Lecture Notes in Mobility

Carolin Zachäus
Gereon Meyer *Editors*

Intelligent System Solutions for Auto Mobility and Beyond

Advanced Microsystems for Automotive Applications 2020

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Lecture Notes in Mobility

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Preface

The road transport sector is changing rapidly. The transformation of the automobile from autarkic cars to intelligent and connected systems is meeting more individual users' needs, improving transport safety and decreasing the environmental impact. Therefore, policy frameworks for sustainable and smart mobility like the European Green Deal are promoting automated and connected multimodal mobility, extending digitalization and bringing technical, legal, economic, human-centred and societal aspects together within co-creation processes.

Smart electronic components, modules, and architectures and their integration into networks of power, data and services are key to enable the auto-mobility of the future. Respective solutions are essential for road vehicle automation, electrification as well as car sharing concepts. Moreover, embedded software, (artificial) intelligence as well as intelligent mobility systems, smart traffic management and data availability are critical to integrate cars into the mobility system and to address the strong diversification of end-user applications.

Beside technological innovation and disruption, changes of human behaviour are necessary to meet sustainability goals. Furthermore, future mobility trends need to be re-evaluated and new concepts for urban mobility beyond the automobile need to be established within a human-centred approach, leading to an integration of technical as well as user-oriented aspects.

However, the overall transformation towards a clean, connected, automated and shared mobility is currently facing new challenges. Beside the paradigm shift to a multimodal use of individual and shared traffic in combination with public transport, the pandemic crisis will result in new user demands from automotive and mobility companies in the short term. It has already been shown that COVID-19 is leading to a rising usage of private cars as well as active and micromobility solutions such as e-bikes and e-scooters, which is making a shift towards shared economy difficult. Therefore, new concepts, e.g. with respect to disinfecting solutions and additional safety measures, have been and will further be discussed.

On the other hand, every challenge also brings great potential to accelerate change. New technological approaches especially with respect to automation will likely experience wider acceptance within society. Advantages of robotaxis are becoming more recognized and may result in a boost for these products and services and further push respective technology developments. Furthermore, automated delivery robots have great potential.

With respect to the current health, but also in view of the ongoing climate crisis, an integral understanding of user-centric, clean, connected, automated and shared mobility as a system is needed to better address technological, societal and political challenges and to achieve an inclusive, sustainable and seamless mobility system.

The International Forum on Advanced Microsystems for Automotive Applications (AMAA) has been exploring the technological foundations of electrified, connected and automated vehicles for many years. Consequently, the topic of the 23rd edition of AMAA, held virtually in Berlin on 26–27 May 2020, has been "Intelligent System Solutions for Auto-Mobility and Beyond". The scope of the conference and, thus, the book has broadened beyond the automobile, during the last years. Besides the traditional technological topics such as smart sensors, connectivity, intelligence as well as safety, security and validation, and electrification, a systemic view on intelligent mobility systems as well as human factors and policy strategies has become more relevant. The AMAA organizers, VDI/VDE Innovation + Technik GmbH together with the European Technology Platform on Smart Systems Integration (EPoSS) and the ECA2030 event series of the Mobility.E Lighthouse of the ECSEL Joint Undertaking, greatly acknowledge the support given for this conference.

Leading engineers and researchers who have participated in the AMAA 2020 wrote the papers in this book, a volume of the Lecture Notes in Mobility book series by Springer. The paper proposals were peer reviewed by the members of the AMAA Steering Committee. As the organizers and the chairpersons of the AMAA 2020, we would like to express our great appreciation to all the authors for their high-quality contributions to the conference and especially to this book. We would also like to acknowledge the support we have received from our colleagues at VDI/VDE-IT.

October 2020

Carolin Zachäus
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Vehicle Localization Using Infrastructure Sensing

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Abstract. Infrastructure supported autonomous driving is getting in the focus of current research. In this work, we investigated the usage of a traffic monitoring infrastructure combined with the environmental model of an autonomous driving vehicle for localization. The forwarded environmental model of the infrastructure contains tracked road users, but the used tracking algorithm is unknown. The result is based on a two-stage transformation process with optimized fusion and tracking by a Kalman filter. Experiments show, that the algorithm provides a consistent localization at the first time step.

Keywords: Localization · Infrastructure sensors · Intelligent vehicles · MEC-View project · Roadside sensors · MEC-Server · Automated driving · Information fusion · Kalman filter · Pose estimation · Optimized fusion

1 Introduction

Automation of vehicles towards fully autonomous driving (AD) has made great progress in the recent years by relying on onboard sensors for localization [1], most of the time coupled with satellite-based global positioning [2]. Besides further improvements by using these ego-centered approaches, usage of roadside-mounted infrastructure sensors offers great potential not only for cooperative perception [3], but also as a means for robust vehicle localization. This is of special importance for areas with cluttered GNSS reception, e.g. due to multipath effects. In addition, as has been noted by others [4], an increased number of orthogonal information sources for localization is vital for self-observation of vehicle localization systems as key component for future AD.

In this work, we present an approach for robust vehicle localization based on infrastructure sensors and centralized information fusion using the Multi-Access Edge Computing (MEC) paradigm for cellular radio [5] as presented in the project MEC-View [6]. In MEC-View, use of infrastructure supported AD is investigated. Limitations of the onboard sensor field of view are dealt with through infrastructure sensors enlarging the observed space. Infrastructure sensor data is processed in a central entity (termed MEC-Server). The result of the centralized fusion in the MEC-Server is a centrally

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computed environment model of the observed areas in form of a list of objects (termed MEC objects). This object list is distributed to all AD vehicles in the proximity using a simple geocasting mechanism [7] and acts as means for localization in our approach. The overall system layout of the MEC-View project is depicted in Fig. 1.

