. participants show up too late or need breaks) may occur hindering the study conduction. However, due to the increased number of participants the chance for these problems is multiplied. Similarly, due to the high number of computers and equipment in multi-road user simulations technical problems are also more likely to occur. Therefore, time buffers between two test sessions have to be considered. Furthermore, using additional back-up participants could help to avoid canceling sessions with participants who drop out.

Especially in multi-road user simulation studies it is important to monitor the group of drivers. In addition to checking whether all participants follow the instructions, experimenters also need to pay attention to whether social interactions take place. Therefore, it is necessary to develop tools which support the experimenters during monitoring. One solution is to observe the test scenery from a bird's-eye-view (see Fig. 23.2).

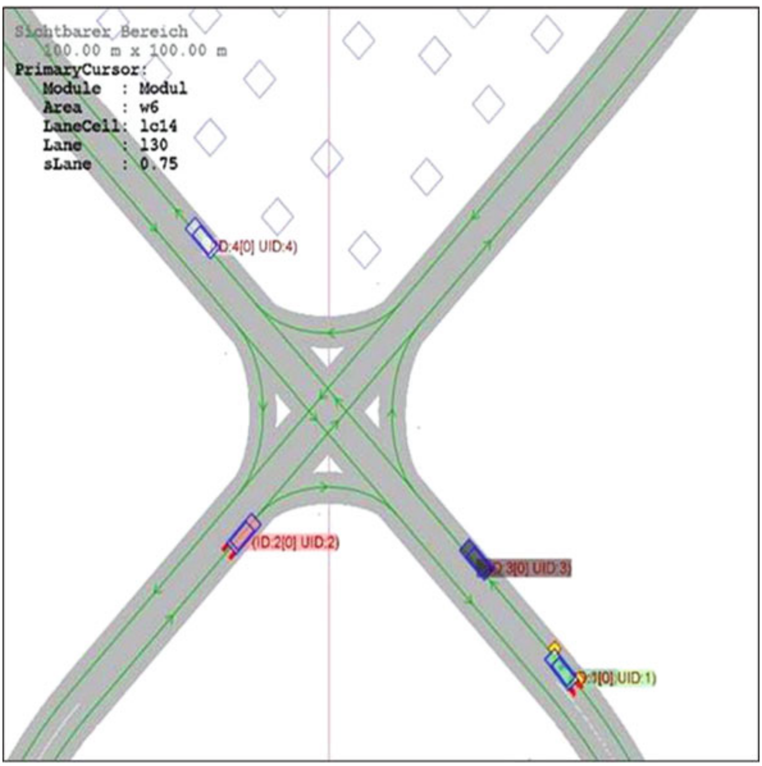

Fig. 23.2 Intersection scenario with four participants in the multi-driver simulation

23.3.2 Communication

In some experiments, participants and the experimenter need to communicate in order to transmit all necessary instructions as well as answer all questions related to the experiment. However, the communication between participants should be limited or even avoided at all, if it is not part of the intentioned interaction as this minimizes the effects mentioned in Sect. 23.2.3. In addition, limited verbal communication between drivers is more realistic as drivers usually do not speak with each other in traffic. To reduce communication between participants, a physical separation of the driving simulators may be a solution: Driving simulators may be put in different rooms or separated with blinds. When using the latter solution, headsets are recommended to minimize background sounds (e. g. conversation of participants with experimenter).

In some cases, it may be useful to enable communication between participants because verbal communication between participants may be valuable for the development of car-to-car-applications. For example, it may be of interest to find out the type and amount of information drivers would like to share with each other, for example, in a lane change scenario. Based on the results, appropriate communication concepts may be developed for car-to-car-applications such as a cooperative lane change assistant.

A limiting factor regarding the communication between drivers is the lack of visibility of the participants' faces and bodies in the multi-road user simulations. Especially in complex and unclear driving situations, communication via gestures or glances is an important factor in traffic [8]. Technical improvements (e. g. embedding of camera streams in the simulated environment) are necessary to enable these ways of communications between road several users.

23.3.3 Gathering Subjective Data

Compared to studies with one participant only, an advantage of multi-road user simulations is that more data are acquired in the same time. This is also valid for subjective data as questionnaires can be answered by several participants simultaneously. Nevertheless, it is more challenging to conduct interviews in a connected driving simulator study. The experimenter has to conduct one interview after another with each participant which takes a lot of time. Alternatively, the interview may be conducted with all participants at the same time. This has the disadvantage that social influences might affect the participants' judgments so that the answers might not be unbiased. This could also be the case when participants sit at the same table filling out questionnaires: they might talk with each other.

In single-driver simulation studies, verbal inquiries via an experimenter can be used to gather subjective data during driving. In multi-road user simulations, however, this is not possible as the experimenter can only ask the participants successively which might impede questions after the test scenarios. In these cases, inquiries via a display are possible. Questions may be shown on displays and drivers may answer via key-press or touchpad.

Another option to assess subjective evaluations during driving is to instruct drivers to use buttons or levers. For instance, in an study using the multi-driver simulation the drivers had to pull a lever attached to the steering wheel every time they were angered by other drivers [9]. This poses a non-intrusive method which allows collecting data of all participants continuously.

23.4 Analyzing Data

23.4.1 Illustration of Data

In order to display interactions of various drivers appropriately, different kinds of illustrations are needed compared to conventional single driver data plots. Having more than one participant in the multi-road user simulation means trajectories, velocities etc. are recorded and need to be illustrated for at least two participants, while the mutual influence between these is of special interest. In the following section two possibilities fulfilling these requirements are recommended. While an interaction plot can show the behaviour of two participants, the time-space-diagram has its strength in covering more vehicle trajectories.

Interaction Plot

One possible solution to address two vehicles' behaviour is the use of interaction plots [10]. These diagrams show a vehicle's longitudinal distance to a reference point on the horizontal axis and the other vehicle's longitudinal distance to the same reference point on the vertical axis. As a result, each line represents the relative approach to the reference point of a pair of participants. A perfect diagonal line starting at the bottom left would indicate that both road users approach the point of interest synchronically. This type of diagram is for example useful to display an intersection approach of two vehicles from different directions (see Fig. 23.3). In this example, a car and a Powered Two Wheeler (PTW) approach an intersection in orthogonal manner. The motorcyclist is equipped with an intersection support system informing the rider about potential conflict partners in cross traffic. Both road users start 100 m in front of the junction (−100/−100 bottom left). Their trajectories form a hypothetical conflict zone (0/0 top right) that is the common reference point. The following information can be retrieved from the interaction plot:

- The farther away one line is from the diagonal, the greater the difference of the two vehicles in distance to the conflict zone (e. g. the line in the lower right corner indicates that the car has about 50 m left to reach the junction whereas the PTW still has 100 m to go).
- At the beginning (0/0 up to about −40/−40) both vehicles cover the same distance at the same time as indicated by straight lines running in parallel to the diagonal line.
- A lot of motorcyclists slow down about 20 m in front of the junction as indicated by lines bending to the right. The lines that run nearly in parallel to the horizontal axis

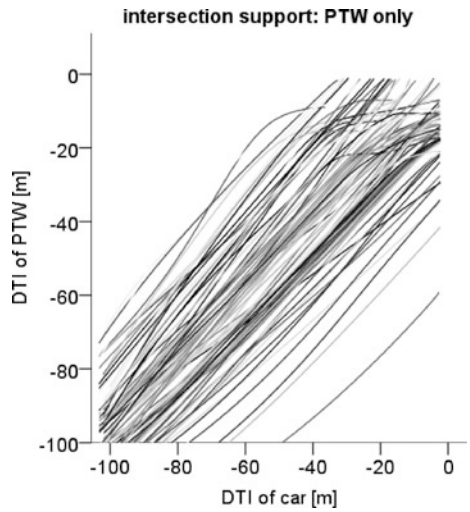

Fig. 23.3 Interaction plot showing an intersection approach of two vehicles in a multi-road user simulation. The Powered Two Wheeler is assisted by an intersection support

show that the PTW almost stands still while the car approaches the junction at constant speed. An interaction plot as shown in Fig. 23.3 can visualise effects produced by variations in conditions. In this case, the deceleration could be due to the intersection support system.

- The number of lines ending on the right side respectively on the upper side of the plot corresponds with the road user reaching the junction first. In the example shown below, more lines lead to the right side, meaning that more cars crossed the junction before the motorcyclist.
- A line crossing the conflict zone (0/0 top right) indicates that a collision occurred between the two road users.

Time-space Diagram

Interactions between more than two drivers can be described by means of time-space-diagrams. A time-space-diagram shows time on the horizontal axis and distance to a reference point on the vertical axis. The trajectories of individual vehicles are shown by sloping lines. The slope of the line represents the speed of the vehicle: A horizontal line represents a stopped vehicle and a higher slope signifies a higher velocity. Acceleration and deceleration are displayed by the change of slope: Deceleration causes the slopes of the lines to flatten, while acceleration causes the slopes to increase. If two vehicles are moving on the same lane on the road, the vertical distance displays the headway between these vehicles. Therefore, crossing lines indicate a collision if the respective vehicles were driving on the same lane.

Fig. 23.4a gives a case example to demonstrate the usage of time-space diagrams to describe the course of interactions between several drivers: While the vehicles 1 and 2 approach the intersection from the left side, the vehicles 3 and 4 approach from the right

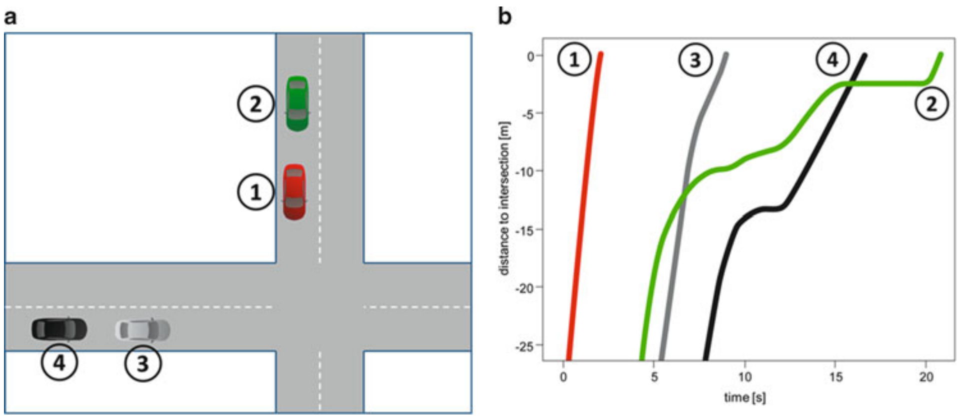

Fig. 23.4 Starting conditions of the case example (**a**). Time-space-diagram for the case example (**b**)

side. Vehicles 3 and 4 have right of way because the priority-to-the-right rule applies at the intersection.

Vehicle 1 reaches and crosses the intersection first (see Fig. 23.4b). Afterwards, vehicle 2 reaches the intersection area. However, the driver decelerates (as the slope of the line decreases) to give vehicle 3 the chance to cross the intersection. Vehicle 4 also decelerates and stops approximately 15 m prior to the intersection (as the line becomes horizontal), but accelerates again and crosses the intersection. Finally, vehicle 2 crosses the intersection.

23.4.2 Selection of Parameters Describing a Platoon of Drivers

Studies conducted in multi-road user simulations enable the investigation of drivers' interaction. As a result of interacting with each other, individual behaviour may be influenced. Thus, the driving behaviour of one driver might not only be affected by the manipulated variable that is focused on in an experiment. As a result, the causal relationship between a manipulated and a response variable cannot be investigated properly. The interaction of drivers must be taken into account to ensure the internal validity of the results. For example, in a lane change scenario, conditions and circumstances leading to cooperative behaviour may be investigated in multi-road user simulation. Drivers might show specific driving behaviour prior to a lane change request (e. g. drive aggressively) that may affect the willingness to cooperatively allow a lane change. Thus, the causal relationship between the circumstances of a lane change request (manipulated variable) and the number of cooperative lane changes (response variable) cannot be analysed without taking into account the interaction of the drivers [11, 12].

To address this issue, parameters describing the interaction of drivers must be developed. Parameters were suggested to describe a platoon of drivers: the *platoon's standard* *deviation of the lateral position* (SDLP) and the *platoon's length* [3]. The *platoon's SDLP* describes the lateral control of a platoon of drivers in an interaction scenario. The *platoon's length* describes the longitudinal control of a platoon. The longitudinal control of the vehicle does not provide any information of each driver's position within the platoon; therefore, this parameter was modified for an URBAN study with three drivers. Their individual car-following behaviour and thus the arrangement within the platoon may differ, although the *platoon's length* is equal. To address this issue, the *difference in distances* (DiD) between two queued drivers within a platoon of three drivers was proposed [11, 12]. The distances between the third and second driver and between the second and first driver are measured followed by calculating the difference between these distances. Here the distance between the third and second driver is subtracted from the distance between the second and first one. A small DiD around zero shows equal distances between the drivers in the platoon (see Fig. 23.5 below). A larger DiD represents unequal distances between the drivers. A large negative DiD indicates a higher distance between the third and second driver than between the second and first driver (see Fig. 23.5 above). A large positive DiD indicates a higher distance between the second and the first driver than between the third and second one (see Fig. 23.5 center).

The DiD can be plotted across relevant scenarios describing the arrangement of three drivers within a platoon over time (see Fig. 23.6). In the example in Fig. 23.6, the DiD was plotted across a start-up manoeuvre from the moment the first driver starts up until the third driver passes the stop line. At the beginning, the DiD increases steadily. This means that

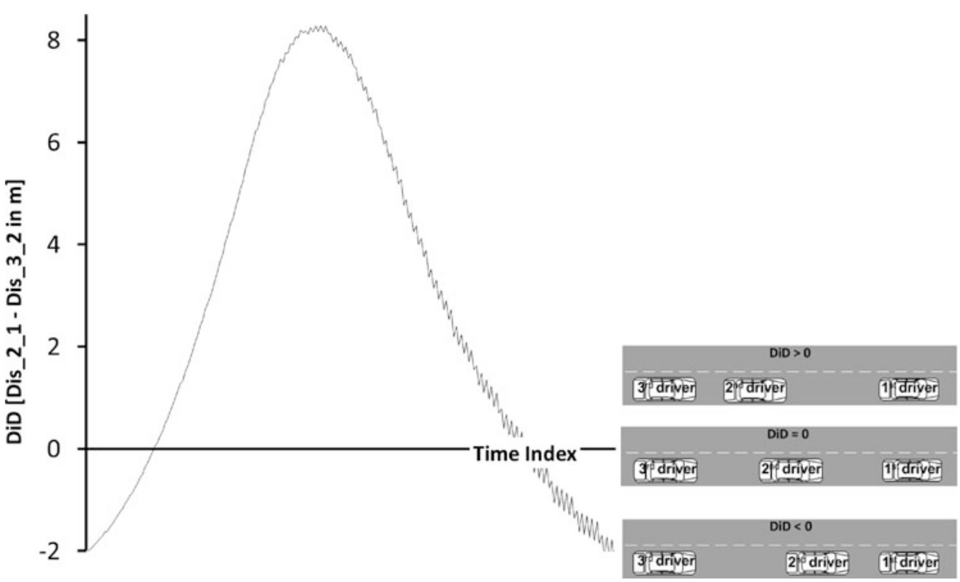

Fig. 23.5 The differences in distances (DiD) represents the formation within a platoon of three drivers

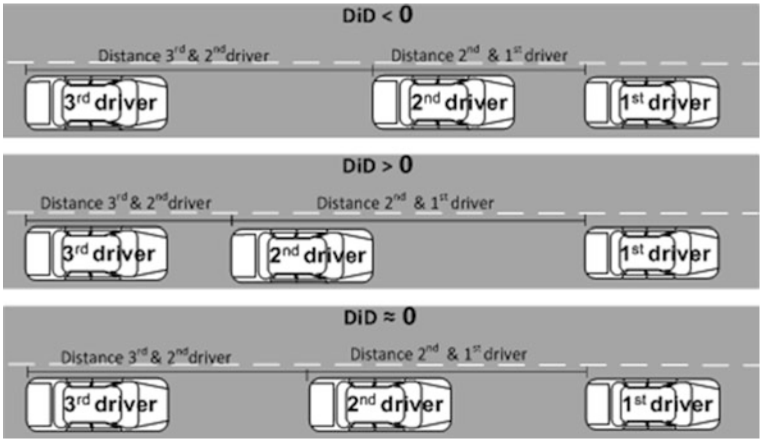

Fig. 23.6 Calculated differences in distances within a platoon of drivers for a start-up manoeuvre

the distance between the first and the second driver increases until reaching its maximum. From this point, the DiD decreases indicating that the distances between the first and the second vehicle decreases. Based on this approach, drivers' interaction behaviour can be described. Parameters such as the mean, maximum, minimum or standard deviation of the DiD describe the behaviour of three drivers in a platoon.

23.4.3 Cross Correlation – A Method to Quantify and Assess Social Interaction in Multi-Road User Simulation

Analyzing driving data by means of safety measures is the common approach. Time-to-collision respectively time-to-arrival (TTC/TTA), post-encroachment-time (PET), average velocity or maximum braking power are just a few to be mentioned when focusing on driving behaviour in real world or simulator experiments. These measures support a cross-sectional analysis concerning the underlying processes and stated hypothesis. However, social interaction between road users is a time-based process and the aforementioned approach lacks the potential to register the mutual behaviour adaption between different traffic participants encountering each other [13].

In urban traffic, these encounters occur more often due to traffic density and more heterogeneous road users compared to rural roads or highways. To consider these social interactions in case of traffic conflict research, time-based methods have to be taken into account when analyzing data of traffic related experiments. These time-series analyses are popular in other disciplines (i. e., physics or climate research) but more seldom in microscopic traffic research.

In driving simulators, it is quite easy to record all the data that are produced by the simulation and additional external equipment such as eye-tracking, driver information, or driver assistance systems as they are implemented in the simulator. Real world observation or field tests require additional effort to extract the data needed for the analysis of the interesting time series. These might contain additional information about the underlying action and reaction of involved road users.

A well-known measure in time-series analysis is the cross correlation of two signals calculating the similarity between them [14]. The correlation depends on the time shift (lag) of one series to the other series. This method aims at finding the necessary lag to produce the maximum correlation between the considered time series and thereupon draw conclusions concerning the interaction of systems.

In the case of two urban road users, using the example of car driver and pedestrian encounters, the cross correlation can be analysed using the speed signals. The latter can be recorded in a driving simulator experiment with connected simulators and different types of crossing situations (free lane, occlusion situation, pedestrian crossing) and types of pedestrians. The different behaviours of the participants are shown in Figs. 23.7 and 23.8.

Fig. 23.7 shows the speed signals of the car driver (top) and the signal of a programmed pedestrian (middle), which is not able to interact with the driver. Its street crossing behaviour is programmed meaning the programmed pedestrian starts to cross the street with a predefined distance to the driver without looking right or left or being able to adapt the behaviour (speed) in regard to the driving behaviour. In this case, the pedestrian is the leading time series (leading road user) and only the driver is able to react which manifests in negative time shift to gain the maximum correlation between the two speed signals. This behaviour is quite uncommon as pedestrians show mainly a safety oriented crossing behaviour due to their human characteristics (i. e. vulnerability).

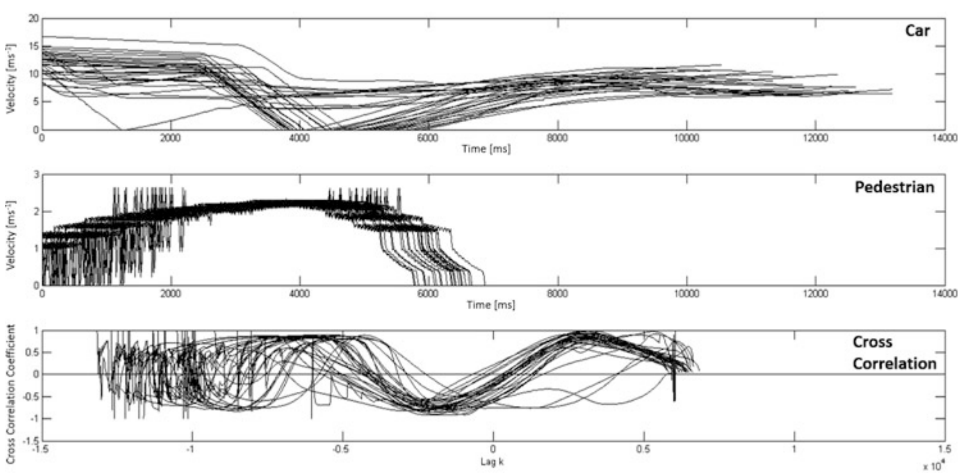

Fig. 23.7 Cross correlation of car and pedestrian speed signals in free lane situation (programmed pedestrian)

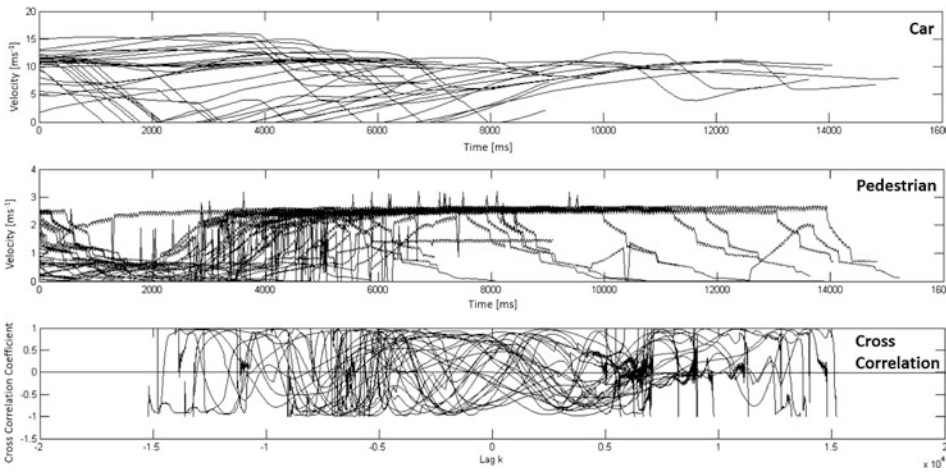

Fig. 23.8 Cross correlation of car and pedestrian speed signals in free lane situation (human controlled pedestrian)

In contrast, Fig. 23.8 shows the cross correlation function of the behaviour adaption process between two humans that encounter each other in a linked driver-pedestrian-simulation. Here, through the heterogeneity of the speed signals and the resulting cross correlation it is obvious that interaction by means of speed adaption took place and is quantifiable by the displayed method. In this case, the car is the leading series (leading road user) because the necessary time shift to identify the maximum correlation is positive.

In summary, cross correlating the two speed signals of road users that intend to use the same traffic infrastructure (i. e. street segment) supports statements concerning their interaction behaviour. Further, it is possible to identify the leading series and the mutual time to reaction (time shift). Therefore, a quantification of social interaction in traffic is feasible through velocity signal analysis. Adding results of glance behaviour of both parties and posture analysis of pedestrians at the curb could complete the image of interpersonal communication in synthetic environments such as driving simulations.

23.5 Conclusion

This chapter provides an overview of methodological aspects relevant for conducting studies in multi-road user simulations. For this purpose, the conclusions based on several studies using various types of multi-road user simulations (driver-driver simulation, driver-pedestrian-simulation, driver-motorcyclist simulation) during the UR:BAN project are taken into account.

It turns out that methodological specifics and challenges are relevant for all stages of a scientific study – from planning and conducting a study to analyzing data. Compared to single-driver simulations, these specifics might have beneficial as much as detrimental effects. On the one hand interaction between road users can be examined. One the other hand, studies in multi-road user simulation constitute the need for a more complex and tailored study methodology. Thus, prior to a study, researchers need to decide what type of driving simulation may be used to most effectively answer the postulated research questions.

It is obvious that using a multi-road user simulation is more complex than working with a single-driver simulation. The scenario design is very important – only with an appropriate design it is possible to create social interactions between road users. Besides, more participants, experimenters and technical equipment are needed for conducting studies in multi-road user simulations resulting in a heighten probability of artefacts, failures and problems. Furthermore, participation of several drivers reduces controllability and reproducibility of the experimental situation. This reduces internal validity, which corresponds to the causal relationship between the independent and dependent variables. Instead, the single-driver simulation guarantees a high degree of internal validity – therefore, it is more suitable for research issues which require highly controlled test situations (e. g. controllability of driver assistance system failures). Besides, connected driving simulators lose their benefit when the focus of research is on the single driver and surrounding traffic is less important. This applies, for example, for the investigation of driver states. When examining the effects of distraction, alcohol, or fatigue on driving behaviour the interaction with surrounding traffic might be of lower priority. As well, the multi-road user simulation might not be appropriate for studies analyzing usability of driver information systems or driver assistance systems, as the interaction with these systems is often investigated and not the interaction with other road users.

In contrast, the multi-road user simulation enables new options to measure, describe, and analyse behaviour of single drivers as well as groups of drivers. Moreover, it allows investigating social interactions – the actions and mutual reactions between drivers which are crucial for traffic safety, traffic flow, and traffic climate. This is a benefit compared to single-driver simulations which use driver models with predetermined behaviour as surrounding traffic. Simulated driver models interact with other road users not at all or only insufficiently. Instead, human drivers show human behaviour, which makes test scenarios more realistic and enhances external validity and, therefore, the generalization of results. Studies in the multi-road user simulation enhance knowledge concerning interactions between road users. This knowledge in turn might be used to improve simulated driver models used in the single-driver simulation.

Due to these benefits, connected driving simulators are suitable for all questions regarding social interactions between road users. Interactions occur every time road users encounter each other and have to react to the other road user's behaviour. Interactions are affected by various factors such as cooperation or aggression. Furthermore, new technologies may influence interactions. Assistance systems (supporting or overtaking a part of the driving task) may produce driving behaviour that is not anticipatable or predictable for other road users. For instance, a traffic light assistant helps drivers to adapt their driving behaviour anticipatorily to the upcoming traffic light status. This manifests itself in, for example, slowing down while the traffic light is still on green or stopping prior to the stop line. Surrounding traffic without the assistance might not understand this behaviour as they have no information about the upcoming traffic situation. A multi-road user simulation allows analyzing the effects of this system on other drivers. Moreover, by increasing the number of drivers in a simulation the effects of different penetration rates on the whole traffic system could be investigated.

If the technical restrictions are solved, a multi-road user simulation consisting of several cars, trucks, motorcycles, bicycles and pedestrians is imaginable. Such a multi-road user simulation would create a real traffic system in a simulated environment which allows investigating more complex and safety-critical phenomena without putting participants at risk. At the same time, external validity increases enables to transfer results to the real world.

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Part VI

Controllability and Safety in Use Assessment of Advanced Driver Assistance Systems

Development and Evaluation of Methods to Assess Controllability and Safety in Use Within the UR:BAN Project

24

Alexandra Neukum and Norbert Schneider

The subproject UR:BAN KON "Controllability" developed and evaluated methods which can be used to assess safety and controllability in early-stage development of new driver assistance systems. The empirical studies focused on assistance systems helping the driver to avoid collisions in time-critical scenarios. Although these advanced driver assistance systems get more and more "intelligent" and "efficient" they also get more complex which poses a great challenge for the assessment and evaluation of safety and controllability. Especially, emergency steering and evasion assistants require strong interventions which makes it more difficult to control a false positive activation. However, these advanced driver assistance systems could also help to avoid casualties, as in many cases it can be assumed that the driver would not have been able to avoid a collision at all.

Within the subproject KON we tried to address this problem by exemplarily analysing emergency steering and evasion assistants which help the driver to avoid collisions in time-critical scenarios. We could identify several factors like the available manoeuvring space, the drivers' attention and characteristics of the system design, which have an influence on controllability in case of a false positive activation and safety in use. To optimize efficiency of the safety and controllability assessment we evaluated the applicability of several existing research environments, like driving simulation, the so called Vehicle in the Loop (VIL), which combines elements of driving simulation and a real vehicle, and real vehicle testing on a closed test track. Additionally, new approaches to assess controllability were tested which focus on the reactions of the surrounding traffic instead of solely considering the reactions of the affected driver.

In the following chapters, we will start with methodological questions of controllability assessment (Chap. 25), which focus on the validity and applicability of different research environments. Using basic driving tasks as an example the results of a study will be pre-

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sented which compares driving simulators (static/dynamic) and the Vehicle in the Loop with real vehicle testing on a closed test track. The results will be discussed regarding potential application areas of the addressed research environments and whether it is possible to generalise the environment specific results.

Chap. 26 focuses on studies with the Vehicle in the Loop. Two studies will be reported. The first study analysed how occupied opposite lanes influence the drivers' reaction in case of an intervention of an emergency steering and evasion assistant. The second study dealt with the reaction of the surrounding traffic in case of steering system failures. Based on the results of this study it will be discussed whether the surrounding traffic can be considered when assessing controllability.

Chap. 27 dedicated to the methodological aspect of test scenario design. It focuses on the influence of the available manoeuvring space in case of a false positive activation. Additionally, methods to detect the drivers' override intention based on objective data will be presented and discussed regarding their applicability to differentiate between true positive and false positive interventions.

With respect to controllability aspects, Chap. 28 discusses potential intervention strategies which can be used to design an emergency steering and evasion assistant and summarises current findings. The results of real vehicle and driving simulator studies will be reported, which focussed on the effect of warning and driver intention/override detection concepts. Based on these results and a literature review recommendations for the design of emergency steering and evasion assistants will be given.

The last chapter (Chap. 29) addresses the influence of secondary tasks on the drivers' reaction in case of an erroneous steering intervention. Different ways to induce driver distraction will be discussed and two exemplary studies will be reported.

25 Validity of Research Environments – Comparing Criticality Perceptions Across Research Environments

Christian Purucker, Norbert Schneider, Fabian Rüger, and Alexander Frey

25.1 Introduction

The German research initiative UR:BAN pursues the improvement of safety in urban traffic by investigating and developing new advanced driver assistance systems (ADAS) and traffic control measures [1]. Various new ADAS are currently subject to research that includes emergency steering and braking functions that may even steer and brake autonomously for a limited amount of time. These systems are likely to increase overall traffic safety, but they also have introduced new challenges for controllability research because systems as well as deployment scenarios have become increasingly complex. According to industrial standards such as ISO 26262 [2], overall system controllability for human drivers must be established even with possible system failures. Various guidelines exist for this context, including the RESPONSE Code of Practice [3] and the European Statement of Principles on Human Machine Interface [4]. Although those guidelines provide some general rules on how to conduct human driver controllability relying on empirical tests with human test subjects, they remain rather coarse with regard to the choice of appropriate research environments (e. g. test track vehicles or driving simulators).

The aim of the KON ("Controllability") subproject within the UR:BAN Human Factors in Traffic key issue is the development and evaluation of new and existing methodologies

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for the assessment of system controllability. The study herein presented addresses the choice of test environments and driving simulator validity for specific questions in the area of controllability research as outlined above. The series of experiments focused on perceptional aspects that are of particular relevance to controllability research on ADAS in urban contexts. In particular, human perceptions of longitudinal distances during car-following, lateral distances when driving through narrow road zones, and perceptions of lead vehicle accelerations and decelerations during car-following were investigated.

The following theory section gives a short overview on related aspects of human perceptions of vehicle speed, longitudinal and lateral distances, and decelerations of lead vehicles during car-following. Problems involved with the choice of research environments in recent controllability research are addressed, e. g. questions regarding how research environments differ from one another and how results obtained in one research environment can be transferred to another. The method section describes the study's general approach, the scenarios that have been used in the research, and the four research environments: a static driving simulator, a dynamic driving simulator, a hybrid between a test track vehicle and simulator (a so-called Vehicle-in-the-Loop, VIL), and a test track vehicle. Subsequently, the results are reported and discussed. Implications for future research are provided.

25.2 Theoretical Background: Validity of Research Environments

In the following section, literature findings from the field of simulator validity research and research on human perception in consideration of the subsequent empirical study are presented. The structure loosely follows a book chapter by Mullen, Charlton, Devlin and Bédard [5], which is also suggested as a comprehensive review on current simulator validity research. The following topics will be addressed: choices and perceptions of vehicle speeds, longitudinal distances to lead vehicles, lateral distances in narrow road passages, and perceptions of braking and acceleration during car-following. If relevant to the current empirical studies, common measures will be described as well. The appropriateness of different research environments for specific research questions will be discussed, and works on the transfer of results from one research environment to another will be noted.

25.2.1 Choice of Vehicle Speed and Speed Perception

It should first be noted that the perception and production of vehicle velocities was not the direct focus of the present study; the scope of the UR:BAN project was German inner-city environments, and therefore vehicle speeds were limited to lower speeds (except on inner-city highways, the speed limit in German cities is 50 km/h). However, the influence of perceived vehicle speeds on the results obtained in the presented study cannot be ruled out, which is why the literature on human vehicle speed perception should be briefly reviewed.

Findings in the literature on choice and perception of vehicle velocities in driving simulators [5] are mixed. Although some studies considered drivers' self-determined choices of vehicle speeds (speed production) and perception of vehicle speeds in driving simulators to be absolutely valid when compared to real vehicles [6–8], other studies claimed only relative validity [6, 9–13], e. g. when looking at the effectiveness of speed-reducing measures on speed production [14, 15]. Other studies found neither relative nor absolute validity of speed behaviours observed in driving simulators [16].

Velocity differences between driving simulations and real vehicles have been reported in both directions [5, 17]. Some works state that drivers tend to drive faster in driving simulators [7, 12, 18, 19], whereas other works report lower speeds [10, 11, 14]. The effects of structural measures on speed reduction in driving simulations compared to real traffic environments have been reported to be similar [14, 20] or greater [15].

Some works have reported a lower perception of speed in driving simulator environments [21–23]. A single work differentiated between speed production and speed perception [12]; the produced speeds tended to be higher in the driving simulation compared to driving in a real vehicle, whereas low speeds tended to be perceived as higher.

Some sources have argued about the reasons for observed differences in speed production and perception between real vehicles and driving simulators [17, 22, 23]; for example, not all environmental cues important for speed estimation are available in driving simulations. Works have also discussed how speed perception in driving simulations can be improved by visual and technical measures, e. g. by extending the available field of view (e. g. [22]).

Although the findings in the literature are heterogeneous in some respects, one can expect that differences in speed perception between driving simulators and real vehicles also lead to differences in perceptions of longitudinal and lateral distances to lead vehicles or narrow road zones.

25.2.2 Choice and Perception of Longitudinal Distances

Longitudinal distances to preceding vehicles in car-following scenarios are usually measured as time distances (Time Headway, THW). There are several studies that describe observed time distances in real traffic and driving simulators (i. e., [24, 25]) or determinants of driven time distances (cf. [26]). For urban areas, reported mean THWs range between 1.75 s (SD = 0.65; [27]) and 2.11 s (SD = 1.00; [25]).

Various predictors have been identified to influence the THW. The speed of the vehicle was found to exert a strong influence on the THW, with lower speeds leading to larger THWs and THWs being roughly constant at a value of 1.25 s for speeds greater than 15 m/s [26]. Regarding road type, researchers found that THWs on highways usually were lower than in urban areas, with values less than 2 s [26, 28]. Another factor that influences the observed THW is traffic density; higher densities decrease mean observed THWs down to approximately 1 s [29, 28].

A large body of research on driving simulator validity provides evidence for at least relative validity (if not absolute validity) in most areas of investigation, including choice of speed, brake onset or risky traffic behaviours (cf. [5]). To our best knowledge, however, in-depth investigations of THW have attracted only limited research interest to date (cf. [30] for an exception), and in particular validity assessments of THW criticality perceptions during car following tasks are largely missing. In a study comparing THWs at different higher speeds, Stam [30] found no differences between a static driving simulator and a test track vehicle. However, the study did not involve lower driving speeds or assess participants' criticality perceptions of the different time distances.

25.2.3 Choice and Perception of Lateral Distances

Common measures for lateral distances in the driving simulator validity literature usually focus on lateral vehicle position within the lane. Measures such as the distance of the front tire on the passenger side of the vehicle to the corresponding lane marking are not uncommon (cf. [5]); however, in simulator research, measures such as the deviation of the vehicle centre from the middle of the lane or the road are often preferred because vehicle dimensions in simulator environments are often only virtually represented rather than represented as physical objects.

Various studies address the validity of lateral vehicle positions between driving simulations and real vehicles. Blana and Golias [31] compared driving on a real road section with a corresponding simulator drive. They observed that drivers in the real vehicle kept closer to the centre of the road and that the standard deviation of the lane position was higher in the driving simulator. However, strongly moderated results were observed for vehicle velocity and type of road section (curved or straight), e. g. these effects generally only emerged at speeds faster than 60 km/h.

Törnros [13] compared tunnel driving between a driving simulation and real world driving. The drivers, who were accustomed to Swedish right-hand traffic, tended to drive in the driving simulator with a lateral displacement to the right of 0.13 m, in effect positioning their vehicles closer to the tunnel wall. The effects of structural measures for speed reduction, e. g. narrow road zones, have been described to be equally [14, 20] or even more effective in driving simulations in comparison to real world driving [15]. Van der Horst [32] investigated the effects of varying narrow road zones between 2.25 m to 2.75 m on speed reduction, but he did not directly compare his results to a subsequent real world drive. Reichel [33] found that a narrow zone of 2.25 m marked by balloon-cars was the narrowest lateral distance that drivers would drive through on a test track.

Summarizing those findings, it can be expected that drivers accustomed to right-hand traffic tend to drive with a lateral displacement to the right-hand side in driving simulators, and narrow road zones might lead to speed reductions as well.

25.2.4 Perception of Braking During Car Following

Common measures to assess a driver's braking behaviour are the time interval between a driving event and the time the driver needs to take his foot from the accelerator pedal, the time he needs to initiate pressure on the brake pedal, the elapsed time until a maximum brake pressure is reached, or until the maximum brake pressure applied. In addition, vehicle dynamics, such as the maximum vehicle deceleration, can be considered.

Only a few works in the literature address the comparison of braking behaviours observed in driving simulators and real world drives (cf. [34]; [35]; [36]). It is generally assumed that braking behaviours in both environments are similar [34]; [35]. As an example, Hoffman, Lee, Brown, and McGehee [35] reported that braking reaction time as well as braking force profiles in driving simulators were similar to those observed in real world driving. Similarly, McGehee, Mazzae, and Baldwin [36] observed that braking reaction times equalled each other. On the contrary, Neukum, Naujoks, Kappes, and Wey [37] reported that braking reaction times, particularly following strong braking manoeuvres of lead vehicles, were slower in a driving simulation than in the real vehicle. Compensating for this, applied braking forces as well as subjective criticality perceptions were higher in the driving simulator.

Based on those latter findings, one could expect that braking reaction times in driving simulators are slower and applied braking forces are higher than those in real world driving. Considering the other empirical works, one would expect that drivers in driving simulators will rate the situations as critical or even more critical when compared to real world drives.

25.2.5 Choice of an Appropriate Research Environment

The choice of an appropriate research environment is a central issue for the generalizability of results obtained from research on human controllability of ADAS. Although there is a wide spectrum of available research environments and methodologies (cf. [38] for an overview from research on forward collision mitigation systems), most methods have unique advantages and disadvantages that must be considered carefully before making a decision. The methodological trade-off between "experimental standardization" and "ecological validity" as depicted in Fig. 25.1 serves as an example trade-off that must be considered when making a decision between, for example, a driving simulator or on-road test drives as a research environment. However, the trade-off between research environments is often not clear-cut and involves multiple judgmental dimensions that may be specific to a particular research question.

For example, safety-critical system functions can hardly be tested in real, naturalistic traffic conditions, although this might be favourable from the viewpoint of generalizability. Although controllability researchers in the past often relied on test track studies to capture participants' reactions towards functional interventions on vehicle dynamics such

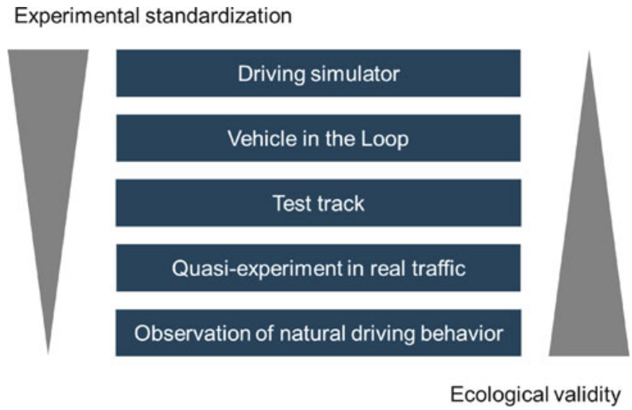

Fig. 25.1 Illustration of a possible trade-off between standardization and validity between research environments

as ABS or ESP, this may not be an adequate choice for the evaluation of ADAS that were developed to assist human drivers in complex urban scenarios. When making a decision to perform research on a test track or even in a naturalistic traffic environment, the following aspects must be considered:

- Safety reasons: In tests involving real vehicles and drivers, safety is always a concern. Adequate measures must be taken to ensure the driver's safety, and some questions may not be addressed this way.
- Standardization: Experimental control is highly desirable to obtain unambiguous results; this can be a problem for naturalistic driving on real roads. On the contrary, high standardization, e. g. on test tracks, may lead to unrealistic and artificial driving situations with obviously low ecological validity.
- Feasibility: Particularly in the early development stages of vehicle functions or when testing interactions with infrastructural measures, some factors under investigation may not be easily represented with a functional or tangible prototype.
- Complexity: Extending the problem of feasibility, complex naturalistic traffic scenarios that involve the coordination of multiple agents such as vehicles or other road users in particular are difficult to realise in a systematic way on a test track or in a naturalistic driving scene.
- Technical and financial effort: The above-mentioned factors may lead to requirements for test track studies or studies in naturalistic traffic that require extended technical and financial efforts.

On the contrary, driving simulators overcome some of the previously mentioned restrictions because complex or potentially dangerous traffic constellations can be simulated with ease and without endangering participants. However, fundamental issues concerning vestibular or visual feedback in simulator environments [17, 39] might limit the validity and therefore the suitability of simulator environments for controllability research.

Several works address these deviations in driving simulator studies and studies using real vehicles [17, 22, 23]. The following list mentions some of these aspects that should be considered when opting for driving simulator research:

- Lack of visual detail: The amount of details of geometries, proportions, object densities, textures, among others are likely to be reduced in even the newest types of simulator environments.
- Other shortcomings of visual display: In addition, other shortcomings in spatio-temporal resolution, graphical performance, colour dynamics, luminance, surface display, and rendering errors may occur.
- Availability of spatial cues: Not all spatial cues used for object location are available in a simulator environment, e. g. a third dimension is often missing for the scenery display.
- Acoustical cues: The presentation of sounds might deviate from that in a naturalistic environment.
- Object physics: Some possibly relevant physical cues may not be displayed in a simulator environment.
- Vehicle dynamics: Even high-end simulators typically are unable to simulate and display all dynamic forces that are at play in the real vehicle (e. g. longer translational forces).
- Ecological or "eyesight" validity: Participants are usually fully aware that they are in a simulated environment; this may, as an example, lead to an altered perception and reaction towards threats.
- Motion sickness: Some participants experience a simulator specific sickness when acting in a virtual space.
- Training efforts: To overcome some of the aforementioned shortcomings and particularly to observe realistic participant behaviours, extended simulator training might be necessary to obtain valid results.

Of course, not all of these aspects apply to all simulators in a similar way – the variety of driving simulators usually relied on extends from very basic desktop simulators to static driving simulators with conceptual or realistic vehicle mock-ups to full-scale dynamic driving simulators that are capable of simulating components of the actual vehicle motion.

As an approach to overcome some of these limitations, a Vehicle-in-the-Loop (VIL) was developed as a hybrid between a test track vehicle and a driving simulator. In a VIL, the driver actually drives a real car on a test track while wearing a non-transparent head-mounted display. Visually, the driver is completely immersed in a virtual world, but he feels real vehicle dynamics from the test track vehicle at the same time [40].

25.2.6 Transfer of Results Between Research Environments

In addition to a consideration of the specific advantages and disadvantages, the question of the validity and generalizability of results is at the core of all decisions in favour of or against a particular research environment. Comparisons and the calculation of transfer functions for results obtained in different research environments may, under certain circumstances, allow research results to be generalized. It has been shown that functions that have been calculated and validated in a certain research environment can be at least partially transferred to other research environments. As an example, Andersen and Sauer [41] showed how model parameters used in the prediction of driver performance and THW can be transferred from a driving simulation to a real vehicle. In another case, Neukum, Naujoks, Kappes, and Wey [37] showed how results on braking reaction times obtained in a simulator experiment relate to braking reaction times in a real vehicle.

25.3 Methodology

25.3.1 Research Environments

A total of four different research environments were used for each of the experiments performed in the study. The research environments were

- a static driving simulator (located at the BASt),
- a dynamic driving simulator (located at the WIVW),
- a VIL (located at the UniBw), and
- a test track vehicle (located at the UniBw).

The experiments were conducted in each of the research environments separately using the same experimental procedures. Each research environment is described in detail in the following section to allow a better intercomparison of the environments. All of the environments allowed the recording of various objective measurement parameters of the vehicle dynamics and driving situations.

25.3.1.1 Static Driving Simulator (BASt)

The static, fixed base driving simulator at the BASt consisted of a fully instrumented, conceptual vehicle mock-up that was positioned in front of projection screens (Fig. 25.2). The size of each screen was 2.8 m to 2.1 m (width x height). In total, the projector screens roughly constituted a 180° front view. Interior and exterior rear-view mirrors were simulated by correspondingly sized small LCD displays. A surround sound system was completed by a seat-mounted bass shaker that provided realistic vehicle sounds and vibrations. The SILAB (v4.0; WIVW GmbH) driving simulation software was used. The simulated vehicle dynamics were derived from a model E39 BMW 520i with an automatic transmission.

Fig. 25.2 The BASt static driving simulator used in the study

25.3.1.2 Dynamic Driving Simulator (IZVW)

The dynamic, moving base driving simulator used by the IZVW was located at the WIVW GmbH (Fig. 25.3). The physical vehicle mock-up was identical to a fully instrumented, production type BMW 520i with automatic transmission. The motion system consisted of a Stewart platform with 6 electro-pneumatic actuators (stroke ±60 cm; inclination ±10°). With its six degrees of freedom, it was able to briefly display a linear acceleration of up to 5 m/s^2 or 100°/s^2 on a rotary scale. Three LCD projectors were installed in the dome of the dynamic simulator and provided a 180° front view; each projector had a screen resolution of 1400 × 1050 pixels. LCD displays served as exterior and interior rear-view mirrors. A Dolby 5.1 surround sound system and a seat-mounted bass shaker contributed to the 3D sound experience. The SILAB (v4.0; WIVW GmbH) driving simulation software was used for environment visualization and vehicle dynamics; as with the static simulator, a BMW 520i's vehicle dynamics were simulated.

25.3.1.3 Vehicle-in-the-Loop (UniBw)

The VIL was a hybrid between a test track vehicle and a driving simulation (Fig. 25.4). The driver moved an Audi A6 on a test track while wearing a head mounted display, which in turn displayed a completely virtual world. The Audi A6 was also used as the test track

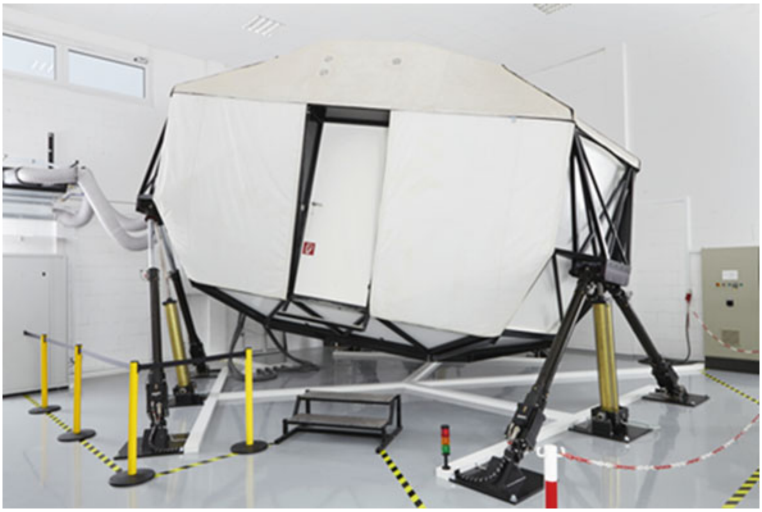

Fig. 25.3 The WIVW dynamic driving simulator used in the study

Fig. 25.4 The UniBw Vehicle-in-the-Loop (VIL) used in the study

vehicle in the studies. A detailed description of the system can be found in Berg, Karl, and Färber [42]; however, the system used for the current experiment used an nVIS ST50 as a head mounted display. Moreover, the head tracking latency had been greatly improved for the current studies. The Virtual Test Drive [43] simulation software was used.

25.3.1.4 Test Track Vehicle (UniBw)

The test track vehicle used in the study was an Audi A6 3.0 TDI Avant with an automatic transmission (Fig. 25.5). It was equipped with on-board computers for measuring vehicle signals and signals for exact position tracking (iTrace RT-F200 and DGPS).

25.3.2 Scale for Criticality Assessment

To assess the situational criticality according to the participant's subjective perception, the scale for criticality assessment of driving and traffic scenarios [44] (Fig. 25.6) was used in the current study's experiments. The scale is based on a two-step rating procedure in which participants have to rate the criticality of a situation they experienced while driving. In the procedure, they classify their judgment into the numerically anchored judgment categories: "imperceptible" (0), "harmless" (1–3), "unpleasant" (4–6), "dangerous" (7–9), or "uncontrollable" (10). The numeric values allowed the participants to indicate tendencies to lower or higher categories. The "dangerous" or "uncontrollable" categories (all numeric values equal or larger than 7) represent scenarios or situations that drivers would not accept in real traffic. The rating scale was originally developed by Neukum and Krüger [45] as an evaluation tool for the evaluation of malfunctions of active steering systems. Later, the scale was extended to the criticality assessment of driving and traffic scenarios, and its validity for research uses has been assessed in several studies (e. g. [37, 44]).

For the statistical modelling procedure used in the current work, the numeric values obtained during the study were recoded into the three main categories: "harmless", "unpleasant" and "dangerous".

Fig. 25.5 The UniBW test track vehicle used in the study

Fig. 25.6 The scale for criticality assessment of driving and traffic scenarios [44]

25.3.3 Ordinal Logistic Regression

To obtain transfer functions for the criticality perceptions across research environments for each of the experiments in the study, ordinal logistic regressions of the following form were calculated:

$$\begin{aligned}&\text{Sit. Crit.}{\sim}\beta_1 \times \text{Exp. Cond.} + \beta_2 \times \text{Res. Env.}_{\text{Dyn. Driv. Sim.}}\\&+ \beta_3 \times \text{Res. Env.}_{\text{Stat. Driv. Sim.}} + \beta_4 \times \text{Res. Env.}_{\text{VIL}} + \varepsilon\end{aligned} \tag{25.1}$$

Ordinal (also called ordered) logistic regression allows modelling ordinal outcome data as in the case of the scale for criticality assessment of driving and traffic scenarios and predicting the probabilities of the categories of the ordinal independent variable from categorical or continuous dependent variables using a logit link function. More precisely, the model estimates the cutpoints on an assumed latent variable that contribute to the realization of the categories of the ordinal independent variable (for a detailed introduction cf. [46, 47]). The model interpretation can be performed by relying on odds ratios or more conveniently, as exemplified below, by the calculation and graphical plotting of predicted probabilities. Following that procedure, it is possible, for example, to make predictions of the percentage of "dangerous" ratings that occur at a certain level of the experimental variable for a specific research environment.

25.3.4 Test Scenarios and Trial Composition

To compare and validate the four different research environments, several scenarios addressing different perceptional aspects were implemented in each of the environments. Three scenarios focused on the perception and evaluation of longitudinal distances to a lead vehicle (perception and production of different THWs and perception of TTCs), one scenario focused on the perception of lead vehicle decelerations, and one scenario focused on the perception of lateral distances in narrow road zones. For each scenario, different variations regarding the situational criticality were created following published findings from previous studies. All participants drove through each of the variations in successive order. To control for learning effects, the order of the various factor levels in each of the experiments was randomized between participants.

25.3.4.1 Perception of Longitudinal Distances

As noted in the theory section, longitudinal distances are likely perceived slightly differently in driving simulators than in real vehicles. The first scenario implemented in the study assessed the criticality perception of the THW of the driver's vehicle to a lead vehicle. The lead vehicle drove with a constant speed of 50 km/h, and the THWs chosen as a following distance were 0.75 s, 1.50 s, and 2.25 s. When the participants had established the desired THW, they were asked to rate the THW on the scale for criticality assessment.

25.3.4.2 Production of Longitudinal Distances

Complementing the experiment on the perception of THWs between the driver's vehicle to a lead vehicle with fixed THWs, another experiment was implemented where the participants had to produce THWs to a lead vehicle according to the three levels of the scale for criticality assessment of driving and traffic scenarios: "harmless" (2 on the numeric scale), "unpleasant" (5), and "dangerous" (8). The lead vehicle drove with a constant speed of 50 km/h. The participants were asked to establish a car following distance to the lead vehicle and confirm when they had successfully established the distance by pressing a button. The respective THW to the lead vehicle was measured at the time of the button press.

25.3.4.3 Occlusion Testing for Longitudinal Distances

To measure the perception of TTCs, an experiment was implemented in which drivers were asked to drive towards a vehicle that was standing directly in their lane. Participants drove at a constant 50 km/h, and the eyesight of the driver was occluded before reaching the standing vehicle. Drivers had to press a button when they thought they would have reached the car at a standstill. The TTCs used for the occlusion were 1.5 s, 2.0 s, and 2.5 s. On the test track, a crash-matic with a painted vehicle silhouette was used. Immediately prior to the crash, the vehicle silhouette was pulled up to avoid a crash. For the occlusion on the test track, the drivers had to wear occlusion glasses. Participants were asked whether they could have braked to standstill at the beginning of the occlusion, and respectively, how critical they judged the distance to the standing car at that point of time.

25.3.4.4 Perception of Decelerations During Car-following

In an experiment to assess the criticality perceptions of lead vehicle decelerations, the participants had to follow a lead vehicle at a distance of 1.5 s whilst driving at 50 km/h. After a while, the lead vehicle suddenly decelerated; the decelerations used in the experiment

Table 25.1 Participant samples across all four research environments in the study

	Age						
	M	SD	Min	MD	Max	N	n_{female}
Static Driving Simulator	30	7.5	21	27.5	46	30	15
Dynamic Driving Simulator	28	8.7	19	26	52	30	15
Vehicle-in-the-Loop	30	11.4	21	26	58	30	15
Test Track Vehicle	31	11.6	18	25.5	59	32	15

were $-1\,m/s^2$, $-3\,m/s^2$, and $-5\,m/s^2$. To make the trials less predictable, the lead vehicles sometimes also accelerated in intervening trials. The drivers were instructed to avoid collisions and had to rate the criticality of the deceleration situation after each ride.

25.3.4.5 Perception of Lateral Distances

To assess the criticality perception of lateral distances, an experiment was conducted in which drivers had to drive through narrow road zones marked by red-white delineator panels. After following a lead vehicle at 50 km/h at a distance of 1.5 s for some time, the lead vehicle suddenly changed lanes to provide sight of the narrow road zone, which the drivers successively had to drive through if possible and afterwards judge the situational criticality. The widths of the narrow zones were 2.25 m, 2.75 m, 3.25 m, and 3.75 m. The narrowest width corresponded to previous research findings [33].

25.3.5 Participant Sample

In all four research environments, participant samples of $n = 30$ (in one case $n = 32$) were recruited for the experiments, resulting in an overall sample size of $N = 122$ (Tab. 25.1).

25.4 Results

In the following sections, results from each of the experiments in the study are shown. The initial data obtained from each experiment are presented via boxplots; the first analyses presented were performed using ANOVAs with planned contrasts. In the next step, ordinal logistic regressions were calculated, and the model results are visualised by plotting the predicted probabilities in cumulative and non-cumulative forms. The independent variable for each of the models was the obtained criticality rating, which was predicted by the experimental condition (a continuous variable) and the research environment (a factorial variable). The model results consist of the coefficients (e. g. the effects of the experimental condition and research environment) and the threshold coefficients (cutpoint values for each of the categories of the scale for criticality assessment). The test track vehicle served as a reference category against which the other research environments were compared. Due to limitations of space in this chapter, the full models are not reported.

25.4.1 Perception of Longitudinal Distances

The longitudinal time distances (THW levels: 0.75 s, 1.50 s, and 2.25 s) that were driven by the participants when following a lead vehicle at 50 km/h received criticality ratings that differed significantly from each other ($F(2, 343) = 254.92$, $p < 0.001$, and $\eta^2 = 0.60$). Generally, shorter THWs to the lead vehicle were perceived as more dangerous, as indicated by higher scores on the scale for criticality assessment (Fig. 25.7a). The range of ratings expanded from "harmless" to "dangerous", in effect covering the whole range of the scale for criticality assessment. In addition, an effect of the research environment was observed ($F(3, 343) = 14.67$, $p < 0.001$, and $\eta^2 = 0.11$). In this case, the dynamic driving simulator and particularly the VIL seemed to obtain slightly higher criticality ratings across all of the varied distance levels, whereas the test track vehicle seemed to obtain consistently lower values.

Modelling the effects using an ordinal logistic regression showed a significant difference of the factor level "VIL" compared to the reference research environment "test track

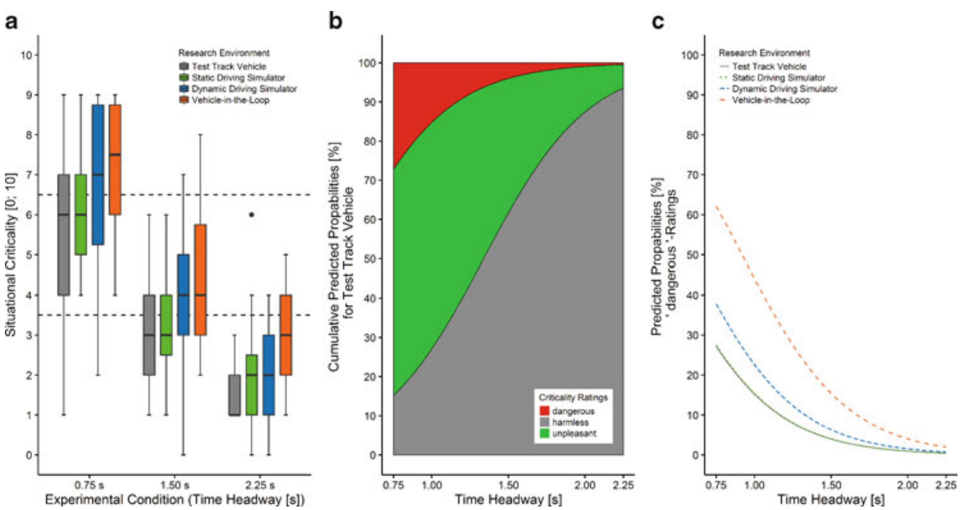

Fig. 25.7 Criticality ratings across the research environments for the perception of THWs (0.75 s, 1.5 s, and 2.25 s) to a lead vehicle driven at a speed of 50 km/h. **a** Boxplot of criticality ratings for each THW level in the experiment. **b** Cumulative predicted probabilities of criticality ratings predicted across the range of THWs in the experiment for the test track vehicle, which was used as a reference research environment. **c** Predicted probabilities for all "dangerous" criticality ratings across the THW range in the experiment for each of the four research environments

vehicle” ($p < 0.001$). The other two research environments did not significantly differ. This is also illustrated by the plot of the predicted probabilities in Fig. 25.7c, which shows that at a THW of 1.50 s, the VIL was already predicted to receive a higher percentage of “dangerous” ratings. The ratings for the dynamic driving simulator seemed to be slightly elevated, whereas the static driving simulator and test track vehicle were almost equal to each other.

25.4.2 Production of Longitudinal Distances

The longitudinal time distances that were driven by the participants when following a lead vehicle at 50 km/h at certain criticality levels (“dangerous”, “unpleasant”, and “harmless”) differed significantly from each other ($F(2, 348) = 313.99$, $p < 0.001$, and $\eta^2 = 0.64$). Generally, shorter THWs to the lead vehicle were observed when driving with more dangerous car following distances (Fig. 25.8a). In addition, a general effect of the research environment was observed ($F(3, 348) = 23.22$, $p < 0.001$, and $\eta^2 = 0.17$). In this case, the participants seemed to drive with consistently larger THWs on each of the criticality levels when riding the VIL, whereas they seemed to drive with THWs in the test track vehicle that were slightly lower than those in the other research environments.

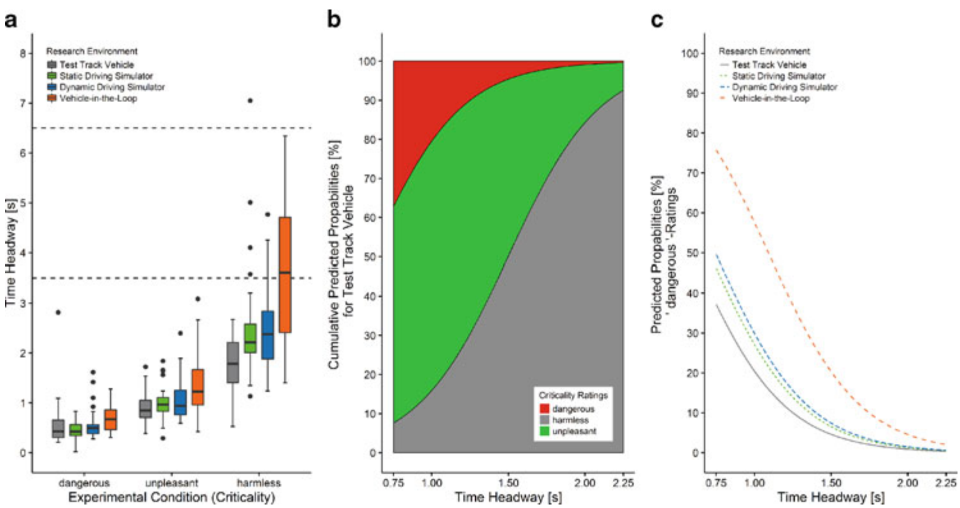

Fig. 25.8 THWs and criticality ratings across the research environments for the perception of THWs to a lead vehicle driven at a speed of 50 km/h. Drivers could decide on the distance according to a pre-set criticality level (“dangerous”, “unpleasant”, and “harmless”) **a** Boxplot of the THW ratings for each criticality level in the experiment. **b** Cumulative predicted probabilities of the criticality ratings predicted across the range of THWs in the experiment for the test track vehicle, which was used as a reference research environment. **c** Predicted probabilities for all “dangerous” criticality ratings across the THW range in the experiment for each of the four research environments

Modelling the effects using an ordinal logistic regression showed a significant difference in the "VIL" factor level compared to the reference research environment "test track vehicle" ($p < 0.001$). The other two research environments did not differ significantly. This is also illustrated by the plot of the predicted probabilities in Fig. 25.8c, which shows that at a THW of 1.50 s, the VIL was already predicted to receive a higher percentage of "dangerous" ratings. The ratings for the dynamic driving simulator and the static driving simulator seemed to be slightly greater than those of the test track vehicle.

25.4.3 Occlusion Testing for Longitudinal Distances

The longitudinal time distances (TTC levels: 1.50 s, 2.00 s, and 2.50 s) that were experienced by the participants when driving towards a standing vehicle at 50 km/h before occlusion received criticality ratings that differed significantly from each other ($F(2, 363) = 29.55$, $p < 0.001$, and $\eta^2 = 0.14$). Generally, shorter TTCs to the standing vehicle were perceived as more dangerous (Fig. 25.9a). Across the experimentally varied TTC values, the observed ratings however were mainly in the range between "unpleasant" and "dangerous". In addition to the effect of the TTC, a general effect of the research environment was observed ($F(3, 363) = 7.72$, $p < 0.001$, and $\eta^2 = 0.06$). In this case, the test track

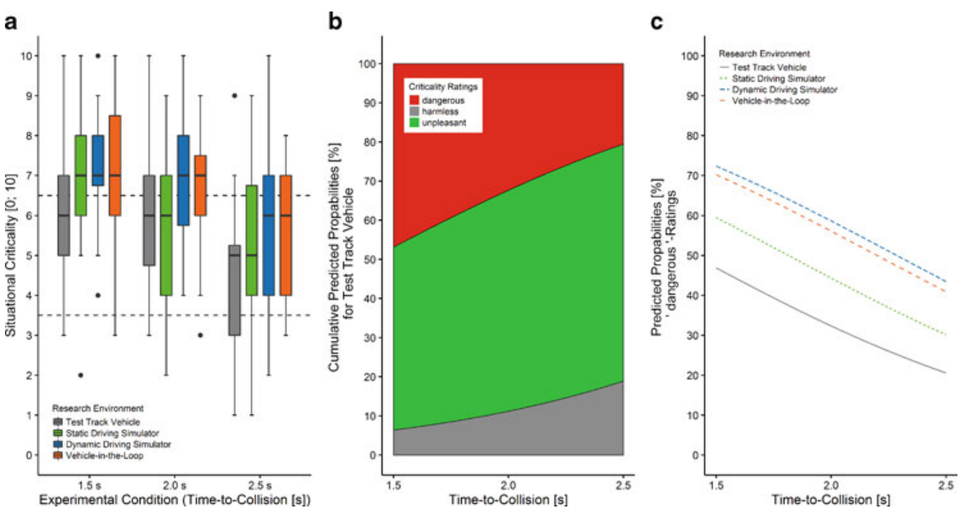

Fig. 25.9 Criticality ratings across the research environments for the perception of TTCs (1.5 s, 2.0 s, and 2.5 s) to a standing lead vehicle driven at a speed of 50 km/h. **a** Boxplot of the criticality ratings for each TTC level in the experiment. **b** Cumulative predicted probabilities of the criticality ratings predicted across the range of TTCs in the experiment for the test track vehicle, which was used as a reference research environment. **c** Predicted probabilities for all of the "dangerous" criticality ratings across the TTC range in the experiment for each of the four research environments

vehicle obtained systematically lower criticality ratings across all varied distance levels, whereas the dynamic driving simulator and particularly the VIL obtained slightly higher values.

Modelling the effects using an ordinal logistic regression showed a significant difference in the factor levels "dynamic driving simulator" ($p < 0.01$) and "VIL" ($p < 0.01$) compared to the reference research environment "test track vehicle". The static driving simulator did not differ significantly. This is also illustrated by the plot of the predicted probabilities in Fig. 25.9c, which shows that at a TTC of 2.50 s, the dynamic driving simulator and the VIL were already predicted to receive a higher percentage of "dangerous" ratings. The ratings for the static driving simulator also seemed to be elevated in comparison to the test track vehicle.

25.4.4 Perception of Deceleration During Car-following

The braking manoeuvres (decelerations: $-5\,m/s^2$, $-3\,m/s^2$, and $-1\,m/s^2$) that were experienced by the participants when following a lead vehicle at 50 km/h that suddenly initiated braking received criticality ratings that differed significantly from each other ($F(2, 378) = 21.62$, $p < 0.001$, and $\eta^2 = 0.10$). Generally, stronger decelerations were per-

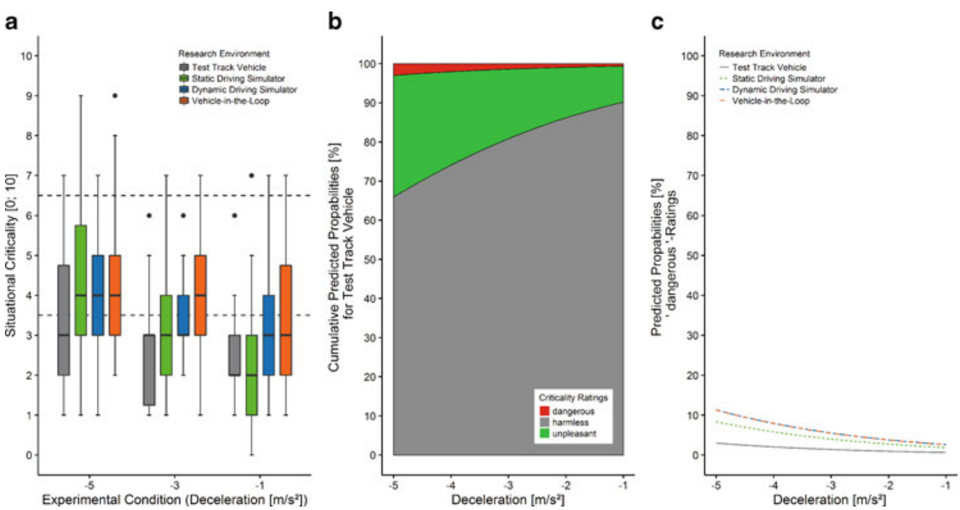

Fig. 25.10 Criticality ratings across the research environments for the perception of sudden decelerations ($-5\,m/s^2$, $-3\,m/s^2$, and $-1\,m/s^2$) of a lead vehicle driven at a speed of 50 km/h. **a** Boxplot of the criticality ratings for each deceleration level in the experiment. **b** Cumulative predicted probabilities of the criticality ratings predicted across the range of decelerations in the experiment for the test track vehicle, which was used as a reference research environment. **c** Predicted probabilities for all of the "dangerous" criticality ratings across the deceleration range in the experiment for each of the four research environments

ceived as more dangerous (Fig. 25.10a). Across the experimentally varied decelerations, the observed ratings covered the lower range of the scale for criticality assessment between "harmless" and "unpleasant". In addition to the effect of the deceleration, a general effect of the research environment was observed ($F(3, 378) = 8.61$, $p < 0.001$, and $\eta^2 = 0.06$). Except for the lowest deceleration of $-1\ \mathrm{m/s^2}$, the test track vehicle obtained slightly lower criticality ratings.

Modelling the effects using an ordinal logistic regression showed a significant difference in the factor levels "static driving simulator" ($p < 0.001$), "dynamic driving simulator" ($p < 0.001$) and "VIL" ($p < 0.001$) compared to the "test track vehicle" reference research environment. This is also illustrated by the plot of the predicted probabilities in Fig. 25.10c which shows that at a deceleration of $-5\ \mathrm{m/s^2}$ all three simulation environments were predicted to receive a higher percentage of "dangerous" ratings. The ratings for the static driving simulator also seemed to be slightly closer to those of the test track vehicle than those of the dynamic driving simulator and the VIL.

25.4.5 Perception of Lateral Distances

The lateral distances (lane widths: 2.25 m, 2.75 m, 3.25 m, and 3.75 m) that were experienced by the participants when driving through a narrow road zone at 50 km/h received criticality ratings that differed significantly from each other ($F(3, 492) = 330.80$, $p < 0.001$, and $\eta^2 = 0.67$). Generally, smaller lane widths were perceived as more dangerous (Fig. 25.11a). Across the experimentally varied lane widths, the observed ratings covered the full range of the scale for criticality assessment. In addition to the effect of the lane width, a general effect of the research environment is observed ($F(3, 492) = 9.45$, $p < 0.001$, and $\eta^2 = 0.06$). In this case, the test track vehicle and the static driving simulator obtained lower criticality ratings across all varied lane widths, whereas the dynamic driving simulator in particular obtained slightly higher values.

Modelling the effects using an ordinal logistic regression showed a significant difference in the factor levels "dynamic driving simulator" compared to the reference research environment "test track vehicle" ($p < 0.05$). The other two research environments did not differ significantly. This is also illustrated by the plot of the predicted probabilities in Fig. 25.11c, which shows that particularly at a lane width of 2.25 m the dynamic driving simulator was predicted to receive a higher percentage of "dangerous" ratings. The ratings for the VIL also seemed to be slightly elevated in comparison to those of the test track vehicle, whereas the static driving simulator was almost at the same level. In addition to these findings, participants were observed to drive with a slight lateral displacement (~0.25 m) to the right in almost all of the driving simulators and experimental conditions from the experiment, compared to the test track vehicle.

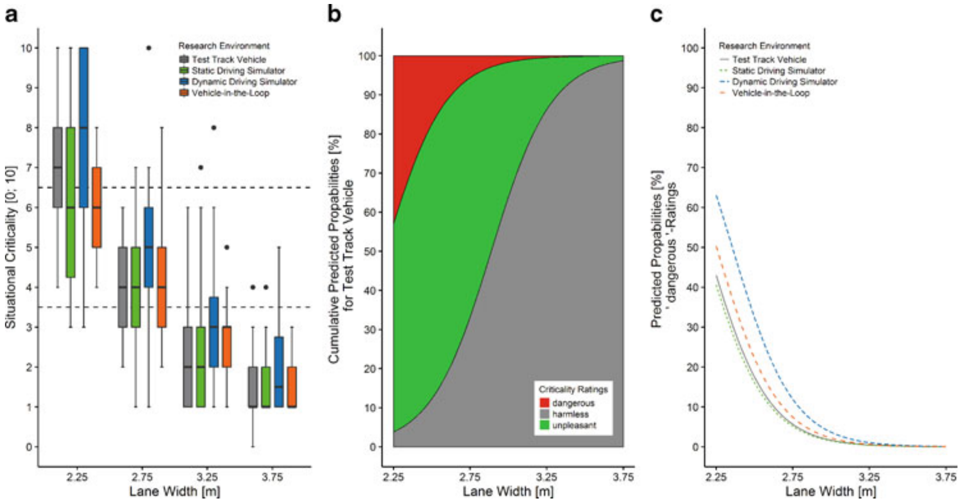

Fig. 25.11 Criticality ratings across the research environments for the perception of lane widths (2.25 m, 2.75 m, 3.25 m, and 3.75 m) in a narrow road zone driven at a speed of 50 km/h. **a** Boxplot of the criticality ratings for each lane width level in the experiment. **b** Cumulative predicted probabilities of the criticality ratings predicted across the range of lane widths in the experiment for the test track vehicle, which was used as a reference research environment. **c** Predicted probabilities for all of the "dangerous" criticality ratings across the lane width range in the experiment for each of the four research environments

25.5 Discussion

In the current study, a series of experiments was conducted in four research environments to assess the participants' criticality perceptions of longitudinal distances to a lead vehicle, lateral distances in narrow road zones, and lead vehicle decelerations. The four research environments were a test track vehicle, a static driving simulator, a dynamic driving simulator, and a VIL, which is a hybrid between a driving simulator and a test track vehicle. In addition to assessing particular differences between the research environments, one of this study's aims was to calculate transfer functions that would allow results to be transferred among research environments.

The general approach pursued in the studies was to confront the vehicle drivers with critical situations after or during car following at a speed of 50 km/h. The situations varied with respect to the degree of the criticality of a core variable such as the THW to a lead vehicle, the TTC to a standing vehicle, the width of a narrow road zone, and the deceleration of a lead vehicle. After experiencing the situations, the participants had to rate each situation for its criticality on the scale for criticality assessment of driving and traffic scenarios [44]. To model the effects of the experimental condition and research environment, ordinal logistic regressions were calculated.

When taking into account the findings from the reviewed literature, which were often heterogeneous or indecisive, we expected at least to observe differences between the test track vehicle and the simulator environments with regard to the perception of lead vehicle decelerations. Indeed, in our research we observed notable differences between the research environments with respect to the perception of criticality in each of the investigated situations. As a tendency, the THWs, TTCs, lane widths and lead vehicle decelerations were perceived as more critical in the dynamic driving simulator and VIL research environments than those of the test track vehicle. The ratings observed in the static driving simulator were mainly at a similar level to the ratings in the test track vehicle, and only in some cases were they slightly more critical.

These findings should clearly be taken into consideration when evaluating research findings from simulator environments in comparison to findings generated on a test track; with respect to some parameters of situational criticality, participants are going to rate the situations as more critical in simulator environments than on test tracks. For controllability research, which we had in mind when conducting this series of experiments, this means that findings generated from simulator research tend to be conservative, at least with respect to those from test track vehicles. This means that a situation that is judged as dangerous by a large proportion of participants in a driving simulator will be less so on a test track – the converse would be more problematic from the perspective of driving simulator research because it would likely lead to safety-critical misjudgements.

Some shortcomings of the current study should not go unmentioned. First, the situations created in the experiments were to some extent artificial and not directly comparable to situations in real-life; clearly, driving simulators can simulate more realistic situations than the situations used in standard test track studies. However, our intention was to investigate situations that were straightforward to parameterize, not easily confounded by other variables, and easy and safe to implement across all research environments in our set, which also involved a test track vehicle. Second, and somewhat determined by the high degree of standardization we pursued in our study, we did not have a real traffic environment to serve as a reference; the test track vehicle was the closest we came to real traffic. Clearly, this issue cannot be resolved easily in the future and points towards a fundamental issue when conducting research in various research environments – one will never be able to replace one research environment completely by another, and some advantages and disadvantages are inherent to a specific research environment. Another certain limitation was the restricted velocity range represented in the experiments. This was mainly due to the inner-city focus of the UR:BAN project, and future studies should employ extended speed ranges.

Nonetheless, we believe that the presented validation study provides a suitable approach for assessing research environment validity. Ultimately, the approach presented is a step towards the generalization of research results that have been obtained using a particular research environment to another. The scenarios used in this study's experiments are designed to assess perceptional key parameters such as THW, TTC, lead vehicle decelerations and lane widths, and the scenarios are easy and straightforward to implement across a range of research environments. The approach presented can help researchers who work in particular research environments to obtain benchmark results that can be easily compared to other research environments. As a final remark, we hope that our results will be replicated in various similar and other research environments.

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Emergency Steering Systems – Controllability Investigations with the Vehicle in the Loop 26

Fabian Rüger and Berthold Färber

26.1 Introduction

In the field of Advanced Driver Assistance Systems (ADAS) the focus is not only on warning and comfort functions but increasingly also on collision avoidance by active safety [1]. Until recently, most existing systems only used braking manoeuvres to prevent or mitigate accidents; systems that employ automatically initiated emergency steering were the subject of recent research initiatives such as interactIVe [2] or UR:BAN [3]. Emergency steering systems aim at avoiding accidents in certain speed-ranges and especially at small overlaps with a potential collision object, even if it is too close for braking to a standstill. These requirements particularly apply to scenarios involving cars reversing out of parking spaces, cyclists or pedestrians, especially in the urban area. The typical urban use case and the autonomous interventions by these ADAS introduce new challenges to controllability research.

The basis for the controllability assessment of ADAS are various industrial standards, such as ISO 26262 [4] or guidelines such as the RESPONSE Code of Practice [5]. According to these works, the human driver must achieve overall system controllability at all times, even with possible false alarms or system failures.

The steering wheel torques that are necessary for successful evasion in the typical use cases could possibly result in yaw rates, which exceed the controllability criteria published in Neukum, Ufer, Paulig, & Krüger [6]. Consequently, system failures might result in an intrusion into the opposite lane endangering oncoming vehicles and the driver.

To handle such systems the method "safety in use" was published by Huesmann, Farid, and Muhrer [7]. This risk-based method considers the probability of exposure, the con-

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sequences' severity and the controllability of driving situations during the usage of an ADAS. For example, the total risk of a system failure is calculated by these factors and should lie below the companies' or population's accepted risk. If the factors' probability of exposure and severity are above a certain risk level, the controllability is a factor that should be assessed. The controllability assessment should use adequate test cases that are similar to real traffic situations but without endangering anybody.

Since methodically sound research of controllability situations requires the use of accurately timed and reproducible scenarios, driving simulators constitute the preferred research environment. Moreover, driver behaviour during the highly dynamic manoeuvres found with automatic steering is likely to be more natural, if the driver is provided with realistic kinaesthetic and vestibular feedback. Both requirements are met in the Vehicle-In-the-Loop (VIL). The VIL constitutes a hybrid testing environment combining a test track vehicle with a driving simulator (see [8]). The driver is wearing a head mounted display, which shows a fully virtual world while s/he is moving a real car on a test field [9], as illustrated in Fig. 26.1.

Previously, the VIL had been validated for the investigation of ADAS in urban environments ([10, 11]; Chap. 27 and 28). The results showed that the experience of driving situations seems to be slightly more critical in the VIL than in a test track environment, while the overall driving behaviour is valid. This generates conservative and reliable results that may be considered in controllability investigations [10]. With these preconditions, the VIL can be used to complement existing methods in controllability research. Two examples are presented in the following.

Fig. 26.1 Vehicle in the Loop (VIL). The picture on the top right shows the driver's view

26.2 Emergency Steering Interventions at Occupied Opposite Lanes

Emergency steering systems aim at avoiding accidents even if it's too late to brake to a standstill. The interventions must use high levels of dynamics and actor potential to achieve that goal. Technically, the driver is a disturbance variable in the system's control chain trying to guide a vehicle around an obstacle on an ideal trajectory. However, the driver provides a great potential regarding controllability of ADAS. In other studies, surveying emergency steering functions (Chap. 27 and 28) the driver is described as a damping element in the closed loop control chain. In a driving situation with a justified system intervention, in which another vehicle approaches on the opposite lane, a damping intervention of the driver with the emergency steering system on-board could reduce the risk of a collision with the oncoming vehicles on the opposite lane. Therefore, this testing case tends to investigate whether drivers are able to adjust interventions of emergency steering systems appropriately to the driving situation. That includes avoiding both collisions with the item triggering an intervention and objects on the opposite lane.

26.2.1 Method

As already mentioned in the introduction of this chapter, the use of the VIL for urban driving situations was generally validated. The interaction of drivers with ADAS depicts a new level of VIL's commitment. Hence, the results attained in the VIL should be compared with classic testing methods to prove reliability. To achieve this goal, an emergency steering function was implemented into a test track vehicle. This vehicle was also equipped with the VIL, which could optionally be operated.

26.2.1.1 Situation

The driver interaction with an emergency steering function should be investigated with a justified intervention of the system. In order to create such a test case a vehicle reversed out of a parking space and achieved a final position one meter in the right side of the driver's lane (lane width: 3.5 m) at a time to collision (TTC) of 1.7 s to trigger the inter-

Fig. 26.2 Driving Situation on the test track (**a**), with occupied opposite lane (**b**) and in the VIL (**c**)

vention. Aiming to classify the influence of the occupation, the opposite lane was blocked with road works (see Fig. 26.2b).

The driver's perspective experiencing this situation in the VIL is shown in Fig. 26.2c. On the test track a pneumatic-driven Crashmatic reversed out of the parking space (see Fig. 26.2a) due to safety considerations.

26.2.1.2 Emergency Steering Function

At a TTC of 1.2 s, the emergency steering function started to guide the vehicle around the obstacle. It aimed to a fixed lateral displacement of one meter to the left. The strength of the wheel torque was adapted in real time depending on the driver's inputs and the vehicle's heading targeting on an ideal trajectory. The occupation of the opposite lane was deliberately not included in the system logics. Based on an instructed middle lane position at the beginning of the evasion manoeuvre, the system would have caused an intrusion into the opposite lane of about 0.25 m and a collision with the road works without a driver's input.

26.2.1.3 Study Design

Every participant experienced two emergency steering interventions, one in a test track vehicle and one in the same vehicle using the VIL in a systematically varied order. Half of the sample found a free, the other half an occupied opposite lane (between-subjects design) whereupon one driver always got the same condition in VIL and test track vehicle (within-subjects design).

A cover story was used to elicit preferably naturalistic driving behaviour in both situations. The subjects were told to take part in a study that compares lane keeping at narrow points between the VIL and a normal car. They drove through different narrow points before and after the evasion situation. The first intervention of the emergency steering system was declared as a test for further investigations. Executing secondary tasks like activating the blinker or the wiper before the relevant situations the drivers had both hands on the wheel.

26.2.1.4 Participants

24 subjects took part in the experiment, with a mean age of 29.7 years with a standard deviation of 8.9 years. The drivers varied in age between 20 and 61 years and everybody's driving experience represented at least a total of 10,000 km.

26.2.2 Results

As previously mentioned, the automatic steering interventions aimed at a lateral displacement of 1 m. The left boxplot in Fig. 26.3 shows the measured lateral displacements depending on testing environment and occupation of the opposite lane. While most drivers achieved lateral displacements of 1 m and higher at a free opposite lane, they damped the

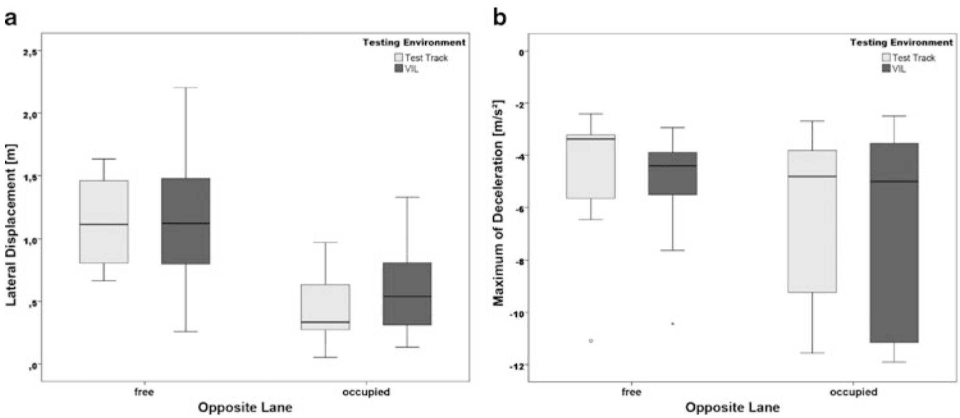


Fig. 26.3 Lateral displacement (**a**) and maximum deceleration (**b**)

steering interventions to an average displacement of only 0.5 m at occupied opposite lanes. Collisions did not happen, neither with the obstacle on the right nor with the road works occupying the opposite lane. Higher lateral displacements found in the "occupied"-condition can be explained with an initial position right of the lane's middle. These results were both found in the test track vehicle and in the VIL.

Every driver braked additionally to the steering manoeuvre when s/he noticed the obstacle entering her/his lane from the right. The distribution of the maxima of the achieved decelerations is shown in the boxplots of Fig. 26.3. A few drivers braked very strongly in the occupied lane condition, while the most breaking manoeuvres showed decelerations below 5 m/s^2. Again, the results did not differ systematically between VIL and test track conditions.

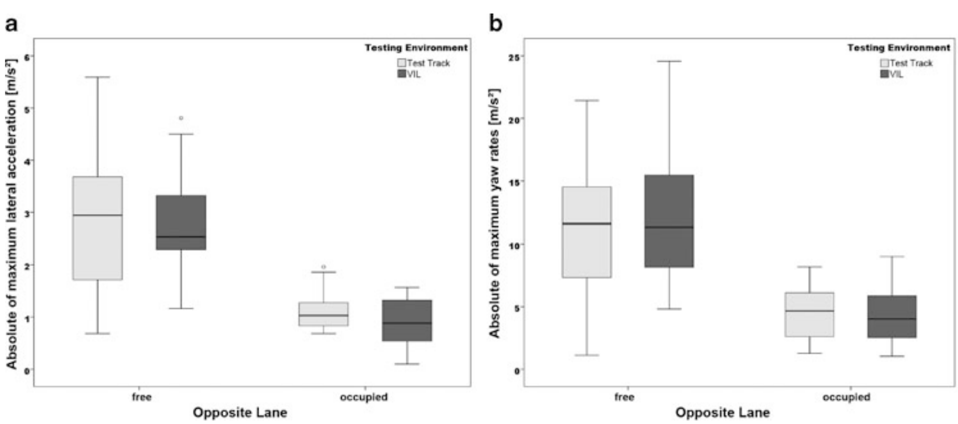


Fig. 26.4 Maximum lateral acceleration (**a**) and maximum yaw rate (**b**)

Differences in driver-system interaction could affect the dynamic of the steering manoeuvre. To distinguish dynamic aspects, the maxima of lateral acceleration and yaw rates are considered (see Fig. 26.4). Hence, absolute values are used to avoid algebraic sign conflicts regarding steering exercises to the left or right. Nevertheless, most maxima were measured while steering away from the obstacle to the left. Both lateral acceleration and yaw rates indicated differences between free and occupied opposite lanes. While drivers allowed or even supported highly dynamic steering manoeuvres with yaw rates above 10 °/s and lateral acceleration of almost 3 m/s^2 in the first condition, they damped the mean dynamics below a yaw rate of 5 °/s and a lateral acceleration of 1.5 m/s^2. Means, medians and the distribution of the measurements are very similar between the test track vehicle and the VIL. For a more detailed inferential statistical analyses, see Rüger et al. [12].

26.2.3 Discussion

The results show big differences in the driver-system interactions with automatic steering interventions depending on the occupation of the opposite lane. In the first app. 400 ms. of the interventions, drivers held the steering wheel firmly which is assumed to be a haptic triggered reaction (Chap. 28). After that short period, most of them followed the system's specification when they found a free opposite lane. At occupied opposite lanes they damped the systems intervention to avoid both a collision with the obstacle entering the lane on the right and the road works occupying the opposite lane. Consequently, drivers are able to adjust steering interventions appropriately to the traffic situation. Acting as a backup level, drivers improve system controllability for automatic steering interventions, even when those interventions are not adequate to the driving situation. Those results were found in a test track vehicle as well as in the VIL. No significant differences between the variables in VIL and test track vehicle and significant correlations confirm the VIL to be a valid test tool for the investigation of steering interventions [12].

26.3 Emergency Steering Seen from Oncoming Traffic

By the definition of ADAS "controllability" in the RESPONSE Consortium [5, p. 13], countermeasures in critical situations aiming to avoid an accident cannot only be performed by the driver with the ADAS on board but also by other road users. Especially emergency ADAS like the afore mentioned emergency steering functions or automatic braking systems can affect traffic substantially. Commercially launched systems of the latter mentioned are able to operate with decelerations over 10 m/s^2 [13]. Naturalistic driving studies and field operational tests show that time gaps between following vehicles found in traffic could lead to hazards when automatic braking manoeuvres used their full performance potential [14]. Therefore, the effects of an emergency braking system on pursuing vehicles were subject to studies by Fach, Baumann, Breuer & May [15] and Neukum, Naujoks, Kappes & Wey [16]. In these investigations, participants followed a leading vehicle at a certain distance when an emergency braking system intervened suddenly in the leading vehicle. The following car's drivers had to brake hard to avoid an accident. Based on the results of this research, design rules for emergency braking systems were found, which most likely allowed the following vehicles' drivers to control the situation [15].

Considering emergency steering systems, other traffic participants could similarly help to improve system controllability. An intrusion into the opposite lane caused by an ADAS for example, possibly resulting in collisions with oncoming vehicles, is a risk against which must be protected [17]. Seeing traffic as a system of cooperating road users, it is conceivable that failures or interventions with the maximum system potential of emergency steering systems can often be ameliorated by appropriate reactions of the oncoming traffic. A similar approach to the mentioned studies of Fach et al. [15] and Neukum et al. [16] can simultaneously be transferred into the context of emergency steering systems by investigating those systems from the perspective of opposing traffic. A requirement for other road users to initiate adequate measures to control the situation could be a limitation of the activation of emergency steering systems to certain restricting parameters. Those might be the maximum intrusion into the opposite lane or a minimum time gap to oncoming vehicles.

Therefore, the aim of this experiment was to provide information about these restrictions for the functional design of oncoming vehicles with an on-board emergency steering system. Furthermore, it was designed to answer whether a driver might be able to compensate a system failure in the oncoming vehicle e. g. by braking and steering to the very right of his/her lane.

26.3.1 Method

Weitzel [18] suggests selecting relevant test cases out of possible combinations of environmental, functional and driver aspects to reduce testing efforts. Hence, in this study an interdisciplinary expert panel including engineers and human factors specialists identified a number of relevant parameters in preliminary tests, which are specified in the following.

26.3.1.1 Environment and Situation

Emergency steering functions aim at avoiding accidents when it is too late for braking to a standstill. Such scenarios with pedestrians stepping onto the street, vehicles reverting out of parking spaces or braking suddenly due to appearing obstacles can be found in urban areas. Most likely these types of critical situations are a result of a chaining of single events involving unattended traffic participants. Hence, the investigated scenarios should offer a comparable complexity. Considering the expected impact of certain factors on driver behaviour and aspects of plausibility, three driving situations were selected for investigation. A busy urban environment was chosen in all situations with lanes of 3.5 m width.

Fig. 26.5a–c Emergency steering situations

In the first situation, a pedestrian runs across a street. Therefore a car turning right has to stop suddenly (see Fig. 26.5a). The driver in the red vehicle behind is too close to stop in time. An emergency steering assist intervenes and leads the vehicle around the braking obstacle. Seen from the investigated view of oncoming traffic (as seen in Fig. 26.5), a car is waiting on the right-hand side of the crossroad prohibiting the driver to leave her/his lane to the right.

In the second situation, a child plays with other children between two houses. Suddenly it runs onto the street (compare Fig. 26.5b) where an emergency steering system leads the red car around the collision object. Equivalently to situation 1, the area adjacent to the right side of the lane is blocked. This time by a parking car, thus prohibiting the use of the pavement as a manoeuvring space.

The third situation is a typical false alarm intervention of an ADAS. For no obvious reason an automated steering manoeuvre is executed by the red vehicle (as shown in Fig. 26.5c). Again, a parking car occupies the pavement adjacent to the right lane.

26.3.1.2 Emergency Steering Function

Fig. 26.6a shows parameters of an emergency steering function that could be relevant for the perception of oncoming vehicles seen from the ego-perspective. Aiming to identify relevant parameters in preliminary expert panel tests a range of parameters was investigated. This was reflecting two constraints: firstly, a trajectory should be designed and limited according to actual developments of emergency steering systems. Secondly, the parameters should be selected to enable and require a reaction of the ego driver in order to avoid a collision. With these constraints the lateral displacements were varied between

a

Set	Δs	Δi	Δt	a_{max}
1	2.0 m	1.25 m	1.0 s	7.5 m/s²
2	1.5 m	0.75 m	1.0 s	7.5 m/s²
3	2.0 m	1.25 m	2.0 s	7.5 m/s²
4	1.5 m	0.75 m	2.0 s	7.5 m/s²

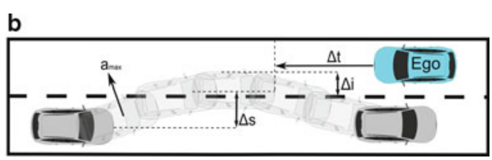


Fig. 26.6 Investigated parameter sets (**a**) and relevant emergency steering function parameters (**b**)

$1.0\,\text{m} \leq \Delta s \leq 2.0\,\text{m}$, maximum lateral accelerations between $5.0\,\text{m/s}^2 \leq a_{\text{max}} \leq 10.0\,\text{m/s}^2$ and time gaps to the peak of the trajectory between $1.0\,\text{s} \leq \Delta t \leq 2.0\,\text{s}$ (see Fig. 26.6b).

The expert panel testing showed that the differences in the perception of different lateral accelerations by oncoming traffic are negligible. Furthermore, the lateral displacements should be at least 1.5 m (resulting in an intrusion of $\Delta i = 0.75\,\text{m}$ into the opposite lane) for further investigation. Based on these findings, a combination of parameters shown in Fig. 26.6 on the left were selected and considered as relevant for user studies. Based on the fact that the evading vehicle is about 2.0 m and the lane 3.5 m wide and the driver is initially positioned in the middle of the lane, a Δs of 2.0 m results in an intrusion into the opposite lane of $\Delta i = 1.25\,\text{m}$. The two different Δs result in gaps of 2.25 m and 2.75 m width on the right of the ego driver's lane.

26.3.1.3 Pass-/Fail Criteria

In order to assess whether a test case is controllable or not, appropriate binary criteria must be found [5]. According to that, a collision with other traffic participants or other objects is considered to be an objective fail criterion, just as an activation of the electronic stabilization program in the ego car indicates that physical limits of the vehicle performance have been reached.

As shown in Neukum et al. [6], subjective criteria based on judgments of the participants according to the scale for criticality assessment of driving and traffic scenarios may be considered additionally. The criteria stipulate that a test case is considered to be not controllable if more than 15% of all participants' ratings classify a situation as subjectively dangerous. Between zero and 15% of the ratings are cross-referenced with the objective data, before a decision regarding controllability is made.

26.3.1.4 Study Design

A mixed-subjects design was chosen in order to investigate the controllability of the presented test cases. Each subject experienced all three driving situations with the same parameter set in a systematically varied order. The number of required participants was identified with a power analysis based on the expected differences according to the preliminary tests. Accordingly, twelve participants were needed for each parameter set resulting in a total number of 48 participants.

In order to elicit natural driving behaviour, the participants do not need to be distracted on purpose but should not expect the tested situations [19]. Therefore, a cover story was used. The participants were told to take part in an experiment exploring human machine interface (HMI) aspects of a cruise control system while driving the VIL. After a short familiarization with the VIL, they experienced five driving situations: two fake situations relating to HMI aspects to sell the coverstory and three relevant ones. The use of cruise control ensured that every driver held a defined speed of 50 km/h at the beginning of each scenario. After accomplishing a situation, they were asked about their criticality according to the scale for criticality assessment of driving and traffic scenarios and some "fake" questions relating to HMI aspects. Vehicle and simulation data were synchronously recorded in each situation.

26.3.1.5 Participants

A normal collective of drivers considering age, gender or driving abilities is sufficient according to the industrial standard ISO 26262 [4]. Therefore 48 persons with a mean age of 27.2 years with a standard deviation of 9.1 years took part in the experiment. The driver's age was between 21 and 58 years and everybody had at least 10.000 km of driving experience.

26.3.2 Results

The results presented in the following contain descriptive data only. A more detailed inferential statistical analysis, is provided in Rüger, Nitsch, and Färber [20].

The subjective ratings of the drivers' perceived situation criticality were collected using the scale of Neukum et al. [6], shown in Fig. 26.7, directly after each situation. According to the instructions, participants should only indicate "dangerous"-ratings if the driving situation would not be tolerable in real traffic. Both the varied situation and the parameter sets influenced the subjective ratings. Fig. 26.8 contains a boxplot of these ratings on the left. The situations are illustrated in different colours and the parameter sets are grouped on the abscissas.

In situations 1 and 3, ten of 48 ratings (app. 21%) scored above 6 (="dangerous" or "uncontrollable") on the scale. In situation 2, even 58% of all ratings are in the "dangerous"-sector (28 of 48).

For parameter set 1, 28 of 36 ratings (78%) scored above the limit of 6, with eleven ratings (31%) for set 2, six for set 3 (17%), and only three (8%) for set 4. For sets 3 and 4, the subjective ratings were compared with the associated objective data, whereby no collisions or uncontrollable events were found.

Those subjective results are confirmed by the objective data. Fig. 26.8 shows a boxplot of the minimum Euclidian distance between the ego car and the oncoming vehicle on the right. Associated collisions are counted in red numbers below each box. Most collisions appeared in situation 2 (17 of 22). The same rate can be found with parameter set 1, where

Fig. 26.7 Scale for criticality assessment of driving and traffic scenarios. (Neukum et al., [6])

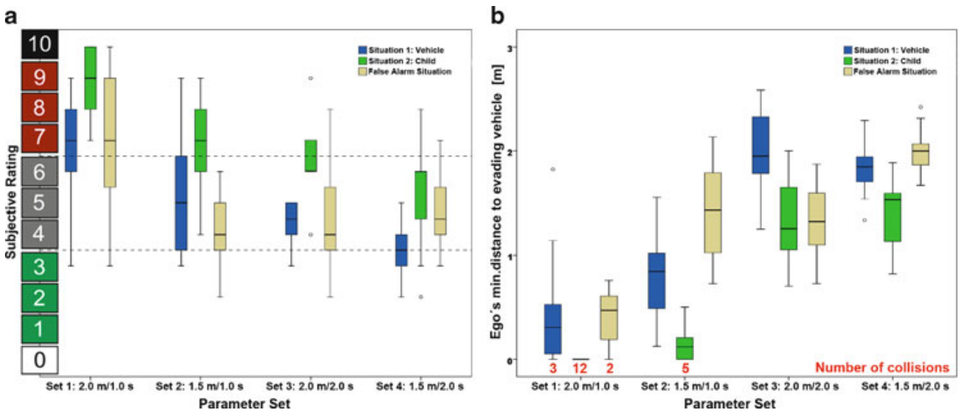
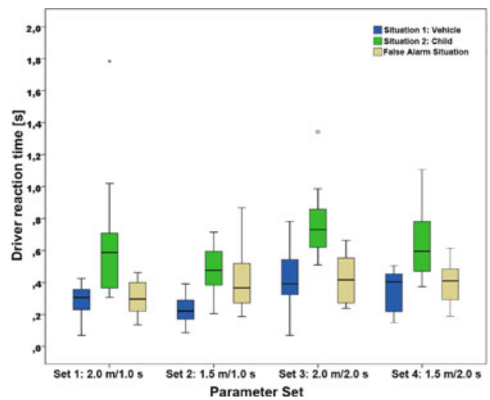


Fig. 26.8 Driver's subjective rating (**a**) and Ego's min. distances to evading vehicle (**b**)

Fig. 26.9 Driver reaction time



also 17 out of 22 collisions were detected. During the course of the study, crashes with other traffic participants except the evading vehicle did not occur. ESP-interventions were not detected as well, indicating that no driver executed an uncontrollable steering manoeuvre. The driver reaction time influences the driving situation's issue and is illustrated in Fig. 26.9. It was estimated from the point of time when the evading vehicle was leaving its lane until the ego driver's first response by braking or steering.

While the reaction time did not differ between the parameter sets, the mean values were about 0.3 s higher in situation 2 than in situation 1.

26.3.3 Discussion

The present study investigated controllability of emergency steering systems from the perspective of opposing traffic. The results show that the situation is influencing the driver's judgment and behaviour. Especially in the situation involving a vehicle veering around a playing child (situation 2), driver reaction times were significantly longer than in the other situations. This caused more accidents and provoked severe reactions in steering or braking. According to self-reports, many drivers focused on a pedestrian leaving a building on the right in situation 2 and expected this pedestrian to enter the street (see Fig. 26.5b). They realised the real threat too late to prohibit a collision, as a consequence of this distraction, or had to perform very intense manoeuvres such as emergency braking.

Parameter sets 1 and 2 generated uncontrollable events subsuming collisions as well as subjective ratings. In parameter set 4 only eight percent of subjective ratings were above the accepted limit and no objective fail-criteria were met. In all situations this parameter set, with a minimum time gap of $\Delta t = 2$ s and an intrusion into the opposite lane of $\Delta i = 0.75$ m, can be classified as controllable. Parameter set 3 indicated no uncontrollable event by objective criteria as well but should be rejected based on drivers' judgments. 17% classified the driving situations that occurred as dangerous which is slightly above the 15%-limit. In any case, all ratings above the limit except one were given in situation 2. The requirements for the investigation were non-distracted drivers (Chap. 29). Following this line of argument, situation 2 must not be considered and set 3 can also be classified as controllable. Based on a lane width of 3.5 m and if time gaps to the peak of an emergency evading trajectory are at least $\Delta t = 2$ s, an intrusion of $\Delta i = 0.75$ m is controllable for opposing drivers. For non-distracted drivers, even intrusions of $\Delta i = 1.25$ m might be considered controllable. If an intrusion into the opposite lane is possible, emergency steering systems must not be activated when estimated time gaps from the peak of the trajectory to the oncoming vehicle are shorter than two seconds. Additionally, it seems that the context of the situation in which ADAS are triggered and the attention of other traffic participants can also have a measurable effect on the results of ADAS controllability investigations. Therefore, this should be considered in future studies.

26.4 Summary

In two studies, controllability aspects of emergency steering systems were investigated with the Vehicle in the Loop (VIL). The goal was to expand controllability methodology using the VIL as a testing environment.

In the first study drivers experienced justified automatic steering interventions in a test track vehicle and in the VIL, with varying occupation of the opposite lane. The results showed that drivers are able to adjust intense steering interventions appropriately to the driving situation. They avoided a collision with the vehicle pulling out of the parking lot on the right as well as with possible obstacles on the opposite lane. This indicates that drivers can act as a backup level to control emergency steering interventions at occupied opposite lanes. Additionally, a comparison of the results between the test track vehicle and the VIL suggests the VIL to be a valid testing environment for the investigation of controllability aspects of emergency ADAS.

The second study considered controllability of emergency steering systems from the perspective of other traffic participants. With this approach, clear limitations for the functional design of emergency steering systems due to the accident-avoiding capabilities of opposing drivers could be found. If those limitations are observed, drivers can perform countermeasures to avoid a collision when emergency steering interventions in oncoming vehicles are not appropriate to the driving situation. This result shows that other traffic participants can make a contribution to controllability of ADAS. A second result of this study focuses on the driving situation in controllability investigations. Indications were found that the complexity of urban driving situations could affect the drivers' capabilities. This finding confirms the increasing use of driving simulators in controllability research, as test track studies do not allow for such complex scenarios without considerable effort.

Acknowledgements
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Consideration of the Available Evading Space for the Evaluation of the Driver Reaction to Emergency Steering Interventions

27

Andreas Pütz

27.1 Introduction and Motivation

The urban driving environment differs considerably from the application focus of Advanced Driver Assistance Systems (ADAS) in production such as highways and interurban roads. While urban arterial roads are comparable to interurban roads regarding lane width and lane number there are also smaller roads which impose much narrower boundaries for the driver in the fulfilment of the driving task. In addition, the fast changing driving context and a high amount of information to be perceived and processed increase the traffic complexity that the driver has to deal with. On the other hand, these conditions might also activate the driver in comparison to more monotone driving environments and might therefore result in faster reactions to unexpected events.

Supporting the driver under these driving conditions by intervening in the lateral vehicle dynamics in situations when an accident is inevitable by braking (e. g. a pedestrian entering the driving path from a sight obstruction) could reduce the number of severe accidents. At the same time these interventions could pose a threat on other road users due to unexpected and inadequate driver reactions. Thus, it should be tested how drivers react to those system interventions.

Due to longer durations of the related steering intervention it should also be considered whether possibilities to retract the intervention may increase the controllability. During false positive activations a retraction might help the driver to reduce the consequences of the intervention. On the other hand, a retraction in case of normal system use (true positive) might reduce the effectiveness of the intervention. Therefore, the differentiation between driver reaction to normal system use and to false positive activations can provide benefit to the overall controllability and effectiveness of these systems.

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The following chapter will derive research questions and hypotheses concerning the driver reaction to system initiated evasive manoeuvers (Sect. 27.3) after summarizing existing knowledge on the influence of the driving context on the driver reaction (Sect. 27.2). Afterwards, the experimental design that has been used to analyse the research questions will be presented (Sect. 27.4). Results of the experiment are broken down into the description of observed reaction patterns (Sect. 27.5), the influence of the available evading space (Sect. 27.6) and the influence of the possibility to retract the intervention (Sect. 27.7). Finally, the insights of the conducted experiment are used to show a possibility to distinguish between situations of false and true positive interventions (Sect. 27.8).

27.2 Existing Knowledge on the Influence of the Driving Context in the Controllability Assessment

How driving context influences the driver reaction to system initiated steering interventions has been investigated in the past with different focuses. One key finding of these studies with regards to this chapter is that drivers damp steering interventions in case of narrowed driving lanes or occupied adjacent lanes (see [1–3]). In the simulator study conducted in [1] no uncontrollable driver behaviour or more collisions with spatial barriers erased from haptic evasion guidance in case spatial barriers by oncoming vehicles. Furthermore, it was shown in [2] that drivers damp steering interventions in narrowed driving lanes to suppress lane exceedance. These results could be confirmed by a study in the subproject KON conducted with the "Vehicle in the Loop" investigating the controllability from the prospective of oncoming traffic [3], see also Chap. 26.

In addition, the driving context was discussed in several studies concerning an appropriate choice of a suitable test scenario for controllability evaluation of steering interventions (e. g. [4–6]). Even though these studies do not directly address the driver reaction to system initiated evasive steering manoeuvres, they give insights to the reasons why the driver reaction varies in different driving contexts: It could be shown that the perceptibility of additional steering torque depends on the current steering activity of the driver. In [4] the authors stated that "additional steering torque can be neglected during stronger steering activities" (based on the subjective driver rating) and suggest "to use only a straight driving context with narrowing of the road for the assessment of consequences of additional steering torques". These findings were supported by additional work in [5] and [6] leading to a quasi-standard of the straight driving context with narrowing for the evaluation of the controllability of steering interventions.

27.3 Deduction of Related Research Questions and Hypothesis for the Experiment

The main research question that arises from the previously discussed shift in the application focus of ADAS in the direction of urban driving assistance is how spatial barriers affect the natural driving behaviour on the one hand. On the other hand changes in the natural driving behaviour will most certainly also affect the driver reaction to system initiated evasive steering interventions. Therefore, this research question is broken down into two hypotheses addressing these two aspects. To assess changes in natural driving behaviour the first hypothesis assumes that in case of narrow spatial barriers an increased compensatory control activity regarding the steering wheel operation can be found. This assumption is based on findings in [7, 8] and [9] which describe the human steering wheel operation as combination of anticipatory and compensatory control activities. Combining this knowledge with the previously mentioned dependency between controllability of steering interventions and the current steering activity of the driver (see [4–6] in Sect. 27.2) it may be assumed that this dependency will also affect the controllability of evasive steering interventions if investigated in different driving contexts (with different natural steering activity of the driver). Hence, the second hypothesis assumes that in case of narrow spatial barriers comparable false positive steering interventions will result in lower effects on yaw rate and lateral displacement. Research question 1 and the related hypotheses are summarized as:

How do spatial barriers affect the natural driving steering behaviour and therefore the driver reaction to system initiated steering interventions?

H1.1: In case of narrow spatial barriers an increased compensatory control activity regarding the steering wheel operation can be noticed.

H1.2: In case of narrow spatial barriers comparable false positive steering interventions show lower effects on yaw rate and lateral displacement compared to cases without narrow barriers.

Due to the fact that steering interventions in this experiment have a longer duration compared to previously analysed steering interventions (e. g. for lane keeping) the possibility to for a retraction and its dependency on the driving context should be considered. Therefore, the second research question addresses the influence of a retraction on the driver reaction and is again broken down in two hypotheses. In general, it is assumed that the consideration of a retraction possibility is able to reduce the failure effect with regard to the maximum yaw rate in case of false positive intervention. Going into more detail the design of the retraction is supposed to be influencing for the maximum yaw rate in the way that a continuous reduction of the additional steering torque has advantages compared to an instant retraction. Here, the occurring reaction patterns are of high importance as it will be shown in Sect. 27.7 and build the link to the influence of the available evading space. The second research question including its hypotheses is therefore:

How does the consideration of a retraction possibility affect the driver reaction in case of system initiated steering interventions?

H2.1: Retraction possibilities are suited to reduce the maximum yaw rate in case of false positive steering interventions.
H2.2: A continuous reduction of the additional steering torque results in lower maximum yaw rates than an instant retraction.

27.4 Experimental Design for the Evaluation of the Influence of the Available Evading Space

The situational influence of driving context on driver reaction to system initiated evasive steering manoeuvres was analysed in a real-vehicle study on the controlled test field in Aachen. 26 naïve test subjects were confronted with steering interventions for an evasive manoeuvre in belief that they were participating in a study to assess the influence of monotone repeating driving situations on driver fatigue.

Fig. 27.1 depicts the driving course that test subjects were asked to follow, consisting of three different driving scenarios: Drivers entered the course in the first section which is a 100 m straight road segment with lane markings for two lanes (width = 3.5 m, in the following referred to as "Lane markings"). Following the course, the lane markings make a smooth bend leading into the second section. Section 2 is an intersection on the vehicle dynamic area of the test track where a foam obstacle entered the driving lane from a sight obstruction requiring an evasive manoeuvre. To generate the necessity for the driver to come back to the initial driving lane after the evasive manoeuvre oncoming and surrounding traffic was simulated with vehicle dummies. Coming back to section 1 of the course the drivers had to pass a 2.5 m wide and 100 m long pylon alley which required precise lateral control due to the narrow spatial barriers in combination with the vehicle width of 1.85 m.

Drivers were asked to maintain a speed between 45 and 50 km/h where possible to represent a common urban driving situation. As mentioned in Sect. 27.2 all sections of system interventions were chosen to be in a straight driving contexts to allow comparison with existing literature. Each driver drove the course 21 times experiencing steering interventions in different use cases in pseudo-randomized order. The first three rounds were used to assess the natural lateral control behaviour of the test subjects. Afterwards, steering interventions in the lane markings and in the pylon alley were presented to the driver as false positive interventions, while true positive interventions could only be investigated in the intersection. To minimize training effects false positive interventions were also initiated in the intersection.

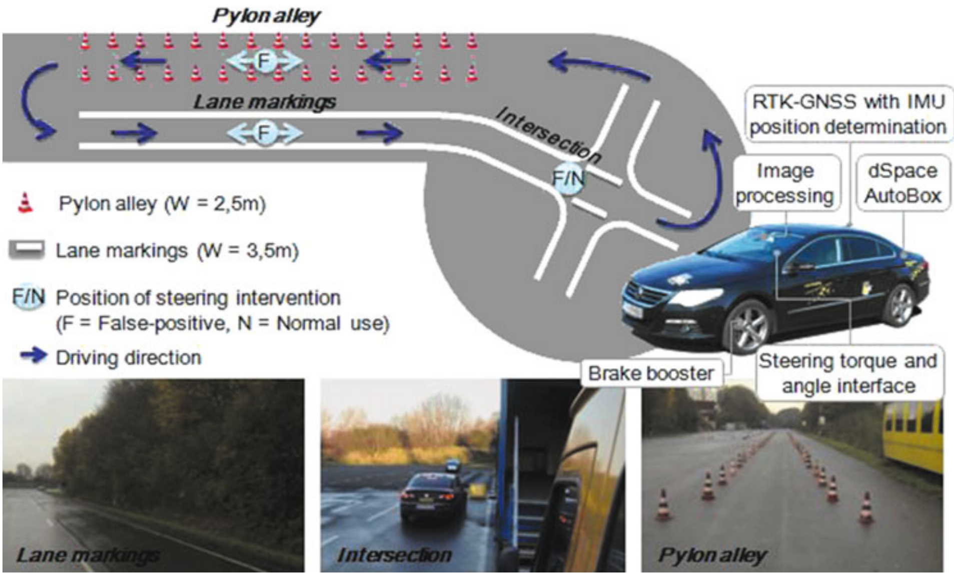

Fig. 27.1 Experimental Setup

Twelve female and fourteen male test subjects participated in the experiment and were assigned to three age groups (under 25, 25 to 45 and over 45 years, see Table 27.1). The average age was 32.4 years. Test subjects had driving experience varying from less than 10,000 km up to over 800,000 km with an average overall mileage of 166,000 km and were monetary rewarded for their participation.

A steering intervention was presented to the test subjects that was based on a desired steering wheel angle signal of a satellite based collision avoidance system which was developed in another research project [10]. The steering wheel angle trajectory (see Fig. 27.2) was triggered by a high precision positioning system to realise a high reproducibility regarding the driving context and considered the driver set steering wheel angle prior to the system activation in case of true positive interventions. In case of no driver interaction it produced a lateral offset of 0.9 m and guided the driver back to the initial

Table 27.1 Descriptive statistics of the driver sample

	Female	Male
Under 25 years	5 (23/56,000)[a]	4 (20/55,000)
25 to 45 years	5 (30/170,000)	6 (31/181,000)
Over 45 years	2 (49/152,000)	4 (55/462,000)
Overall	12 (30/120,000)	14 (35/209,000)

[a](avg. age/avg. mileage in km)

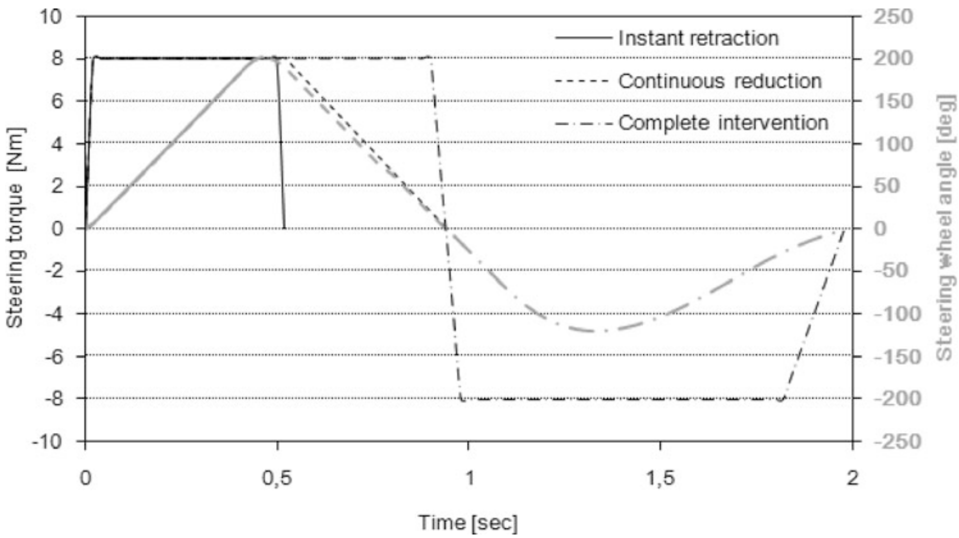

Fig. 27.2 System steering wheel torque and angle

driving lane after the evading manoeuvre. To achieve the desired steering wheel trajectory an additional steering torque of 8 Nm with a gradient of 250 Nm/s (measured at the steering wheel) could be applied.

Due to the intervention duration of about two seconds the possibility to retract the evasive manoeuvre was investigated with regards to its interdependency to the driving context. The retraction could be initiated by the driver by applying a steering wheel torque of more than 4 Nm for more than 300 ms in the opposite direction to the system. The first 200 ms were excluded from this possibility because of the initial reaction triggered by the motion of the steering wheel, see [11]. Therefore, the earliest point in time for the onset of the retraction was 500 ms after the beginning of the intervention.

Two different retraction versions of the additional steering torque were analysed: While in the first case the currently applied additional steering torque was retracted instantly, a continuous reduction over 500 ms was realised in the second case. Both versions were compared to intervention without the possibility to retract the intervention where drivers experienced the complete intervention. For each system intervention it was predefined which version was presented to the driver.

27.5 Reaction Patterns to System Initiated Emergency Steering Interventions

The results of the previously described experiment start with a description of the observed driver steering behaviour. First, the reaction patterns in case of false positive interventions are described with special focus on those interventions that can be retracted (Sect. 27.5.1). In the second part, different reaction types to true positive interventions are investigated (Sect. 27.5.2) which are of high relevance for a suitable design of an override criterion serving as a trigger for a possible intervention retraction (see Sect. 27.8).

27.5.1 Driver Reactions to False Positive Interventions

To understand what the differences in the driver reaction between different driving contexts are, one should take a look at typical reaction pattern first. Assuming that the driver is willing to override a false positive steering intervention, three different phases in the driver reaction can be found: After the onset of the additional steering torque an increase of the steering wheel angle can be observed until the driver prevents a further increase. This phase is called failure phase because it is dominated by the failure characteristic and ends with a first peak in the steering wheel angle that is also called maximum failure induced steering wheel angle (compare [11]). The driver answers the increase of the steering wheel angle with a haptically triggered countersteering. The failure induced steering wheel angle is reduced and often inverted by applying a steering wheel torque that is higher than the additional steering torque of the system. When this initial countersteering motion ends in the second peak of the steering wheel angle, the compensation starts and leads over to the normal driving condition.

Fig. 27.3 shows two different reaction patterns to a steering intervention that could be retracted with a continuous reduction of the additional steering torque. On the left side the driver shows a commonly fast reaction to the onset of the steering intervention. Due to the fact that the initial countersteering is finished when the continuous reduction starts, the driver is already in the compensation phase and experiences the change in the additional steering torque as a further error. In the following, this reaction pattern is referred to by "no interference" (of countersteering and additional steering torque reduction).

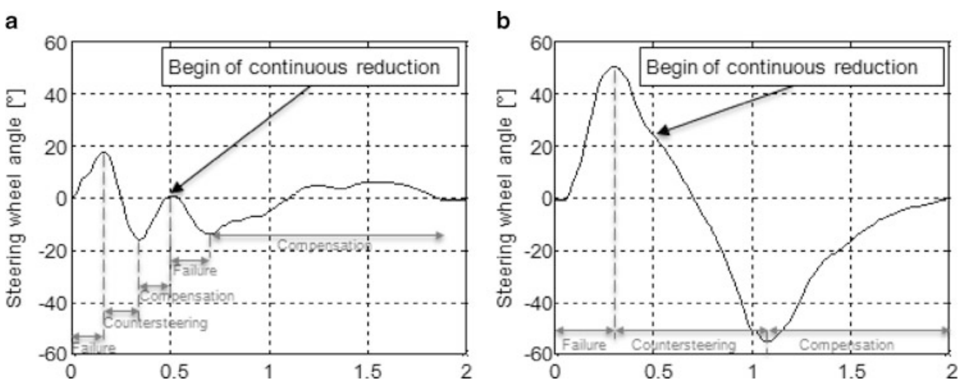

Fig. 27.3 Reaction patterns to false positive interventions (**b** without interference, **a** with interference)

Table 27.2 Occurrence frequency of reactions patterns to false positive interventions

	No interference	Interference
Lane markings	59% (103/174)	41% (71/174)
Intersection	67% (68/102)	33% (34/102)
Pylon alley	76% (132/173)	24% (41/173)

The reaction pattern on the right side to the contrary shows a delayed driver reaction to the onset of the steering intervention, noticeable by the higher failure induced steering wheel angle at a later point in time. Due to the delayed reaction, the initial countersteering overlaps with the reduction of the additional steering torque (at $t = 0.5$ sec) which results in significantly higher amplitudes of the steering wheel angle. The prolonged countersteering is followed by the compensation phase and results in a longer overall failure compensation with noticeable higher vehicle dynamics. Similar reactions are called "interference" (of countersteering and additional steering torque reduction) in the following.

Taking a look at the occurrence frequency of these two reaction patterns during the experiment reveals the first evidence for the influence of available evading space on the driver reaction (Table 27.2): In the pylon alley with its narrow spatial barriers the lowest percentage of interference reactions was observed, the section with lane markings and no physical barriers revealed the highest number. For the intersection which had some spatial barriers, but not as narrow as the pylon alley, the percentage lays in between the lane markings and the pylon alley.

Two important aspects can be derived from this result: First, it can be concluded that for the analysed steering intervention the existence of narrow spatial barriers decreases the number of delayed reactions to the steering intervention onset (and therefore the occurrence of reactions with interference between initial countersteering and the reduction of the additional steering torque). A second way of interpreting these results suggests that drivers adapt their behaviour to the current driving environment. In situations when there is only little available space for compensating steering disturbances drivers act faster and allow less lateral deviation. This interpretation is in line with the findings on behavioural adaptations due to changes in the demand by the driving task which has been shown by e. g. [12–14].

27.5.2 Driver Reactions to True Positive Interventions

When analyzing the driver reactions to system initiated steering interventions during normal system use – i. e. in an emergency evasive manoeuvre – one can categorize three types of drivers: The first two types show an obvious tendency to solve the critical situation by steering. Least often drivers show active steering support of the steering intervention. Characteristic for this type of reaction is a drop in the steering torque applied by the driver which can be seen after roughly 350 to 450 ms (see Fig. 27.4). At that point in time the

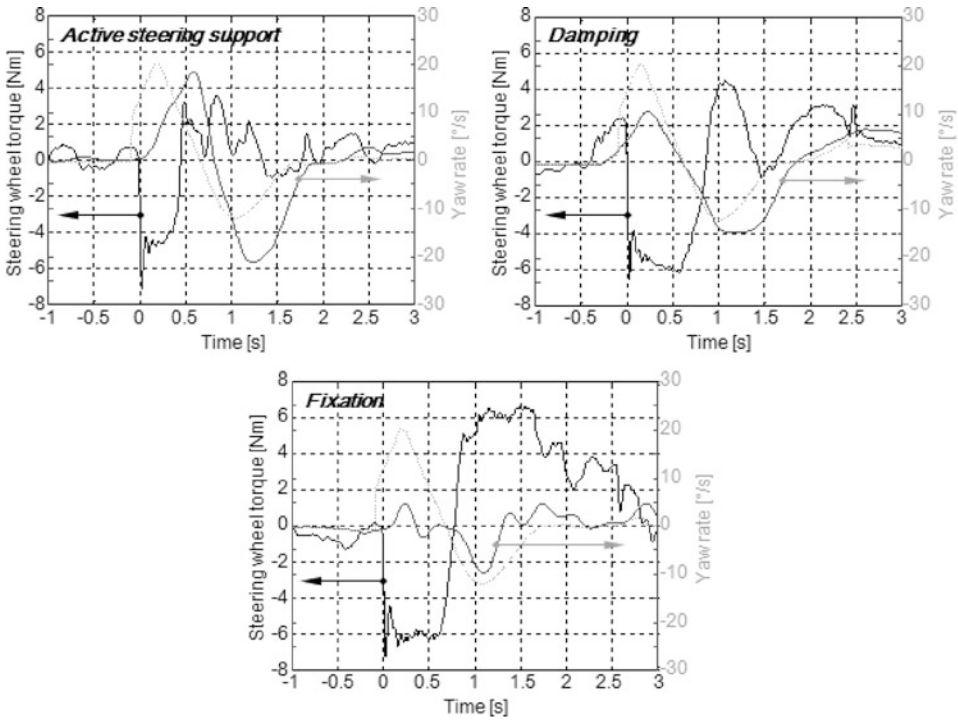

Fig. 27.4 Reaction patterns to true positive interventions

initial reflex-like fixation is changed into an active support by turning the steering wheel actively into the same direction as intended by the system. As a consequence, this type of reaction shows the highest yaw rates during the execution of the evasive manoeuvre.

The second type of reaction that allows assuming an evading intention of the driver is damping. A taking up of the system steering input by the driver cannot be found for this type, but the yaw rate shows a typical evasive behaviour of the vehicle with a damped amplitude in comparison to the system planed yaw motion. This means that the driver allows the vehicle to evade, but with reduced vehicle dynamics. At this point, it has to be mentioned that not the full dynamic of the planed steering intervention was necessary to avoid the foam obstacle due to the desired safety margins in the experimental design. Hence, it cannot be finally determined whether the damping behaviour is caused by the wish of the driver not to exceed certain vehicle dynamics (possibly to avoid a subjectively perceived loss of control) or a planned, situation adequate reduction of the dynamics.

The reaction pattern of the third type does not differ from damping and can be seen as a maximum damping, called fixation in the following. Compared to the previous reaction types (active steering support and damping) drivers showing this reaction type allow almost no vehicle dynamics. Especially an evading trajectory cannot be recognised based on the yaw rate signal. The recorded vehicle dynamics result from the differences between the additional steering torque and the compensating torque by the driver. This type of reaction is most comparable to reactions when driver try to suppress any steering wheel motion and vehicle dynamics as good as possible (e. g. during false positive interventions).

Differences between those reaction types are important to consider for the system based evaluation of the driver intention (Chap. 28), e. g. in the design of an override criterion (see Sect. 27.8). Especially the distinction between fixation and damping seems to be challenging. However, this distinction it needed due to the assumed differences in driver intention which is only reflected in small parameter-differences and leads to very similar reaction patterns.

27.6 Influence of the Available Evading Space on the Driver Reaction

As it has already been shown in the description of reaction patterns to false positive interventions the experiment revealed an influence of the driving context which was also described in the literature (see Sect. 27.2). To further investigate this influence with focus on its influence in the context of the controllability assessment, changes in the natural steering behaviour (meaning without influence of steering interventions) due to the driving context are analysed (Sect. 27.6.1) and used in the following to explain differences in the driver reaction to system initiated steering interventions (Sect. 27.5).

27.6.1 Differences in the Natural Steering Behaviour

Sect. 27.3 described behavioural adaptations due to changes in the demand by the primary driving task that have been documented by [12–14]. Enhancing the deployment of ADAS in urban areas as intended by the UR:BAN project has to consider these possible behavioural adaptations by the driver. Focus of interest in the context of this chapter is the change in the steering control activity by the driver. For the evaluation of the driver reaction to the steering interventions to be investigated it has to be analysed whether differences between driver reactions originate e. g. from inter-individual variability or have a systematic background based on to the driving context and the related steering activity.

In [15] several parameters for the evaluation of the driver's steering control activity are discussed. One is the frequency spectrum of the driver steering torque input. Previous work on the human steering wheel operation [7–9] showed that certain frequency bands are associated with different control strategies of the driver: Frequencies between 0 and 0.1 Hz are due to the road curvature. Above that frequency one can distinguish between anticipatory (also called feed forward) and compensatory (also called feedback) control activity. Anticipatory control activities lie in the range between 0.1 and 0.3 Hz and represent steering input that drivers set for the planed course with a certain time horizon. Since drivers also have to fulfil other tasks while driving (e. g. observation of the surrounding traffic) they do not maintain a continuous control of the lateral vehicle position. Therefore,

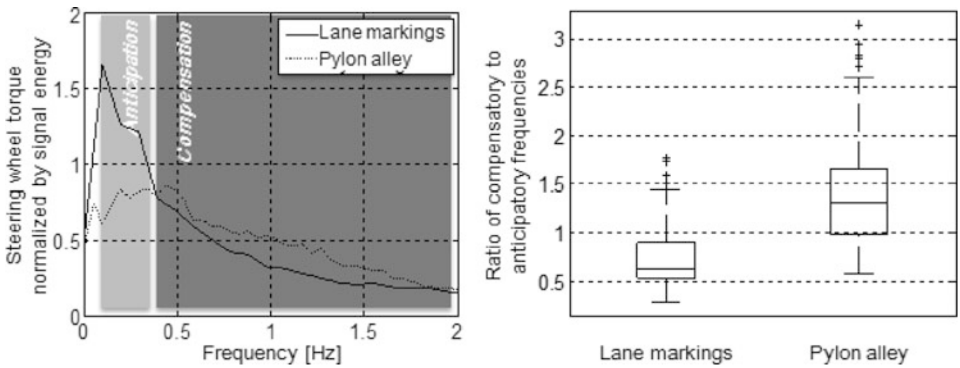

Fig. 27.5 Frequencies of natural driving behaviour

they correct possible deviations from the planed course intermittently. Those corrections are executed with control activities in the frequency band above 0.3 Hz.

To compare changes in the natural steering control behaviour data from the first three passages through the lane markings and the pylon alley were analysed. The data for each driver was recorded prior to the first system intervention to avoid possible influences from expectations of further interventions. Fig. 27.5 shows on the left side the averaged frequency spectrum of the driver input normalized by the signal energy. In the frequency band of anticipatory control activities a distinct peak for the lane markings can be recognised. The steering input for the pylon alley is noticeably lower in this frequency band. Right at the transition between anticipatory and compensatory frequencies the ratio between lane markings and the pylon alley changes. To quantize this observation Fig. 27.5 shows on the right side the distribution of the ratio between compensatory and anticipatory frequencies for all drivers. While the ratio is below one for the lane markings (i. e.: higher input of anticipatory frequencies compared to compensatory frequencies), there is a significant difference to the ratio for the pylon alley which is above one ($t(25) = -10.09$, $p < 0.001$). Hypothesis 1.1 (see Sect. 27.3) is therefore confirmed: *In case of narrow spatial barriers an increased compensatory control activity regarding the steering wheel operation can be noticed.*

27.6.2 Differences in the Driver Reaction in Case of False Positive Interventions

The different versions of the steering intervention were investigated within the experiment in different order per test subject, a uniform distribution in the two analysed sections was required leaving 15 participants for the following evaluation of the driver performance. More details about the influence of the intervention characteristics on the driver performance are described in [16].

Two objective measures were chosen to quantify the effects of the noted behavioural adaptations in cases of system steering interventions: The maximum yaw rate as well as the lateral displacement is commonly used to evaluate the controllability of lateral acting ADAS. In Fig. 27.6 distributions of both measures for false positive steering interventions can be seen. For both parameter the maximum was assessed from the onset of the steering intervention until they driver restored normal driving conditions (determined by the yaw motion of the vehicle). Significantly higher values of yaw rate and lateral displacement were measured in the section without narrow spatial barriers (yaw rate: $t(14) = 5.16$, $p < 0.001$; lateral displacement: $t(14) = 4.41$, $p < 0.001$). Hence, also hypothesis 1.2 is confirmed: *In case of narrow spatial barriers comparable false positive steering interventions show lower effects on yaw rate and lateral displacement compared to cases without narrow barriers.*

Beside lower amplitudes of these parameters also a lower variance was documented for the pylon alley. Lower variance is also found in the time of the failure induced steering wheel angle which is often interpreted as reaction time in the context of steering interventions (compare Fig. 27.7). Like yaw rate and lateral displacement also the reaction time shows a significant effect of the driving context ($t(14) = 4.41$, $p < 0.001$). Even though, the effect size is not very big, one can assume that the lower yaw rate and less lateral displacement result from a faster reaction by the driver due to overall higher steering activity in the pylon alley. In summary, it can be assumed, that drivers show a situation-adequate reaction to the false positive interventions: In situations when a fast reaction is required to avoid collision with spatial barriers drivers do react fast. Whether this effect is attributable to the lane width or to the existence of spatial barriers cannot be finally determined based on the present data set since both parameters were varied at the same time in the chosen experimental set up.

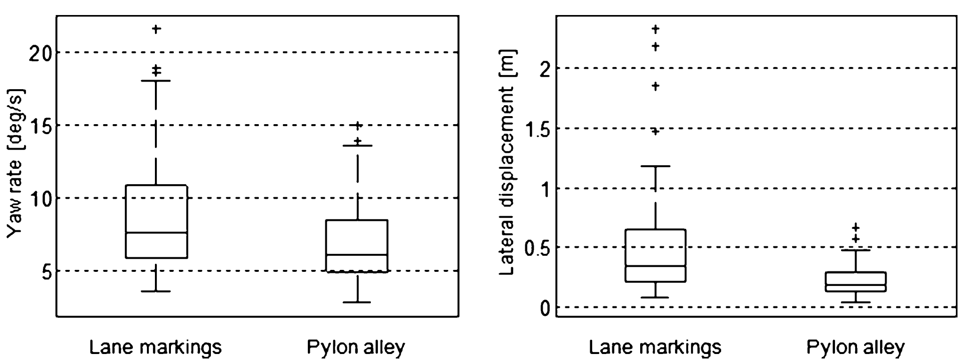

Fig. 27.6 Yaw rate and lateral displacement during false positive interventions

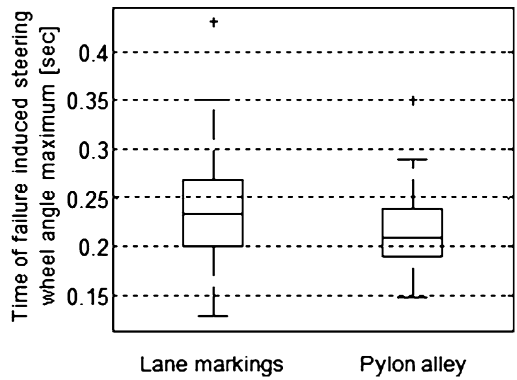

Fig. 27.7 Time of failure induced steering wheel angle maximum during false positive interventions

27.7 Influence of a Retraction Possibility on the Driver Reaction

In Sect. 27.5.1 it was shown that the driver reaction pattern to false positive steering interventions depends on the driving context. Beside this situational influence it is obvious that the reaction and its consequences regarding the vehicle dynamics are also depending on the intervention characteristics. Due to the prolonged duration of the discussed steering interventions two different retraction possibilities have been tested in the experiment. They aim on reducing the consequences of interventions that do not meet the intention of the driver, e. g. during false positive interventions. To this end, two aspects are of importance: First, an override criterion has to be developed that is able to detect the driver intention (prior or during the intervention). Insights on the differences between driver reactions to different use cases as shown in Sect. 27.5.1 and 27.5.2 can be beneficial for the development of a suitable override criterion (see Sect. 27.8). The second aspect addresses the design of the retraction procedure in case an override intention is detected. In the following the data of the experiment are used to evaluate two approaches with regard to their suitability to reduce the consequences of situations with diverging intentions of system and driver (e. g. during false positive interventions).

In Sect. 27.3 the research question was formulated how the consideration of a retraction possibility affects the driver reaction in case of system initiated steering interventions. Here, the focus is set on a possible reduction of consequences in cases diverging intentions of system and driver and not on the detection accuracy of the rudimentary override criterion (see Sect. 27.4). The basis for the evaluation is the maximum yaw rate. As previously described it is assumed that considering a retraction possibility is (in general) able to reduce the maximum yaw rate in case of false positive interventions (see H2.1 in Sect. 27.3). To that end Fig. 27.8 shows the maximum yaw rates for the two different retraction versions that were implemented in the experiment. Maximum yaw rates from driver reaction to system interventions that could not be retracted by the driver serve as a reference. All three conditions are split into driver reactions with and without interference of the reduction of the additional steering torque. For the reference condition the interference with the

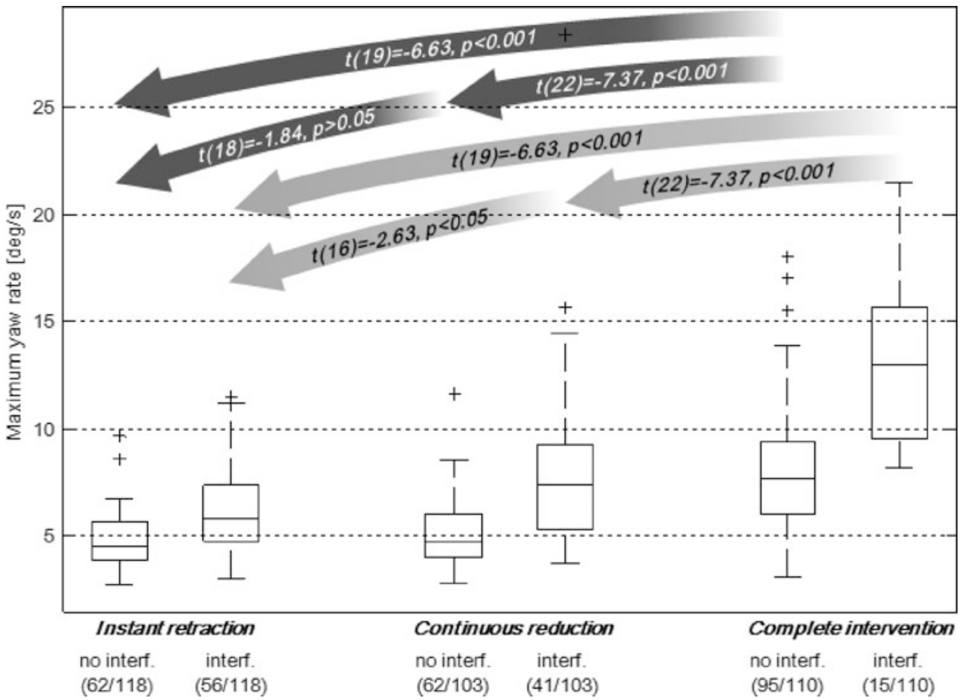

Fig. 27.8 Maximum yaw rate depended on retraction possibility

countersteering motion of the steering angle trajectory was determined. Both retraction approaches reduce the maximum yaw rate significantly for driver reaction with as well as without interference meaning that H2.1 is confirmed: *Retraction possibilities are suited to reduce the maximum yaw rate in case of false positive steering interventions.*

Taking a more detailed look at the differences between the two retraction approaches for H2.2 reveals a dependency of the reaction type: While there is a significant difference in the direct comparison between the maximum yaw rates for the continuous reduction and the instant retraction, the effect size is lower and not significant for reaction without interference. This means that the retraction design has only influence for the conducted experiment in cases where the driver shows a delayed reaction to the onset of the steering intervention. However, the data shows no advantage for the continuous reduction compared to the instant retraction as it was assumed by H2.2 which is therefore rejected: *A continuous reduction of the additional steering torque results in lower maximum yaw rates than an instant retraction.*

27.8 Design of an Exemplary Override Criterion

In Sect. 27.7 it was shown that the consideration of a retraction possibility is able to reduce the consequences regarding the vehicle dynamics for situations with diverging intentions of system and driver. As it was pointed out one elementary step is the design of an override criterion that is suitable to distinguish between different reaction patterns and their related driver intention. Reactions patterns have been described in Sect. 27.5 and form the basis of the intention evaluation. The goal of this distinction is to retract the additional steering torque if an override intention is detected or to continue the steering support if the drivers' steering behaviour complies with the steering intervention. The goal of the design of a retraction possibility is to take the decision to retract the additional steering torque in case an override intention (reaction pattern: fixation) or to continue the steering support when an evading intention is detected (reaction patterns: active steering support and damping).

The data of the conducted experiment has been used to evaluate different approaches for a suitable override criterion. The different approaches were tested offline on the data. Most promising was an approach based on the comparison of the desired steering wheel angle velocity and the one implemented by the driver (Eq. 27.1). The underlying idea is that the driver steers different than the system intends operationalised to "the system tries to increase the steering wheel angle whereas the driver tries to decrease it (or is steering in the other direction)"

$$\mathrm{sign}(\dot{\varphi}_{\mathrm{System}}) \neq \mathrm{sign}(\dot{\varphi}_{\mathrm{Driver}}) \tag{27.1}$$

To avoid erroneous classifications due to short time effects a trend analysis can be considered for the override criterion: The override criterion is then only fulfilled if the condition described in Eq. 27.1 is continuously present for a specific time (t_{Trend}). The described approach has been tested on data sets from the previously described experiment and one additional experiment in the driving simulator of the WIVW GmbH. In both data sets only those steering interventions which included no retraction possibility were analysed to avoid influences from intervention characteristics.

The results from the offline classification are depicted in Table 27.3. They show in how many cases and after which time the criterion would be fulfilled for true positive and false positive interventions. The time indicates when the steering torque would be retracted. Evaluating the data including the videos from interior observation showed that especially for true positive intervention not all drivers have an evading intention, but try to override the intervention. Possible explanations for this behaviour may be a general fear of loss of control over the vehicle dynamics or the chosen wide safety margins in the design of the evading situation (see Sect. 27.4). But also in false positive cases some drivers allowed high amplitudes of lateral deviation when enough evading space was available. These phenomena make it difficult to assign a general reference for the evaluation of the accuracy of the developed criteria: While for false positive interventions the goal of 100% criterion fulfilment would be beneficial for the controllability, the intuitive goal of

Table 27.3 Classification results for most promising override criterion

	True positive cases		False positive cases	
ika INSTITUT FÜR KRAFTFAHRZEUGE RWTH AACHEN UNIVERSITY	Criterion fulfilled	Time [s]	Criterion fulfilled	Time [s]
$t_{Trend} = 0$ ms	39%	0.17	83%	0.16
$t_{Trend} = 10$ ms	33%	0.175	83%	0.17
$t_{Trend} = 20$ ms	27%	0.18	69%	0.18
IZVW	Criterion fulfilled	Time [s]	Criterion fulfilled	Time [s]
$t_{Trend} = 0$ ms	52.4%	0.22	53.3%	0.14
$t_{Trend} = 100$ ms	11.9%	0.42	*Insufficient consideration of damping*	

0% criterion fulfilment in true positive cases seems unrealistic and based on the observed behaviour also not correct. Nevertheless, three aspects can be seen from Table 27.3:

1. For the chosen approach a compromise has to be found: Increasing the time frame for the trend analysis decreases the percentage of situations in which the criterion is fulfilled for both, true and false positive cases. While this may be positive for the true positive cases (assuming that the ground truth is below the shown values for that use case), the decrease for false positive cases is rather negative. The parameter t_{Trend} may therefore serve as a design parameter to choose a more liberal or conservative system design.
2. The time window for the detection of an override intention starts roughly 200 ms after the start of the measurable driver reaction for the chosen approach. Naturally, increasing the trend analysis time postpones the detection time of the override intention, but provides more reliability that the observed behaviour is due to the driver's override intention and not just a short variation in the driver set steering wheel angle.
3. The classification accuracy has its limitations in the variety of the individual driver behaviour. One example can be seen in the condition with $t_{Trend} = 100$ ms of the second data set: In false positive cases some drivers showed initially damping behaviour, but started a steering motion afterwards and were therefore insufficiently considered.

27.9 Conclusions

Two research questions regarding the effect of spatial barriers on the driver behaviour and the influence of a retraction possibility have been formulated and investigated in this chapter. The main results are be used in the following to answer these questions.

How do spatial barriers affect the natural driving/steering behaviour and therefore the driver reaction to system initiated steering interventions?

It was shown that the natural driver behaviour is influenced by narrow spatial barriers. Drivers adapted their lateral control behaviour to a significantly higher compensatory control activity. This behavioural adaptation led to faster reactions and lower maximum yaw rates in case of false positive steering interventions. In addition, some of the observed reaction patterns to false positive interventions occurred more often in a specific driving context than others. Overall, one can say that drivers adapt their behaviour to the driving context: In case of narrow spatial barriers drivers react faster and allow less lateral deviation. If enough evading space is available drivers also allow higher lateral deviations. This knowledge should be considered in the experiment design of the controllability evaluation methods.

How does the consideration of a retraction possibility affect the driver reaction in case of system initiated steering interventions?

Retraction possibilities could help to reduce effects of false positive steering interventions with regard to the maximum yaw rate. In the present study, the implemented continuous reduction of the additional steering torque showed no clear improvement compared to an instant retraction/reduction. On the contrary, for delayed driver reactions – meaning higher maximum failure induced steering wheel angles – the instant retraction revealed slightly lower maximum yaw rates.

For the design of an override criterion a comparison between the system intended and driver implemented sign of the steering wheel angle velocity seems to be a good indicator. Especially, in combination with a trend analysis for the criterion the approach is able to distinguish between drivers with and without override intention with a good accuracy. Evaluating the detection accuracy of the override criterion involves the problem of a clear reference (ground truth): Also during true positive interventions some drivers override the system intervention. In addition, not all drivers override a system intervention in false positive cases but only damp the additional steering torque allowing noticeable lateral deviation if the space is available. Therefore, a reference like "true positive = 0% override criterion fulfilment and false positive = 100% override criterion fulfilment" is not realistic. However, to increase the reference accuracy the test situation should be defined so that during the false positive intervention overriding is required to avoid a collision with other obstacles. Also the situation of the normal system use should impose a high reaction urge to avoid the obstacle enabling a sharp distinction between overriding and acceptance intention.

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Designing Emergency Steering and Evasion Assist to Enhance Safety in Use and Controllability

28

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28.1 Introduction

To date most driver assistance systems associated with steering focus on increasing driving comfort by supporting the driver during manual driving. This includes primarily lane keeping, lane centring and parking assistance. However, up to now no assistance system has been introduced to the market featuring an emergency steering and evasion assistant. Although research activities have increased in the last years, several challenging issues still remain to be solved. This includes the design of steering and evasion assistants that effectively help to avoid collisions and can be controlled in case of a false positive activation.

To effectively avoid collisions in time-critical scenarios, the intervention of a steering and evasion assistant has to be highly dynamic. However, to be controllable in case of a false positive activation, the intervention of a steering and evasion assistant has to be limited. This goal conflict between the effectiveness in a true positive scenario and the controllability in case of a false positive activation cannot be easily solved. Moreover, research suggests that drivers reduce the effectiveness of steering and evasion assistants

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based on steer torque actuators by holding the steering wheel firmly at the beginning of an intervention. This reaction of the drivers reduces the collision avoidance potential of steering and evasion assistants. Several strategies were developed to overcome these problems, like using different steering actuators, decoupling of the driver input from the actual steering (cf. steer-by-wire functionality), using override detection or implementing warnings prior to an intervention. However, it is difficult to assess which measures are most promising to influence effectiveness and controllability of a steering and evasion assistant. To date most publications solely focus on technical aspects of different system designs leaving the interaction of the system design with the driver out of scope. Nonetheless, for the assessment of the influence of different system designs it is important to have detailed knowledge about the interaction of the system design with the driver. This chapter describes different designs of an emergency steering and evasion assistant and discusses advantages as well as disadvantages of these designs with a focus on the interaction of the system with the driver. Additionally, current research activities focusing on the interaction with the driver are summarized.

At the beginning of this chapter we will discuss different intervention concepts (Sect. 28.2), followed by actuators which can be used to implement these intervention concepts (Sect. 28.3). The chapter concludes with the summary of current research activities which are discussed regarding their implications for the collision avoidance potential and controllability of different system designs (Sect. 28.4).

28.2 Intervention Concepts

There are several concepts of steering and evasion assistants, which differ in the level of automation and support they provide. The shown categorization is based on the work of Dang, Desens, Franke, Gavrila, Schäfers and Ziegler [1] and was slightly adapted to focus on the required interaction of the different concepts with a/the driver:

- directional steering recommendations,
- driver initiated evasion assistance,
- automatic evasion assistance.

28.2.1 Directional Steering Recommendations

Directional steering recommendations support the driver by making a recommendation regarding the required steering direction to avoid a collision with an obstacle (e. g. [2, 3]). Besides visual and acoustic recommendations directional steering torques [1, 4], steering wheel vibrations [5, 6], or unilateral braking [4, 7] can be used. Although visual and acoustic recommendations are more likely to be associated with warnings and do not influence the vehicle trajectory directly, directional steering torques can slightly alter the vehicle's trajectory. However, the decision to start an evasive manoeuvre is still up to the driver and the driver is thought to have full control of the vehicle. Nonetheless, the driver could be startled by directional steering torques, or rely on the recommendation which could have a negative impact on safety in use. Research has shown that the impact on the vehicle's trajectory and the driver's reaction is influenced by the configuration of the directional steering torque's amplitude and gradient [8–12].

28.2.2 Driver Initiated Evasion Assistance

A driver-initiated evasion assistance (e. g. [13]). requires the driver to initiate the evasive measures. Typically, the system detects a steering reaction made by the driver who wants to avoid a collision with an obstacle. If the driver's steering direction corresponds with the planned trajectory, the system supports the driver by optimizing the trajectory to avoid a collision with the obstacle. Beside the driver's steering reaction brake reactions have also been discussed to be used to initiate the evasion assistance [14]. Compared to automatic evasion assistance, a possible benefit is the reduced risk for false positive activations.

28.2.3 Automatic Evasion Assistance

An automatic evasion assistant predicts a collision with an obstacle within a critical time span and automatically starts an evasive manoeuvre by steering the vehicle along a planned trajectory around the obstacle (e. g. [4, 7, 15, 16]). A possible benefit of this concept is that it does not rely on the driver's reaction to avoid a collision. However, safety issues in case of a false positive activation have to be considered when designing such systems and according to current legal rules and regulations the driver should be able to override the assistance [17]. Additionally, it is still unclear how the takeover process has to be designed to minimize risks when the driver regains the control during or after an intervention.

28.3 Actuators

Besides the described evasion concepts, several steering actuators or technological concepts exist which can be used to influence the lateral movement of the vehicle [18]. Depending on the technical solution that is used to implement the emergency steering and evasion assist, the driver gets direct feedback from the steering wheel or indirect feedback from the vehicle and vehicle dynamics. Additionally, the same driver reactions can lead to different results depending on the used actuator. In the following section four different actuators are described which have been subject to participant studies, and advantages as well as disadvantages are named.

28.3.1 Steer Torque Actuator

The steering torque actuator uses a directional steering torque overlay to change the steering direction (for further information see [1, 19]). Interventions by the steering torque actuator give a direct and intuitive feedback to the driver at the steering wheel by influencing steering torque and steering wheel angle. The driver is capable of influencing or suppressing the intervention by counter steering, as long as the applied steering torques are not too strong. Research indicates that sudden steering torque changes, which are needed to implement an emergency steering and evasion assistance might irritate the driver or trigger driver reactions which lead to a reduction of the collision avoidance potential. Steering torque actuators and reaction patterns to additional steering torques have been subject to many studies (e. g. [8–12, 20, 21]), and a large section of the available research has focused its studies about emergency steering and evasion assist or steering assist in general on steering torque actuators (e. g. [1, 3–5, 7, 13, 15, 22–26, 26, 27]).

28.3.2 Steer Angle Actuator

The steer angle actuator uses an angle overlay. The desired steer angle is added to the steer angle applied by the driver at the steering wheel (for further information see [1, 28]). To reach full collision avoidance potential with the steer angle actuator the driver has to hold a short reaction torque at the steering wheel at the beginning of the intervention [1]. This behaviour could lead to an initial counter steering reaction by the driver which might have a negative impact on collision avoidance potential or controllability in case of a false positive activation. The overall feedback of the steer angle actuator is thought to be not as direct and intuitive for the driver as the steer torque actuator. Additionally, the steer angle actuator influences the steer ratio. This could result in an offset of the steering wheel during the intervention, which might irritate the driver as the correlation between steering wheel angle and the lateral movement of the vehicle is changed. A combination of the steer angle and steer torque actuator might help to improve the consistency of the feedback for the driver.

28.3.3 Unilateral Braking

A yaw rate can be created by braking only the left or the right wheels of the vehicle. In this case, no direct feedback is given to the driver via the steering wheel. All information about the intervention has to be obtained from vehicle dynamics or from additional warnings. The driver can influence the desired trajectory by counter steering. However, unilateral braking is thought to be suitable only for rare and short interventions [1] and the driver's steering behaviour might interfere or overlap with the system intervention. A combination of unilateral braking and steering torque actuators could help to overcome these limitations and increase the collision avoidance potential of steering torque actuators (e. g. [4, 7]).

28.3.4 Steer by Wire

Contrary to the other actuators, steer-by-wire does not necessarily have a mechanical connection between the steering wheel and an actor who changes the angle of the wheels (for further information see [29]). The steering command is transmitted electrically from the control unit to the actor. This allows a wide variety of different system designs resembling the characteristics of steering torque and steer angle actuators as well as unilateral braking or combinations of the aforementioned. Additionally, a total or temporary decoupling of the driver could be implemented which could help to increase the effectiveness of steering and evasion assistance systems (e. g. [15, 27]). However, safety issues in case of a false positive activation have to be considered when designing such a system as current legal rules and regulations require the possibility for the driver to override the assistance at all times.

28.4 Design Implications Based on Experimental Studies

In the following, we report the results of current research activities which focus on the influence of different designs on the collision avoidance potential, safety in use and controllability of an emergency steering and evasion assistance. Therefore, results are summarized and discussed according to the following key aspects:

- reaction pattern,
- steering recommendations vs. automatic evasion assistance,
- potential of warnings,
- potential of override detection,
- decoupling of the driver.

28.4.1 Reaction Pattern

Almost all studies featuring steering interventions of an automatic or driver initiated steering and evasion assist with a steer torque actuator report an undesired damping of the steering intervention by the driver in collision avoidance scenarios. This reduces the collision avoidance potential in true positive scenarios and the lateral offset in case of a false positive activation (e. g. [3, 4, 7, 15, 24, 27]). The characteristics of this damping reaction have not been reported in detail so far, although they could play an important role for the design of a steering and evasion assist. This effect could also be observed in several studies within the UR:BAN KON project (Chap. 27). A detailed analysis of the driver's reaction pattern at the steering wheel revealed two reaction phases (Fig. 28.1):

The first phase is dominated by the damping reaction of the driver which starts approximately 200–300 ms after the beginning of the steering intervention. This reaction is assumed to be triggered by the sudden change in steering torque (see also [8, 9, 30]) and could be observed in true positive as well as false positive scenarios. Additionally, it could be shown that this timeframe is influenced by the characteristics of the steering intervention. A lower steering torque gradient delays the damping reaction slightly [3, 31].

The second phase is dominated by the driver's intention to suppress or pick up the steering intervention and follows directly after the first phase, starting approximately 400–800 ms after the beginning of the steering intervention. Prior to this, it is difficult to distinguish between drivers who want to suppress, damp or pick up the intervention based on the driver behaviour.

This reaction pattern could play an important role in the design of an emergency steering and evasion assistant based on a steer torque actuator. Although further confirmation is needed, the observed time frames indicate how long it takes for the driver to react to the steering intervention. Research suggests that similar reaction patterns can be observed for unilateral braking [32] or steer angle actuators [33, 34]. This could be used to estimate the consequences of a false positive activation or the timespan needed to detect the driver's intention of an override detection algorithm. Additionally, it could be used as an objective measure to compare different system designs. System designs leading to a faster reaction

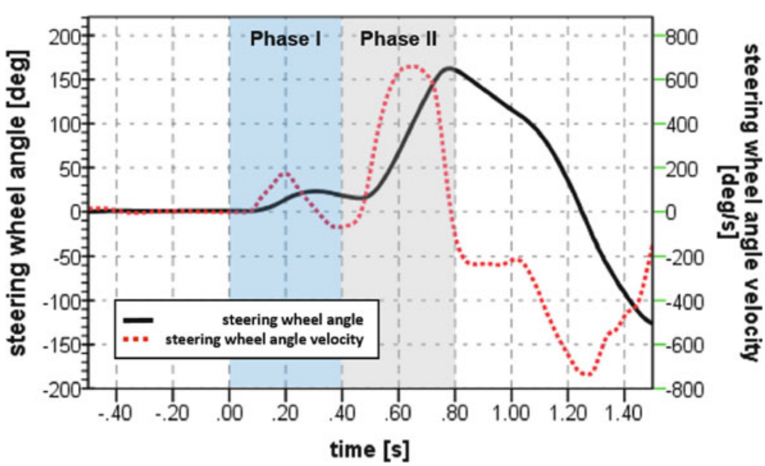

Fig. 28.1 Observed reaction pattern of a driver based on steering wheel angle (*black line*) and steering wheel angle velocity (*dotted red line*). Phase I indicates the damping reaction of the driver at the beginning of the intervention. Phase II indicates the intention of the driver to follow the steering intervention

of the driver could be beneficial for controllability as well as the effectiveness of an automatic steering evasion assistant. However, to date most studies did not focus on analysing differences in the reaction pattern as a consequence of system or scenario design.

28.4.2 Steering Recommendations vs. Automatic Evasion Assistance

Within the project UR:BAN KON we compared directional steering torques to a steering intervention which applied a steering wheel angle following a sinusoidal curve producing a defined lateral offset in a dynamic driving simulator.

Although directional steering recommendations showed a similar collision avoidance potential in true positive scenarios, some drivers produced extreme steering wheel angles. This resulted in large lateral offset which could have endangered surrounding traffic. The tested steering intervention helped to prevent the occurrence of extreme steering wheel angles by actively limiting the applied steering wheel angle. However, if the driver is only assisted during the start of the evasive manoeuvre, the risk for the occurrence of a great lateral offset is still increased compared to an intervention which helps to realign the vehicle.

Therefore, it can be concluded that steering and evasion assistants which limit the applied steering wheel angle and assist the driver in realigning the vehicle help to maximize safety in use.

28.4.3 Potential of Warnings

Several authors suggested the implementation of visual, acoustic and haptic warnings in collision avoidance scenarios in order to assist the driver in his decision to start an evasive manoeuvre [2, 5, 35] or to prepare the driver for the intervention of a steering and evasion assist [7, 15, 27]. The following sections summarize the research regarding different warning designs, as well as their influence on collision avoidance potential (true positive) and controllability in case of a false positive activation of a steering intervention. Additionally, two studies will be reported in more detail, which were conducted within the project UR:BAN KON and focused on the influence of warnings.

Visual Warnings

According to Weber [35] visual warnings depicting the trajectory of the evasive manoeuvre on street level lead to a significant increase of drivers successfully avoiding a collision by evasive measures. However, to our knowledge no study has reported the effect of visual warnings on effectiveness, safety in use or controllability of steering interventions to date. Additionally, it should be considered that visual warnings or warnings in general could also be distracting and too complex to be perceived and understood within the available timeframe [36].

Acoustic Warnings

Acoustic warnings prior to the intervention increased the effectiveness of an automatic steering and evasion assist in true positive scenarios. Similar effects of the acoustic warning in true positive scenarios case have been reported by Sieber et al. [7]. However, the acoustic warning in Hesse et al. [15] lead to higher lateral offsets in case of a false positive activation, which could affect controllability. Although the acoustic warning in Sieber et al. [7] seemed to have positive effects in the use case, the increased lateral offset reported by Hesse et al. [15] could also lead to problems with surrounding traffic.

Directional Steering Torques

Directional steering torques (in the direction of the steering and evasion assist's manoeuvre) used as a haptic warning prior to the steering intervention seem to increase effectiveness (in terms of successful collision avoidance and observed lateral offset in the use case) and controllability (in terms of lateral offset in case of a false activation of a steering intervention) of the steering and evasion assist compared to a system without any warning prior to the intervention according to Hesse et al. [15] and Schieben et al. [30]. Although directional steering torques seem to elicit steering behaviour (see Sect. 28.4.3 Empirical Studies), studies indicate that the timing could be crucial. A directional steering torque at a TTC of 1.6 s (400 ms prior to the steering intervention) increased the collision avoidance potential of a steering and evasion assist. However, a directional steering torque at a TTC of 1.4 s (200 ms prior to the steering intervention) did not. The reason for this could be the reaction pattern of the driver following steering torque overlays (Sect. 28.4.1).

28.4.3.1 Empirical Studies

Although the aforementioned studies indicate that warnings might help to increase the effectiveness in the use case and the controllability of false positive activations, additional confirmation is needed to understand how warnings prior to an intervention of a steering and evasion assist have to be designed to achieve this effect. Within UR:BAN KON, two studies were conducted which compared different warnings and their effect on the collision avoidance potential, safety in use and controllability. In the following sections the design and observed results of the conducted studies will be summarized.

Description of Study I

The first study was conducted on a test track with a prototype vehicle. Two different warnings prior to a steering intervention of an automatic steering and evasion assist were compared to an intervention with no prior warning in a between-subjects design with $N = 60$ participants. Participants experienced true positive and a false positive activation of an automatic steering and evasion assist, either with or without a prior warning. As warnings a directional steering torque (amplitude of 5 Nm in the direction of the evasive manoeuvre of the assistant) and a short brake pulse (maximum deceleration 1.5 m/s^2) prior to a steering intervention were implemented. Both warnings were triggered at a time-to-collision (TTC) of 1.9 s and were presented for 0.2 s.

Results of Study I

In the *true positive scenario* the directional steering torque prior to the steering intervention influenced drivers' steering behaviour, leading to more steering reactions, whereas the brake pulse influenced the drivers' braking behaviour, leading to more brake reactions. As there were no collisions observed in the study, no differences in collision avoidance potential were found. However, in case of a *false activation* of the steering intervention warnings increased the observed lateral offset which indicates that warnings could have a negative impact on controllability.

Description of Study II

The second study was conducted in a dynamic driving simulator. In total, five different warning designs were compared to a steering intervention with no prior warning in a between subjects design with $N = 60$ participants. Directional steering torques, a brake pulse, a combination of a directional steering torque or a tone and a visual display were used as warnings. All drivers experienced a true positive scenario and a false positive activation of the steering intervention.

- The **directional steering torques** were implemented with an amplitude of 4 Nm which was presented for 300 ms. They were triggered either at a TTC of 1.4 s or at a TTC of 1.6 s. Additionally, a **combination** of the **directional steering torque** at a TTC of 1.6 s and a **visual warning** was implemented.
- The **visual warning** displayed the steering intervention's trajectory on street level with a simulated head-up-display. Additionally, a small warning triangle was presented at a fixed position.
- The **visual-acoustic warning** used the same visual warning but was accompanied by a sinusoidal tone with a frequency of 1200 Hz which was presented for 500 ms.
- The **brake pulse** was implemented as a short deceleration of 1.5 m/s^2 for 300 ms which was triggered at a TTC of 1.6 s.

Results of Study II

In the *true positive scenario* almost all warnings increased the collision avoidance potential of the steering and evasion assist compared to an intervention without a prior warning, except for the directional steering torque at a TTC of 1.4 s. Best collision avoidance potential was observed for the directional steering torque at a TTC of 1.6 s and the combination of the directional steering torque and the visual warning. In case of a *false activation* of the steering intervention all warnings increased the observed lateral offset except for the directional steering torque at a TTC of 1.4 s. However, most drivers were able to reduce lateral offset compared to the target value of 1.75 m (Fig. 28.2).

Conclusion

The literature and the results of the reported studies further support the notion that design, modality and timing of the warning might influence driver behaviour even with the

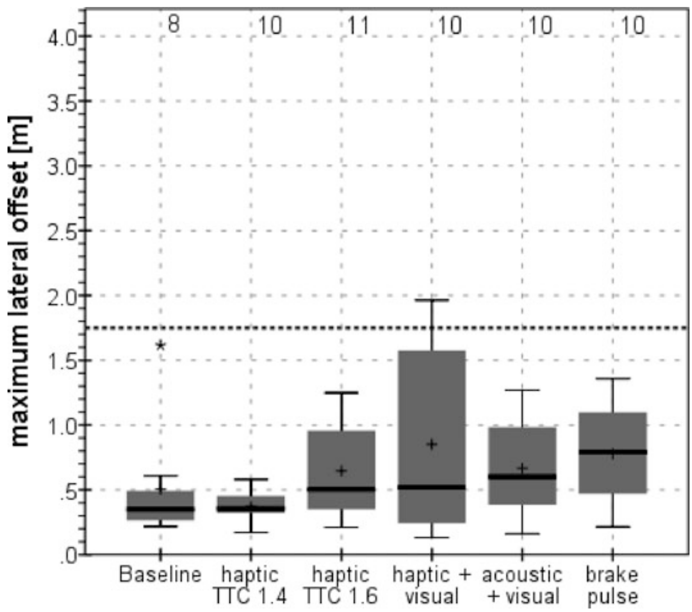

Fig. 28.2 Maximum lateral offset as a consequence of a false activation of the steering intervention

limited timespan. Directional steering torques seem to elicit steering behaviour whereas brake pulses seem to elicit braking behaviour. Additional visual warnings could help to strengthen these effects if they are designed accordingly.

In general, it seems to be difficult to design a warning which increases both the collision avoidance potential of steering and evasion assistants and the controllability of a false activation. Therefore, no recommendation can be given whether a warning prior to a steering intervention should be implemented when designing a steering and evasion assist. Additionally, it should be considered that warnings could have a stronger impact when drivers are distracted (Chap. 29). However, most of the reported studies focused on attentive drivers, which makes it even more difficult to give a recommendation regarding the implementation of warnings in an emergency steering and evasion assistant.

28.4.4 Potential of Override Detection

In order to increase the controllability of false positive system activations of an automatic emergency steering and evasion assistant the implementation of an override detection mechanism has been discussed (e. g. [6, 15, 27]). The override detection mechanism observes the driver's steering reactions and tries to detect whether the driver is acting against the steering evasion assistant or not. If the system detects that the driver is acting against the steering intervention, the intervention gets retracted and the control is handed back to the driver. A simple override mechanism has been reported by Hesse et al. [15] and Schieben et al. [27] for a steer-by-wire emergency steering and evasion assistant, which uses a steering wheel threshold. However, the results indicate that it did not help to increase the controllability (in terms of reducing the lateral offset) of a false positive system activation. Additionally it seems difficult to reliably detect an override intention prior to 0.7 s after the beginning of a steering intervention [6, 15]. In general the development of a fast and reliable override detection based on the drivers steering behaviour seems to be challenging. Although counter steering can be observed very early (see also Chap. 27), the tendency of drivers to dampen or counter steer even in true positive scenarios (see Sect. 28.4) require an elaborate design of an online override detection mechanism, which has no negative impact on the effectiveness in true positive scenarios.

28.4.4.1 Empirical Study

In the following section an additional study is reported which was conducted within the project UR:BAN KON. The study focused on the development and test of an online override detection mechanism and analyses whether the override detection and subsequent retraction of the system initiated steering intervention has an impact on the collision avoidance potential and controllability of an emergency steering assistant.

Study Description

The study was conducted with a prototype vehicle on a test track. The influence of an oversteering classifier was analysed with $N=63$ participants in a between-subjects design. $N=32$ participants experienced a true positive and false positive system activation of an automatic emergency steering assistant with an online oversteering classifier and $N=31$ without. The online oversteering classifier was developed based on the data of prior study which was conducted with $N=60$ participants. It uses the steering wheel angle and additional situation parameters (lateral deviation and time reserve) to detect whether the driver shows the intention to act against the system initiated emergency steering manoeuvre. To consider different types of occurring driver reactions, the oversteering detection is ready to respond 400 ms after the emergency steering manoeuvre has been started and is active until the obstacle has been passed. In the true positive scenario (cf. Fig. 28.3a) a pedestrian dummy was moved into the lane before the steering intervention was started. In case of the false positive activation the manoeuvring space was restricted by marking posts (cf. Fig. 28.3b). In order to avoid a collision with the marking posts participants had to oversteer the steering intervention of the emergency steering assistant.

Results

In the *true positive scenario* (cf. Fig. 28.3a) all participants successfully avoided a collision with the pedestrian dummy. Oversteering reactions were only detected in rare cases, shortly (200 ms) before the obstacle was reached, when participants fell below the emergency steering assistant's intended safety distance to the obstacle, which was parameterized rather conservatively in this study. However, at this point in time this has almost

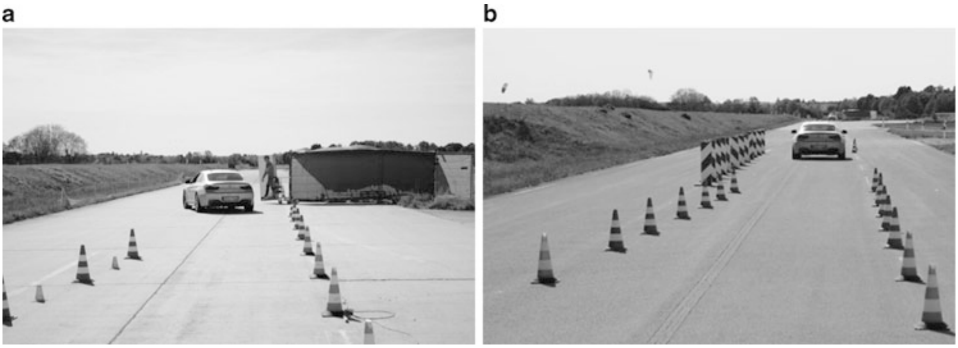

Fig. 28.3 True positive scenario with the pedestrian dummy (**a**) and false positive scenario with the marking posts limiting the available manoeuvre space (**b**)

no consequence for the passing trajectory and did not influence the collision avoidance potential.

In the *false positive scenario* (Fig. 28.3b) all participants were able to avoid a collision with the marking posts in the direction of the evasive manoeuvre and showed oversteering behaviour, leading to a retraction of the system intervention. Typically, the oversteering could be detected after a time span of 550 to 750 ms. Although the detection performance of the oversteering classifier was 100% under the experimental conditions, no significant effects of the oversteering classifier could be observed based on the objecting driving data (e. g. reduced lateral offset). This indicates that beginning with their intentional reaction drivers were able to suppress and compensate the applied steering wheel torque of up to 8 Nm without apparent difficulties and adapt the vehicle's trajectory to avoid a collision with the marking posts. Although no differences were found regarding objective driving data, subjective measures indicate that participants rated the system intervention as more "natural" and "reliable" with an oversteering classifier compared to those who performed the test without an oversteering classifier. Additionally, more participants were convinced that the system was adapted to them if they experienced the interventions with an oversteering classifier.

In general, the tested oversteering classifier proved to be an appropriate approach to detect oversteering intentions of the driver as soon as possible and to distinguish it from spontaneous steering reaction patterns as they can be observed within the first phase of the reaction (Sect. 28.4).

Conclusion

Although participants seem to be able to handle false positive activations of an emergency steering and evasion assistant based on a steer torque actuator, an appropriately designed online override detection can provide a reliable approach for detecting a driver's oversteering intent. Based on the results, it can be concluded that the implementation of an oversteering classifier is not necessarily needed to guarantee or improve the controllability of evasive manoeuvres triggered by an emergency steering assistant. Nevertheless, the possibility for an early withdrawal of the system intervention and the resulting steering wheel moments could be appreciated by the drivers. Regarding the effectiveness of true positive interventions no drawbacks were observed. However, as the reported effects are strongly linked to the experimental conditions and the specific implementation of the system, it remains to be tested if other system designs (e. g. steer-by-wire based concepts) can benefit more strongly from the implementation of an oversteering classifier.

28.4.5 Potential of Driver Decoupling

To overcome the negative effect of the damping reaction of the driver (Sect. 28.4.1) some authors suggested to decouple the driver for a limited amount of time (e. g. [15, 27]). by using a steer-by-wire concept. The decoupling of steering wheel and steer angle for the first 800 ms of an intervention increased the collision avoidance potential of an automatic steering and evasion assist in true positive scenarios according to Hesse et al. [15] and Schieben et al. [27]. However, the lateral offset in case of a false positive activation was also increased compared to an intervention with a coupled steering and evasion assist. An additional implementation of a rudimentary override detection, allowing the driver to recouple, did not help to decrease the observed lateral offset in false positive scenarios which was used as indicator for controllability. Although 100% of the drivers were able to initiate the recoupling, the authors reported that the driver recoupled after an average of 670 up to 710 ms [15] which was too late to effectively reduce the lateral offset in the false positive scenario. Another approach [7] used unilateral braking which can also result in a steer angle without changing the steering wheel angle (which can be seen as a partial decoupling of the driver). The results indicate that unilateral braking did not increase lateral offset compared to a fully coupled steering and evasion assist.

Moreover, an explorative study conducted in a dynamic driving simulator within the UR:BAN KON project indicated that the driver's reaction to false positive activation of a steering intervention might be delayed (approximately 200 ms) compared to an intervention based on a steer torque actuator. The reason for the delayed reaction is still unclear, although the missing haptic and proprioceptive feedback on the steering wheel could play an important role. However, further confirmation based on a real vehicle study is needed to rule out an effect of the used research environment.

Taken together, a decoupling of the driver likely increases the collision avoidance potential of an emergency steering and evasion assistant in true positive scenarios. However, several challenging problems have yet to be faced including the development of an efficient override detection and a safe recoupling strategy. Without these measures it seems difficult to design a decoupled emergency steering and evasion assistant which is able to meet current controllability requirements.

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Integrating Different Kinds of Driver Distraction in Controllability Validations 29

Rico Auerswald, Alexander Frey, and Norbert Schneider

29.1 Introduction

The RESPONSE 3 Code of Practice [1] defined driver distraction as "the process of diverting the attention of the driver from the driving-task to something else" (p. 5). Regan and Strayer [2] have assigned driver distraction into a taxonomy categorizing different causes for driver inattention. This taxonomy is not limited to driver distraction only, but covering also inattention-causes such as *driver neglected* or *cursory attention*. However, as another category Regan and Strayer define *driver diverted attention* equivalently to driver distraction. Moreover they subdivide this category into *driving-related* and *non-driving-related tasks*. In this chapter we refer to diverted attention through non-driving-related tasks when focusing on driver distraction due to secondary tasks.

Due to the increased usage of mobile or handheld devices while driving, driver distraction is still responsible for a huge amount of accidents with serious injuries. NHTSA [3] reported that about 10% of all serious crashes were related to distracted drivers with a total of 3331 killed road users in 2011. Additionally, naturalistic driving studies (NDS) revealed an increased risk to get into safety critical situations. Olson et al. (e. g. [4]) found, that 71% of all crashes and 60% of all safety critical events in their data set were related to distracted drivers. Due to the fact that driver distraction decreases the driving performance [5] it may also affect the controllability of intervening driving functions. For example, driving distraction can cause increased reaction times or decreased lane keeping performance. In addition, Huemer & Vollrath [6] pointed out that drivers turn their attention to

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secondary tasks for a significant amount of the travelling time. In their study, 80% of the participants reported to have done at least one secondary task within the last 30 min of driving.

Therefore, it can be assumed that drivers are often engaged with secondary tasks while driving and are more likely to get into safety critical situations. This increases the likelihood for distracted drivers to be confronted with an emergency assistant like emergency braking or emergency steering. Although it is the aim of these systems to assist the driver in these critical situations, it shows that it is important to consider driver distraction when analysing the driver behaviour, especially when interacting with emergency assistants.

To date research has neglected the effect of driver distraction on controllability of intervening driving functions. Therefore, we try to answer the question whether driver distraction has to be addressed in controllability research and give methodological recommendations for the implementation of driver distraction. Additionally, we conducted two experimental studies to demonstrate the influence of driver distraction on controllability.

29.2 Methodological Implications & Recommendations

29.2.1 Prevalence of Executing Secondary Tasks While Driving

For methodological implications and recommendations it is necessary to have a basic knowledge about drivers' real world behaviour executing secondary tasks while driving. The prevalence of these tasks was often measured by means of observations or interviews, as reported by Huemer and Vollrath [6]. They assigned secondary tasks into nine categories, e. g. eating and drinking, using (portable or vehicle-related) devices or self-initiated actions like mind wandering. Based upon those categories, the authors conducted a survey on frequency and duration of different kinds of secondary tasks within the last 30 min. The most frequent activities were associated with vehicle-related devices (58% of the sample). However, drivers where engaged with those tasks only for short time intervals. Focusing on the time drivers spent to secondary tasks conversations with passengers (37.4%) or the usage of portable devices (33.9%) certainly required longer time intervals. While conversations with passengers occurred with high frequency, portable devices were used rarely. Kubitzki [7] revealed similar results concerning the prevalence of secondary tasks: The interaction with (portable and vehicle-related) devices and passengers as well as distracting elements in the environment seem to be the most relevant reasons for driver distraction which should be taken into account when analysing the influence of driver distraction in controllability research.

29.2.2 Impact of Secondary Task on Drivers' Performance

Young, Regan and Hammer [8] categorised the requirements of secondary tasks for the driver into visual, auditory, biomechanical and cognitive components. They revealed different amounts of interference with the driving task depending on which components the secondary tasks primarily required, which has also be stated by Wickens [9] based on his multiple resource theory. In a simulator study, Muhrer and Vollrath [10] compared the effects of visual and cognitive demanding tasks in car-following scenarios. The visual distraction task relocated human's perception away from driving-relevant objects, therefore negatively affecting the driver's capability to respond to unpredictable, sudden events. However, cognitive distraction led to negative impacts on the predictability of future actions of surrounding road users. Therefore, it can be concluded that both distraction types lead to constraints regarding the driving performance, whereas they affect the situation awareness in different ways. Endsley [11] structured the situation awareness into the perception of surrounding elements in spatial and temporal manner, the comprehension as well as the interpretation of their meaning and the projection of the elements' characteristics in the (nearby) future. Following this taxonomy, visual distracting tasks would disturb mostly the perception step, while cognitive distraction would disturb the comprehension and interpretation due to the sharing of cognitive resources between the driving and secondary tasks [12]. This reduction of perceptual capacities could lead to a general reduction in secondary task and driving performance, whereas a lack of cognitive capacities in the working memory could probably lead to a missing link between surrounding elements on the road and the knowledge stored in the working memory [13].

As shown in the preceding section, tasks like the interaction with devices or conversations with passengers have a high prevalence in real traffic (see Sect. 29.2.1) and it is very likely that secondary tasks will be executed prior to an event which requires the intervention of an emergency steering and evasion assistant. According to the findings in this section, visual and cognitive secondary tasks should be considered when analysing the influence of driver distraction.

29.2.3 Impact of Secondary Tasks on the Controllability of Intervening Driving Functions

Driver distraction might not only affect the interaction of the driver with emergency steering assistants in a use case where the intervention is justified but also when there is no apparent reason for an intervention (false activation).

In this chapter, we discuss how driver distraction could influence the controllability of false activations. As stated, false activations can appear without an apparent reason. However, in order to be able to regain the control over the vehicle and to minimize the consequences e. g. on the lateral movement, drivers have to react quickly by selecting the correct response with an appropriate intensity. In order to select the correct response the driver needs a reflection of the environment (situation awareness). However, based on the results we reported it can be assumed that driver distraction has a negative influence on the driver's situation awareness. Therefore, we assume that their ability to control false activations is significantly reduced. As both visual and cognitive distracting tasks affect the situation awareness (although in quite different ways), they should both affect the controllability of false activations. However, biomechanical distraction (e. g. using handheld devices) could also reduce the driver's ability to handle a false activation, because the driver might be physically limited in the quality of his response.

Empiric knowledge regarding the influence of driver distraction on the controllability of false activation of a steering intervention is still missing. However, it is important to know if driver distraction should be taken into account when assessing the controllability of these false activations. Therefore, we want to demonstrate how driver distraction can be realised when assessing the controllability of false activations of a steering intervention and how it affects controllability. Based on the results, we want to provide recommendations whether driver distraction has to be considered and which standardised secondary tasks can be used in the assessment.

29.2.4 Recommendations of Secondary Task Characteristics

As described in the previous chapters, the primary modality of the secondary tasks should be visual, biomechanical, cognitive or any combination to have the highest likelihood affecting the controllability of false activations in the case of driver distraction. Regarding the interruptability especially visual and biomechanical tasks should be designed in a way allowing the driver to pause the secondary task within short intervals. This is necessary to ensure the continuous execution of the (primary) driving task and to comply with the guidelines of NHTSA [14] in which only secondary tasks requiring single gaze-contributions of less than 2 s are recommended. Cognitive tasks without a visual component (e. g. phone calls) however do not need to follow this guideline. However, it is much more challenging to measure the drivers' task involvement when no visual or biomechanical distraction appears. One option could be the application of the Detection Response Task (DRT; ISO/DIS 17488, [15]) but its temporal resolution may be not sufficient. Another opportunity is a driver-instruction to respond verbally.

It is worth noting that all tasks contain a varying, cognitive proportion. So it is necessary to check which modalities are affected in which proportion by the used secondary task (see [9]). Moreover, the implemented secondary task should require a continuous interaction between the driver and the task to ensure the measurement of the distraction-degree with a high temporal resolution. Such a resolution is required to ensure that the driver is distracted previously as well as immediately when the false activation appears. The first case would mainly decrease the situation awareness while the second forces the driver to relocate his attention from the secondary task towards the driving task. Furthermore, we recommend to avoid extremely difficult or very easy tasks. Standardised secondary tasks can be useful to control the difficulty towards a desired level. Concerning primarily visual-motor tasks, the Surrogate Reference Task (SuRT; ISO/TS 14198, [16]) and the Critical Tracking Task (CTT; ISO/TS 14198, [16]) are shortlisted. Because of the insufficient possibility to interrupt a tracking task, we would prefer the SuRT over the CTT for the application as a secondary task executed while driving. However, for primarily cognitive tasks there are no standardised secondary tasks available. Frequent examples in empirical studies are n-back, audio book or counting backwards tasks. In the ISO/DIS 17488 [15] they recommended the n-back task for the Detection Response Task which could also be sufficient for controllability validations.

While under realistic driving conditions drivers could initiate the execution of secondary tasks on their own, in the context of a high empirical reliability it could be more appropriate letting the driver execute secondary tasks with a test-paced timing. This ensures that the driver is distracted when the experimental procedure requires this condition. In addition, as described above, self-regulated behaviour triggered by self-paced execution of secondary tasks (see [17]) may not have an effect on the controllability of false activations and can be neglected.

29.3 Case Studies

Unfortunately, an extended amount of scientific investigations and literature on how secondary tasks affect the controllability of false activations of steering torque overlays was missing. Therefore, we assumed that all mentioned modalities would have an influence on controllability. A gradation between them was not feasible. To gather more information on how different kinds of driver distraction might influence the drivers' ability to control false activations, we accomplished a comparison between different modalities of distraction in an event of a false activation of steering torque (s. Sect. 29.3.1). In a second study we increased the complexity of intervention by implementing a false activation of a complete steering intervention (Sect. 29.3.2).

29.3.1 Case Study I

Based on the theoretical background and the assumptions in Sect. 29.2, the following research hypotheses were constructed:

- There should be more critical subjective ratings related to the controllability in case of false activations of an emergency steering function under distraction than without distraction.
- Driver's subjective workload should be increased under distracting conditions.
- Distracted drivers should show a weaker lane keeping quality compared to attentive drivers – regardless if there is a false activation or not.
- Distracted drivers should show a lower oversteering behaviour compared to attentive drivers in an event of a false activation. In this study, the oversteering behaviour refers to the maximum of driver's allowed lateral deviation.

29.3.1.1 Methods

Participants

The sample consisted of 48 participants (20 female, 28 male) which were all employees of the Federal Highway Research Institute (BASt). Their mean age was about 41 years ($SD = 14$ years) with an annual driving performance of $M = 16{,}200$ km ($SD = 9700$ km) and a mean driving experience of 23 years ($SD = 14$ years).

Instruments

An experimental vehicle from BASt was used to reproduce the lateral disturbance by steering torques as realistically as possible. The vehicle consisted of two separate cabins: Participant's (driver's) cabin in the front of the vehicle and instructor's cabin in the back. The vehicle contained a computer to control and initiate the steering interventions and to collect the data. Furthermore, a touch screen (tablet-pc, 10″screen diagonal) was integrated next to the driver in line with the in-vehicle infotainment system (Fig. 29.1). The participants were instructed to execute a secondary task on this touch screen.

The test vehicle was able to overlay the driver's steering torque through an additional steering motor. In the experiment we exclusively simulated a false activation, initiated by the experimenter. As we only considered influences of driver distraction in the initial phase of a false activation, no complete trajectory was necessary. Furthermore, to reduce the possibility that the physiological limitation of the driver while one-handed driving could mask influences of distraction, a moderate steering torque of 3 Nm over 2 s was

Fig. 29.1 Experimental setup of the driver's cabin including an additional touch screen for executing secondary tasks

Fig. 29.2 Test site of BASt

chosen. After the intervention a counter steering followed for 0.5 s aiming to neutralize any deflection of the steering wheel.

Without any intervention of the driver (open loop) the test vehicle turned with a maximum yaw rate of 16.5 °/s and a maximum lateral acceleration of 3.3 m/s^2 after a false activation was initiated while driving 30–40 km/h. The complete false activation turned the test vehicle about 25 degrees.

The test site of BASt was chosen for the experiment. Fig. 29.2 illustrates the test track (length about 350 m). The potential evasion space was limited by traffic cones with a lane width of 3.5 m. To ensure the driver's safety, a false activation only occurred in the target area with a length of 70 m.

Independent Variable

As an independent variable (IV), we systematically varied the secondary tasks between the three conditions *none*, visual-motor (*visual*) and cognitive-auditory (*cognitive*) task. Referring to a standardised method often used in IVIS-validation (see Sect. 29.2.4), the Surrogate Reference Task (SuRT) was implemented as a visual-motor secondary task in this study. In the selected application, the participants saw 50 randomized circles (diameter: 35 arc minutes visual angle) on a touch screen (distance between driver's eye and display: about 70 cm) and a target circle with bigger size (diameter: 44 arc minutes visual angle). The participants were instructed to detect this target circle (visual component) and mark it by touching the screen at that particular position (motor component). In the cognitive-auditory secondary task, the participants were told to count backwards in steps of seven from a three-digit number. Beforehand, a selection of ten numbers was determined and presented by the instructor in a randomized order. To check the counting and to ensure permanent cognitive load, all results had to be spoken out loudly.

The second independent variable was the false activation described in the *instruments* section. There were two conditions: Either the presence of a false activation in a test lap (*FA*) or its absence (¬*FA*). As a baseline, the latter condition allowed us to collect data about the driving behaviour of the participants in combination with secondary tasks and to isolate the effect of the false activation under the FA condition.

Dependent Variables

Subjective as well as objective variables were measured in this study. Regarding participant's subjective ratings, the well-known and often validated "NASA-Task Load Index" (NASA-TLX) was used to record participant's workload while executing the driving task and (depending on the condition) a secondary task [18]. It was also possible to compare the relative difficulty between the visual-motor and the cognitive-auditory secondary task indicated by the measured workload. Besides that, the assessment scale for the criticality of driving- and traffic situations (here called "SBS"; based on [19]) was used to collect information about participant's subjective perception of the criticality of the situation.

For the purpose of evaluating the effect of driver distraction on the driver's steering behaviour, the test vehicle was equipped with sensors measuring mainly lateral accelerations ($\ddot{y}$) and yaw rates ($\dot{\psi}$). Both recorded data with a frequency of 100 Hz. We assumed that two phases could be relevant: First, the effects of distraction appearing on the driving behaviour prior to a false activation and second, the steering behaviour the driver shows as a reaction to the false activation.

For the first phase we integrated $\dot{\psi}$ in test tracks without any false activation to obtain the yaw angle (ψ) and added up its absolute value as an indicator for the overall steering behaviour of the driver with or without induced distraction. In the second phase we referred to classical parameters in controllability validations, especially the maximum lateral acceleration ($\ddot{y}_{\max}$) and the maximum yaw rate ($\dot{\psi}_{\max}$). Like Neukum, Paulig, Frömmig, and Henze [20] we focused on the extreme values of both parameters, caused by the false activation (first reaction) and by compensation of the intervention (compensating reaction).

Design

False activations should occur only in rare events. The expectation of the participants for such system failures should be more or less non-existent. Therefore, we focussed on the first contact of participants with a false activation resulting in a between-subjects design with three groups of $n_i = 16$ participants. The groups were assigned to the factor steps of the independent variable "secondary tasks". As a baseline, group 1 did not receive any secondary tasks while driving whereas group 2 received the visual task and group 3 the cognitive task. All participants experienced a false activation.

After the first contact with a false activation we switched to a within-subjects design. In the subsequent 15 laps every participant experienced the conditions no, visual or cognitive task in combination either with the FA or the ¬FA condition. In every condition of the IV "secondary task" the participants drove four times without a false activation and once with in randomized order.

Procedure
At the beginning, participants were asked to give some demographics (their age, sex, handedness, driver-license acquisition and driving experience). The participants were told to drive between the markings and traffic cones on the test track and to use only their left hand on the steering wheel. It was hereby possible to ensure the same hand position in every trial over every condition of the independent variables. The participants were instructed to drive with an appropriate lane keeping performance and with a speed in between of 30 and 40 km/h. They were uninformed towards the possibility of a false activation. Before the experiment started, the participants drove the course several times to get familiar with it as well as with the test vehicle. After finishing an experimental lap, participants were asked to assess their experience of the situation using the SBS. Following this, the participants continued driving overall 16 test laps. Afterwards, the participants were asked to report their workload combining the drive with the particular secondary task (none, visual, cognitive) using the NASA-TLX.

29.3.1.2 Results

Subjective Variables
Fig. 29.3 shows the overall workload (over every subscale of the NASA-TLX) using boxplots for the particular distraction type. The box contains the upper and lower quartile, the

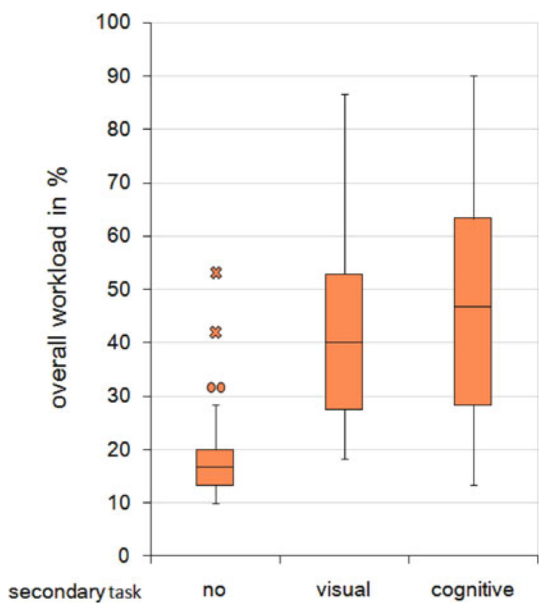

Fig. 29.3 Overall workload of NASA-TLX for the particular distraction

whiskers show the minimum and maximum rating of workload. Outliers and extreme values are marked if values differ from a distance between the 1.5-fold and 3-fold (outliers) respectively more than the 3-fold (extreme values) of the interquartile range.

According to the hypothesis, a Friedman-Test pointed out that there was a statistical significant effect of the IV "secondary task" on the overall workload ($\chi^2(2, 48) = 63.19$, $p < 0.001$). Post-hoc-comparisons using a Bonferroni-corrected alpha error of 0.017 showed that the overall workload of "no secondary task" differed statistically significant from "visual secondary task" ($p < 0.001$) as well as from "cognitive secondary task" ($p < 0.001$). The statistical comparison between visual and cognitive secondary task failed the significance level ($p = 0.06$). Thus, it indicates a quite low overall workload for the condition "no secondary task" and a much higher overall workload for the visual and cognitive condition with no statistically significant difference.

Fig. 29.4 illustrates the boxplot of the subjective critical assessment depending on the particular distraction for the first lap (participant's first contact with the false activation).

In the statistical analysis a Kruskal-Wallis-Test showed a statistically significant effect of the between-group IV "secondary task" on participants' subjective critical assessment in the first lap ($\chi^2(2, 48) = 9.31$, $p < 0.01$). Post-hoc-comparisons using a Bonferroni-corrected alpha error of 0.017 showed that the first lap driving without distraction was assessed statistically significant less critical in contrast to the distraction by the visual-motor secondary task ($p < 0.01$). In tendency, the first contact with the false activation without distraction was perceived less critical than being distracted by the cognitive-auditory secondary task ($p = 0.03$). In summary, the situations with visual and cognitive secondary tasks were perceived "uncomfortable" on average. Subjectively perceived differences be-

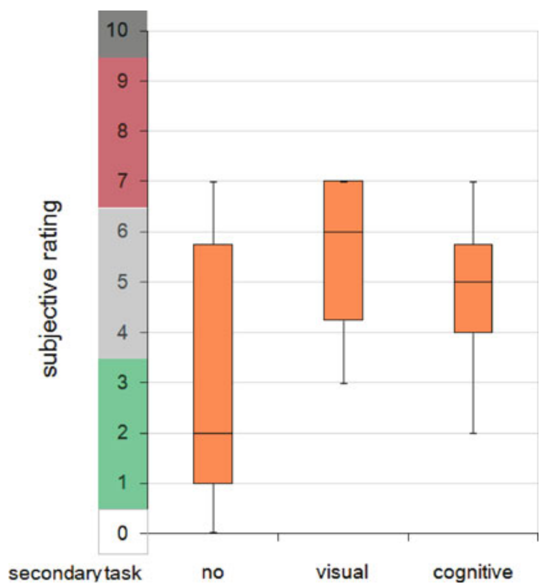

Fig. 29.4 Subjective critical assessment depending on the particular distraction for the first lap

tween visual-motor and cognitive-auditory secondary task did not differ in the first contact with a false activation ($p = 0.18$).

Fig. 29.5 shows the boxplot of the subjective critical assessment depending on the particular distraction for all following laps, with or without false activation.

A Wilcoxon-test indicated a significant effect of the IV "false activation" under every distraction condition. So laps with false activation were assessed more critically in contrast to laps without a false activation, regardless whether the participant conducted a secondary task or not. For no secondary task: $z = -5.93$, $p < 0.001$, for the visual-motor secondary task: $z = -5.57$, $p < 0.001$, and for the cognitive-auditory secondary task: $z = -5.44$, $p < 0.001$. Thus, indicating a successful experimental manipulation of the IV "false activation".

Regarding only following laps with no false activation, a Friedman-test indicated an effect of the IV "secondary task" ($\chi^2(2, 48) = 71.29$, $p < 0.001$). Post-hoc-comparisons using a Bonferroni-corrected alpha error of 0.017 showed that participants evaluate laps with visual-motor distraction statistically significant more critical than laps with cognitive-auditory secondary task ($p < 0.001$) and with no secondary task ($p < 0.001$), again in laps with cognitive-auditory distraction, there were statistically significant more critical assessments in contrast to laps with no secondary task ($p < 0.001$). Regarding only following laps with false activation, a Friedman-test also indicated an effect of the IV "secondary task" ($\chi^2(2, 48) = 27.49$, $p < 0.001$). Post-hoc-comparisons using a Bonferroni-corrected alpha error of 0.017 showed – analogous to the results of laps with no false activation – that participants gave more critical assessments in laps with visual-motor ($p < 0.001$) and with cognitive-auditory distraction ($p < 0.01$) in contrast to laps with no secondary task. The statistical comparison between visual and cognitive secondary task failed the significance level ($p = 0.02$). Descriptively, the critical assessments of laps with no secondary task and

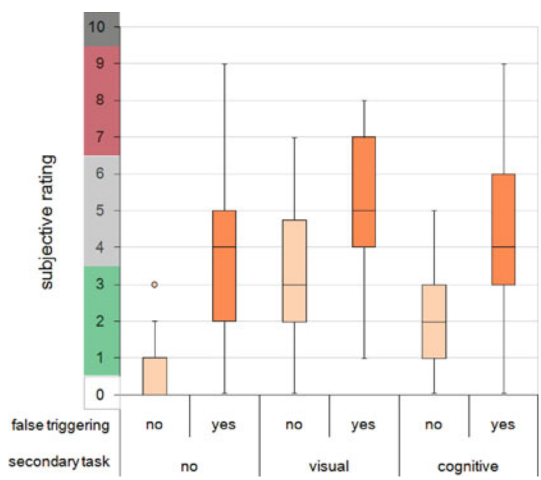

Fig. 29.5 Subjective critical assessment depending on the particular distraction for laps 2 to 16

a false activation as well as laps with visual secondary task and no false activation are approximately at the same level ($p = 0.12$).

Objective Variables

The test track was limited at the road boundaries with traffic cones to force participants to stay on course. As another purpose, we used the traffic cones as an instrument measuring possible lane departures. First of all, no participant hit a traffic cone, thus no lane departure revealed out of false activations or while driving under distraction.

Focusing on the direct driver reaction to the false activation, we investigated the maximum lateral acceleration in situations participants experienced the intervention for the first time. The mean maximum lateral acceleration caused by the first reaction was $\ddot{y}_{max} = 0.74\,m/s^2$ ($SD = 0.74\,m/s^2$), which equals 30% of the maximum possible of 3.3 m/s^2. Whereas, $\ddot{y}_{max}$ caused by compensation of the intervention was $\ddot{y}_{max} = 0.64\,m/s^2$ ($SD = 0.25\,m/s^2$). In subsequent situations with false activations the test vehicle reached on average $\ddot{y}_{max} = 0.73\,m/s^2$ ($SD = 0.29\,m/s^2$) through the false activation and $\ddot{y}_{max} = 0.59\,m/s^2$ ($SD = 0.24\,m/s^2$) through the drivers' compensatory reaction. A one-way ANOVA with an alpha error of 5% revealed no significant difference between the conditions of the IV "secondary tasks" for the first reaction ($F(2, 45) = 0.68$, $p = 0.51$, $\eta^2 = 0.03$) as well as for the compensating reaction ($F(2, 45) = 0.33$, $p = 0.72$, $\eta^2 = 0.01$). Also, we could not reveal any significant difference between the different conditions in terms of secondary tasks for following contacts with false activations (first reaction: $F(2, 94) = 1.95$, $p = 0.15$, $\eta^2 = 0.02$; compensating reaction: $F(2, 94) = 0.89$, $p = 0.41$, $\eta^2 = 0.01$).

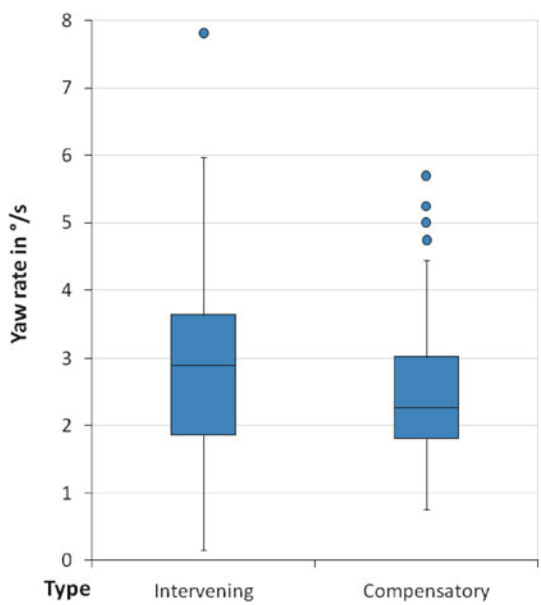

Fig. 29.6 Comparison of both types of maximum yaw rate (intervening and compensatory) in situations participants experienced the false activations for the first time

We found similar results with regard to the maximum yaw rate. Fig. 29.6 shows only slight differences in the median between the first and the compensating reaction when participants experienced the false activation for the first time. However, it revealed no significant differences between the two reaction types ($t(47) = 1.32$, $p = 0.19$). This means that the drivers executed both reaction types comparably. Inappropriate behaviour in general (e. g. overcompensation) has not been observed.

As illustrated in Fig. 29.7, in the mean all maximum yaw rates for the different conditions of the secondary tasks in situations with a first contact were below the criteria of 4 °/s from Neukum, Ufer, Paulig, and Krüger [21]. The highest value of $\dot{\psi}_{max}$ the participants tolerated was $\dot{\psi}_{max} = 3.3\,°/s$ ($SD = 2.0\,°/s$) when they had been visually distracted (intervening type of $\dot{\psi}_{max}$). However, no significant differences were detectable between the conditions no, visual and cognitive secondary task for the first reaction ($F(2, 45) = 1.98$, $p = .15$, $\eta^2 = .08$) as well as for the compensating reaction ($F(2, 45) = 0.4$, $p = .67$, $\eta^2 = .02$).

However, the summed yaw angles imply an effect of the induced distraction on the drivers' steering quality, as shown in Fig. 29.8 although those results were not linked to a false activation. Every participant had to drive through the 25°-curve of the test track explaining the general offset in the conditions. A one-way repeated measures ANOVA revealed significant differences between the conditions of the IV "secondary task" for the summed yaw angle ($F(2, 94) = 49.75$, $p < .001$, $\eta^2 = .51$). A post-hoc paired comparison resulted in a significant higher ψ for the visual secondary task compared to no

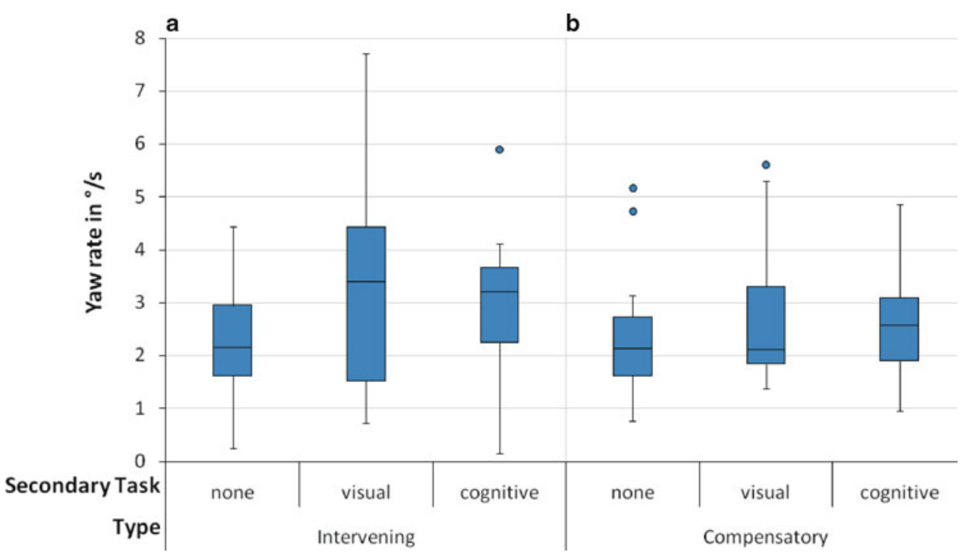

Fig. 29.7 Influence of secondary tasks to both intervening (**a**) and compensatory (**b**) types when participants experiencing false activations for the first time

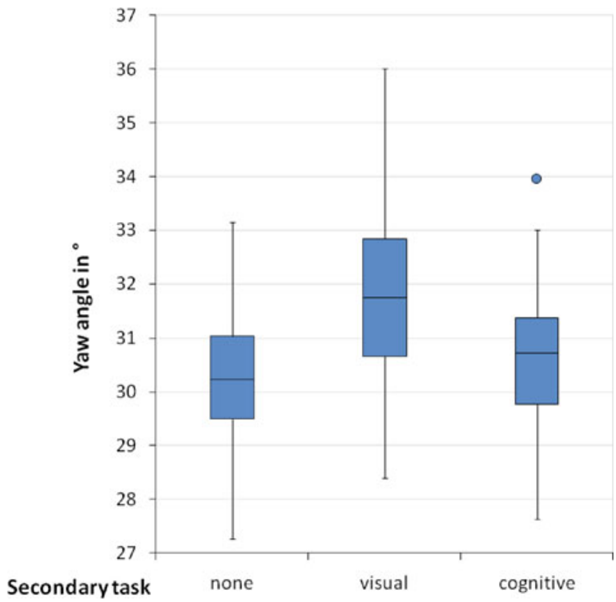

Fig. 29.8 Summed yaw angle over the whole test laps without any false activation depended on the condition of the secondary task

secondary task ($p < .001$). Comparing the conditions cognitive to no secondary task, we found a significant higher ψ for the cognitive task ($p = .010$). Contrary to the subjective evaluations of the overall workload, there was also a significant higher ψ for the visual secondary task compared to the cognitive task ($p < .001$).

29.3.1.3 Discussion

In this study we aimed on finding evidence whether driver distraction has to be considered in controllability validations. Based on the methodological implications in Sect. 29.2 we demonstrated a possible application of standardised secondary tasks to answer this research question.

The drivers' workload assessment while doing secondary tasks showed, according to the hypothesis, higher ratings in the overall workload instead of driving without distraction. Therefore, we could confirm our experimental manipulation. Interestingly, the visual-motor and cognitive-auditory task did not differ significantly in this case. Hence, we conclude a comparable task difficulty between both secondary tasks, because they stressed the driver comparably. However, we have to point out that the assessed workload is based on the participants' subjective experience. In contrast, the participants' steering performance revealed a significant difference between both distraction types. While executing the visual-motor task our participants showed a poorer steering behaviour compared to the cognitive-auditory task. This could be a hint that despite similar perceived workload of both tasks, the visual-motor secondary task has a higher negative impact on the steering performance than mainly cognitive tasks.

A similar effect was revealed in the participants' subjective critical assessment. In the first contact with the false activation the criticality rating varied depending on whether drivers were engaged in a secondary task or not. Regarding the visual-motor secondary task in comparison to no additional distraction, there was a significantly higher subjective criticality assessment. In tendency, the cognitive-auditory task also caused a higher assessment. An analysis of the following contacts showed, according to the first contact, marginal lower criticality ratings compared to the first contact, but in the same direction. Additionally, participants' ratings of driving situations containing visual-motor distraction were more critical than the others. Interestingly, driving without any distraction but with a false activation is assessed on the same criticality level as driving exclusively distracted by a visual-motor secondary task – of course this finding is based on driving situations investigated in this study only. Referring to Sect. 29.2.2, a distraction mostly interfering with the driving task itself should also have the greatest impact on controllability. This indicates a very critical interference of secondary task with a visual and motor component on controllability's assessment. Based on these findings and effects in the drivers' steering performance, we suggest to consider mainly secondary tasks containing visual and motor components when an evaluation of the influence of driver distraction in controllability validations seems to be necessary. Further research is required to investigate the influence of combined secondary tasks, such as visual-motor tasks with higher cognitive demands.

In terms of the objectively measured steering behaviour we identified two possible scenarios in which driver distraction could be considered for controllability aspects: The time immediately prior to a false activation, describing the initial situation in which a false activation could occur as well as the event of a false activation per se. For the first scenario (the initial situation) our results of the yaw angle indicated a significant decrease in driver's steering performance when they were distracted by a visual-motor or a cognitive-auditory task. This confirmed our hypothesis and revealed a possibly disadvantageous initial situation prior to a false activation. Additionally, it corresponded with the results of the workload assessment. Regarding a possible influence of driver distraction on the maximum lateral acceleration in the second scenario (the phase within a false activation), we distinguished between the consequences of the false activation and compensational reaction of the driver, causing two maxima in the lateral acceleration. The results did not indicate statistically significant differences between attentive and distracted drivers. This outcome was also confirmed by the results of maximum yaw rate. Additionally, all yaw rates did not exceed the yaw rate criteria defined by Neukum, Ufer, Paulig, and Krüger [21]. Following this, we were able to assume a consistent oversteering behaviour of the participants. We could not find any impact of driver distraction on the ability to control the false activation, at least for the underlying system design of the false activation. In general, we did not find much support for a connection between subjective and objective data at all. Although the secondary task did not lead to a significant decrease in objective driving performance, higher criticality ratings were observed which indicates that drivers perceived the situation to be more critical.

In controllability research it is quite difficult to decide whether a false-positive event should be presented to participants more than once a time. Maintaining the unpredictability of false activations may cause an inefficiency of experimental designs. Because effect sizes are often unknown, the sample size needed for a between design rapidly increases. This study was able to distinguish between the first and following contacts with false activations. In subjective as well as in objective data, there was no valid hint of habituation to the occurrence of a steering torque which was, on average, in every fourth lap. However, we suppose that other factors, e. g. the credibility of the cover story, explicit participants' instructions and of course the whole experimental setting with its system design and a comparable secondary task difficulty could have an impact on drivers' perception and their expectation. Nonetheless, the standardised secondary tasks we used turned out to be able to ensure comparability in task difficulty.

Additionally, it has to be considered that all results relied on the specific system design of the false activation and cannot be generalized for other system designs. E. g. we used an additional steering torque, according to Sect. 29.3.1.1. Furthermore, the results are only valid for driver's perception and reaction to a false-positive event. Therefore, it is necessary to examine the controllability and safety in use in a use-case while considering driver distraction. Finally it should be mentioned that this study contained controllability questions in a manual driving task. Controllability research of automated driving functions in case of driver's unavailability is another important field of research in the near future.

29.3.2 Case Study II

The results of the first study did not indicate an effect of driver distraction on controllability in case of false activations of steering torque overlays with an amplitude of 3 Nm. However, the question still remains how driver distraction affects the driver's behaviour in case of false activations of steering interventions of a potential collision avoidance system. To date most studies which featured unjustified steering interventions focused on attentive drivers (e. g. [22–27]) and thereby might overestimate the driver's ability to handle a false activation. Additionally, the influence of additional warnings prior to a steering intervention is still unclear. Warnings prior to a steering intervention might not just improve the driver reaction to justified steering interventions as indicated by [28–30] but also the driver reaction to false activations (see also Chap. 27). Especially distracted drivers might benefit from additional warnings as the warning could help to reduce the driver reaction time to false activations. However, using additional stimuli could also have detrimental effects by increasing the driver's workload or attracting too much of the driver's attention.

29.3.2.1 Study Design

To analyse the influence of driver distraction and warnings prior to a false activation a between-subjects study design with two experimental factors was chosen. The study was conducted in the dynamic driving simulator of the WIVW GmbH (Wuerzburg Institute

Table 29.1 Overview of the experimental groups

Group	Audio-visual warning	Distraction
No warning (att)	No	No
No warning (dist)	No	Yes
Audio-visual (att)	Yes	No
Audio-visual (dist)	Yes	Yes

for Traffic Sciences). Driver distraction (attentive drivers vs. distracted drivers) and the occurrence of an audio-visual warning prior to the false activation were varied resulting in four experimental groups (see Table 29.1).

To distract the drivers they were repeatedly confronted with a rapid serial visual presentation (RSVP) as a secondary task. Each task lasted for approximately 20 s and was only started at straight sections of the test track approximately 10 s prior to the intervention. This was done to ensure the drivers were distracted at the onset of the unjustified steering intervention. The drivers were instructed to press a button with the right hand if an arbitrary number appeared on the display. Letters were used as distractors (Fig. 29.9). As a consequence of performing the secondary task, drivers had only one hand on the steering

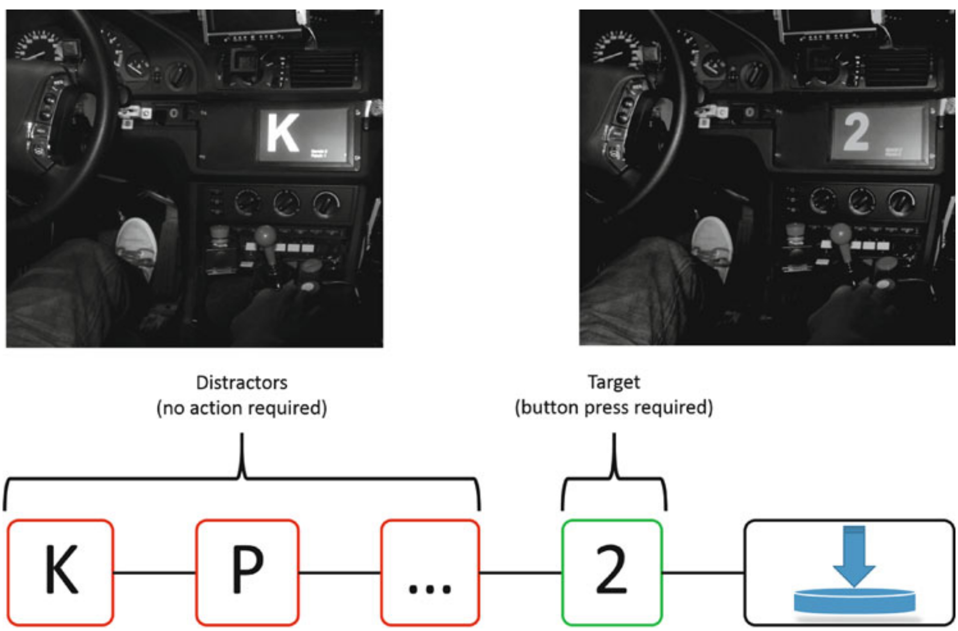

Fig. 29.9 Illustration of the rapid serial visual presentation (RSVP) task used to distract the drivers in our study. Letters were used as distractors whereas numbers were used as targets. Drivers were instructed to press a button with the right hand if a number appeared on the display

Fig. 29.10 Illustration of the visual warning used in the study

wheel at the beginning of the intervention, whereas drivers who were not distracted had both hands on the steering wheel.

The visual-acoustic warning was a combination of a simulated Head Up Display and a sine wave with a frequency of 1200 Hz which was applied for 500 ms. The visual warning was shown until the end of the steering intervention. It projected the aspired steering trajectory of the steering intervention on the street. Additionally, a small warning triangle was displayed at a fixed position (Fig. 29.10). The warning was presented at a TTC of 1.6 s and 400 ms prior to the steering intervention which started at a TTC of 1.2 s.

The false activation was implemented as a predefined sinusoidal course of the steering wheel angle, which was applied to the steering wheel with a maximum torque of 6 Nm. The maximum steering wheel angle was 75°. This resulted in a lateral offset of approximately 1.75 m (without interference of the driver).

29.3.2.2 Results

The results focus on the driver's steering behaviour and the resulting vehicle movement. The analysis of the driver's steering behaviour is based on the steering wheel angle, whereas the analysis of the vehicle movement is based on the lateral offset of the vehicle. The failure induced yaw rate was neglected for the analysis as it cannot be compared to the yaw rates reported in the first study (s. Sect. 29.3.1.2). The assessment of the controllability is primarily based on the resulting lateral offset as it offers an intuitive measure in terms of a possible lane departure. However, research indicates that the observed lateral offset depends on the design of the test scenario and the available space (Chap. 27).

Steering Behaviour

Distracted drivers who did not receive a warning showed greater maximum steering wheel angles compared to drivers who were not distracted ($m_{\text{no warning (att)}} = 34.11°$;

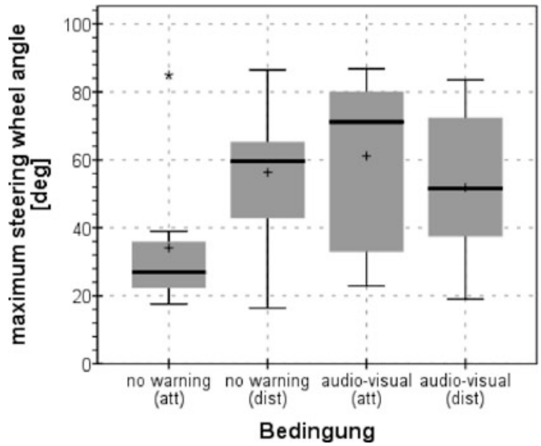

Fig. 29.11 Boxplot of the maximum steering wheel angle dependent on the experimental group

$m_{\text{no warning (dist)}} = 56.34°$; s. Fig. 29.11). For drivers who received a warning prior to the unjustified intervention, no significant difference was observed ($m_{\text{audio-visual (att)}} = 61.15°$; $m_{\text{audio visual (dist)}} = 51.90°$). Contrary to the expected benefit of an additional warning, higher steering wheel angles were observed for drivers who received a warning prior to the false activation.

A classification based on the steering behaviour to identify drivers who suppressed the false activation reflected these results (Fig. 29.12). In the condition without a warning 88% of the undistracted drivers were classified as suppressing false activation, whereas only 31% of the distracted drivers were classified accordingly. For drivers in the experimental groups, which received a warning, almost no difference was observed. In the undistracted group 40% of the drivers and 31% in the distracted group were classified as suppressing the intervention.

The time of the first maximum steering wheel angle did not differ significantly between the experimental groups ($m_{\text{no warning (att)}} = 0.51$ s; $m_{\text{no warning (dist)}} = 0.60$ s; $m_{\text{audio-visual (att)}} =$

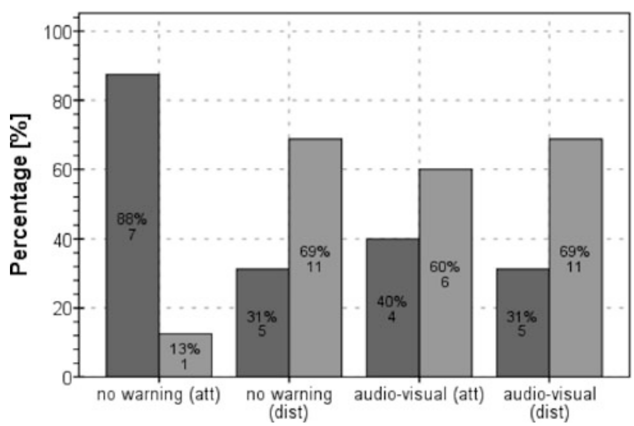

Fig. 29.12 Frequencies of drivers who were classified as suppressing the intervention (*dark grey*) or not (*light grey*)

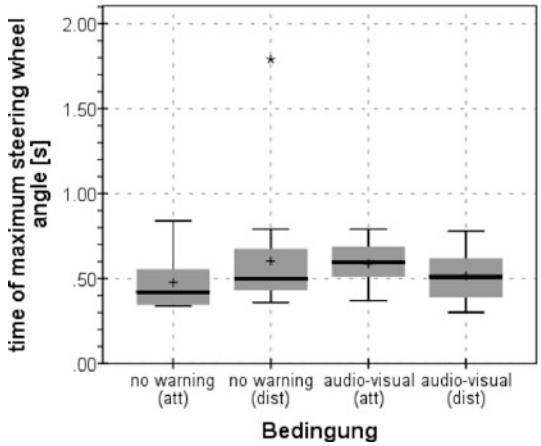

Fig. 29.13 Boxplot of the time the first maximum steering wheel angle occurred after the onset of the false activation of the steering intervention ($t = 0$)

0.59 s; $m_{\text{audio visual (dist)}} = 0.52$ s) indicating that all drivers, whether being distracted or not as well as being warned or not, needed the same time to react to the false activation (s. Fig. 29.13).

Lateral Offset

Descriptive measures show slight differences (s Fig. 29.14). However, no statistical significant differences were observed ($m_{\text{no warning (att)}} = 0.51$ m and $m_{\text{no warning (dist)}} = 0.70$ m; $m_{\text{audio-visual (att)}} = 0.67$ m and $m_{\text{audio visual (dist)}} = 0.76$ m). Almost all drivers were able to reduce the maximum lateral offset compared to the target offset (1.75 m) of the intervention.

However, a classification based on whether the drivers left their own driving lane (lane width 3.5 m), as a consequence of the false activation, showed slightly higher frequencies

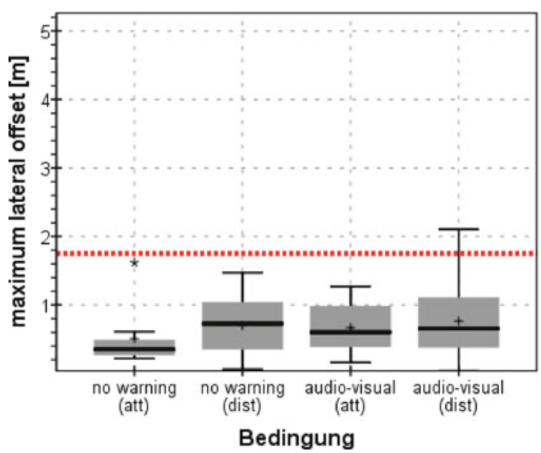

Fig. 29.14 Boxplot of the maximum lateral offset as a consequence of the false activation. The *red line* depicts the target offset of the false activation (1.75 m)

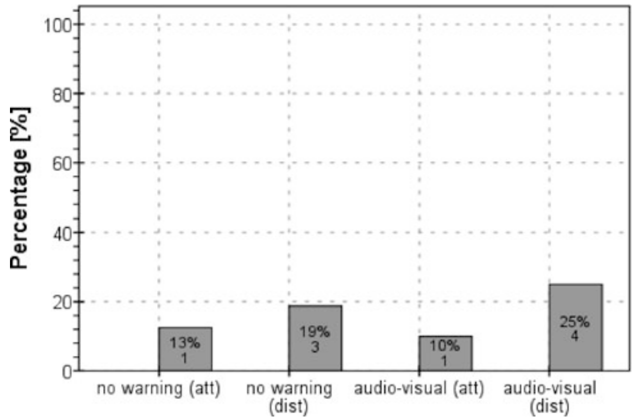

Fig. 29.15 Frequency of drivers who were classified as leaving their own driving lane as a consequence of the false activation

for distracted drivers (19%–25%) compared to drivers who were not distracted (10%–13% s. Fig. 29.15).

29.3.2.3 Discussion

At first sight the results seem to suggest that distracted drivers perform worse than undistracted drivers when being confronted with a false activation of a steering intervention. However, this is only the case for drivers who did not receive a warning prior to false activation. When drivers received a warning prior to a false activation, almost no differences were found. Contrary to the expected benefit of the warning, the audio-visual warning prior to the false activation leads to higher maximum steering wheel angles and fewer drivers were classified as suppressing the intervention compared to drivers who did not receive a warning. For attentive drivers warnings not seem to improve controllability. However, the observed steering behaviour indicates that distracted drivers might slightly benefit from the warning although this interpretation is based only on descriptive tendencies making a meaningful recommendation impossible.

The observed differences between the distracted and undistracted drivers who did not receive a warning might not be the result of the visual distraction of the secondary task but of the hand positioning on the steering wheel. Distracted drivers had only one hand on the steering wheel whereas attentive drivers had both hands on the steering wheel. Although researchers assessing the controllability of false activations of steering torques instructed drivers to use only one hand on the steering wheel [26], no systematic comparison of the effects of one and two handed driving has been reported to date. However, this systematic comparison is needed to distinguish the influence of the driver distraction from the influence of the hand positioning on the steering wheel and to give a recommendation whether driver distraction should be considered in the controllability assessment of emergency steering and evasion assistants.

29.4 Conclusion

The aim of the present case studies was to find indications whether future controllability validations should take driver distraction into account as an additional requirement. In case of a false activation typical behavioural patterns can be observed. It is possible to distinguish between two temporal phases describing the drivers' reaction (see also Chap. 27 and Chap. 28): The first phase is a compensatory reaction of the driver triggered by the haptic feedback on the steering wheel. In the second phase the reaction pattern is dominated by the driver's intention (which might be a continuation of the compensation as well as a compliant reaction with the intervention or something in between). After the first compensatory reaction of the driver it is very likely that the driver has already regained the control over the vehicle's lateral guidance. Therefore, we focused on investigating the influence of driver distraction on the first phase. In case study I (s. Sect. 29.3.1.2) we could not find significant influences of distraction on maximum yaw rate or lateral acceleration. Also, the intensity between the first reaction of the drivers and their following compensation did not differ significantly between the different distraction's conditions. Besides a possible effect of distraction to intensity of the drivers' reaction in the first phase, we investigated the reaction times in case study II (s. Sect. 29.3.2.2). Especially due to the decreased situation awareness and the additional workload, a distraction of the drivers could lead to longer reaction times in case of false activation of an emergency steering and evasion assistant. In the second case study – in contrast to the first case study – participants show higher maximum steering wheel angles under distraction in comparison to attentive drivers (without a warning). However, the measured point of time for maximum steering wheel angle did not differ between attentive and distracted drivers. It is very likely that this effect was not caused by distraction but rather by the different hand positioning between the experimental groups in the second case study (one handed against two handed driving), because driver distraction had no effect on the drivers' reaction in the first case study. Therefore, we suggest to investigate the role of hand positioning in further studies. Additionally, we propose to focus on one handed driving when evaluating the controllability of false activations of steering interventions based on a steer torque actuator like electronic power steering (EPS).

Although we did not find significant evidence for an effect of driver distraction on objective driving performance, participants assessed the criticality of the situation in case of a false activation significantly higher when being distracted. This finding underlines the importance of assessing both objective driving data and subjective perception of drivers.

Besides the consequences of a false activation it has to be considered that the initial situation prior to a false alarm could be influenced by driver distraction. The first case study shows that steering quality can be decreased by driver distraction (higher amplitudes of steering) and could therefore indirectly increase the criticality of a subsequent false activation (e. g. by driving near the road boundaries or other obstacles). These findings correspond with studies in both the simulator environment (e. g. [31] or [32]) and also in field tests (e. g. [33]).

Using standardised secondary tasks in controllability research has many advantages, e. g. high methodological controllability and adaptable task difficulty which could be shown in both case studies. Especially the possibility to create similar task difficulties should be considered when a comparison of different tasks' modalities is required. However, we did not find evidence for an effect of driver distraction on the controllability of false activations of a steering intervention. Nonetheless, driver distraction might gain greater value especially in the use case when drivers have to decide what they should do after their initial motor triggered compensation reaction. Especially visually distracted drivers might take longer to assess the situation in a use case and adapt their behaviour accordingly. This could be important for the design of an override detection mechanism, as it could increase the failure rate when drivers are distracted and show a delayed reaction. Additionally further studies should verify whether visual-motor tasks really have a stronger effect on the drivers' steering task compared to cognitive-auditory tasks [32]. Nonetheless, in order to receive reliable and comparable results, we recommend to implement standardised secondary tasks, with a focus on visual motor tasks when trying to further analyse the influence of driver distraction on controllability in the context of emergency steering functions.

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