By leveraging the globally referenced coordinate system of MEC objects, we can robustly determine the global ego position without the need for GNSS reception, previously stored static localization features or additional beacons [8]. In our system, all data needed for global localization is available and computed online. Thus, our approach is not susceptible to serious errors like aging of information stored in the digital map [9].

The remainder of this paper is structured as follows. First, we review the current state of the art in vehicle localization. In Sect. 3, we present our proposed system, followed by real-world experiments, which validate the presented concepts. Lastly, conclusions and future research directions are drawn.

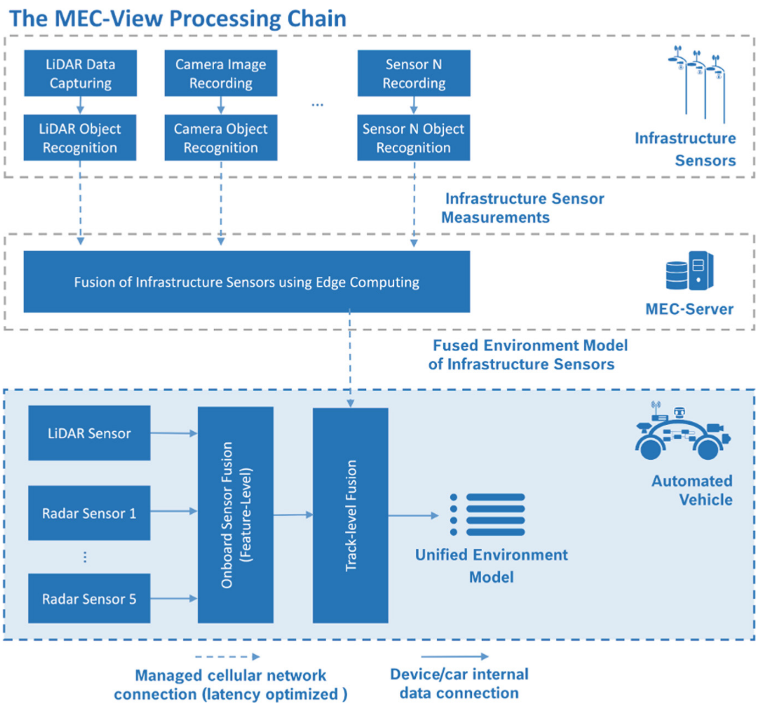

Fig. 1. System overview over the MEC-View processing chain.

2 Related Work

In this section, we provide an overview over the related work, covering vehicle localization, data fusion and cross-correlation estimation. Localization has been investigated a lot in the past and new publications are released regularly. In [10, 11] and [12] researchers deal with the simultaneous localization and mapping (SLAM) [13] problem. Used methods are i.e. graph based [14], grid based [15] or the Monte Carlo localization [16] to tackle the problem. The approaches use raw measurements or features without cross-correlation of static objects. So the problem of dynamic features with unknown cross-correlation has not been addressed in these publications. Roy et al. presented a localization in dynamic environments [17], but these dynamic features are identified and excluded by the algorithm.

The fusing of contradictory information has long been the subject of various investigations. Allig and Wanielik [18] present a possible solution for heterogeneous track-to-track-fusion. Non-linearity's are tackled by the unscented transformation. By using equivalent measurement only the new information of the recent time step is used, thereby cross-correlation is considered. However, the information gain can only be calculated by detailed knowledge of the local tracking algorithm. Nevertheless, this information is not available in this problem definition. The infrastructure only provides the estimated state and the estimated accuracy. Ellipsoidal Intersection, presented by Wu et al. [19], does not need any information about the used tracking algorithms. It computes the largest ellipse inside the cross-section of two covariance ellipses by optimization. Since it is limited to two estimations, it does not apply in this paper, since the number of estimations varies.

In his publication [20] Bar-Shalom shows how to compute the cross-correlation of two-tracks. This information is valuable, since the optimal fusion of two estimates is possible. However, there are requirements that both tracks are done with the same system dynamic and the Kalman gain matrices must be known. Since our problem does not fulfill these requirements, we had to find another solution to the problem.

3 Vehicle Localization Using Dynamic Objects

In this section, we present a solution to localize a vehicle based on poses of tracked dynamic objects with unknown cross-correlations. There is no information about the used tracking algorithms, but a normal distribution is assumed. As an input, the algorithm gets two object lists: The first list is forwarded to the vehicle by the infrastructure containing the tracked poses of the road users, including the pose of the ego-vehicle, called features. The second contains the tracked poses by the vehicle itself, called measurements. The corresponding features and measurements are already matched by the perception system using additional dimension, such as velocity and size of the objects. Please refer to [3] for details.

Next, the developed algorithm is outlined to give a short overview before we get into detail.

3.1 System Overview

Figure 2 provides an overview of the overall system. On the left side, the determination of the ego pose based on the information of the vehicle perception, the infrastructure sensors and the inertial measurement unit of the vehicle is shown. First, the global orientation is calculated to keep the error propagation low. This is done by fusing the transformed orientations with the predicted one and the ego-feature orientation. Followed by the transformation of the poses using the predicated ego-orientation. The fusion of the transformed poses with the pose from the first-person feature results in the optimized pose, used as an update in the Kalman filter. The filter predicts the pose into the next time step supported by the inertial measurement of the acceleration and angular velocity of the ego-vehicle. Thus, past states are also included and supported with a-priori knowledge.

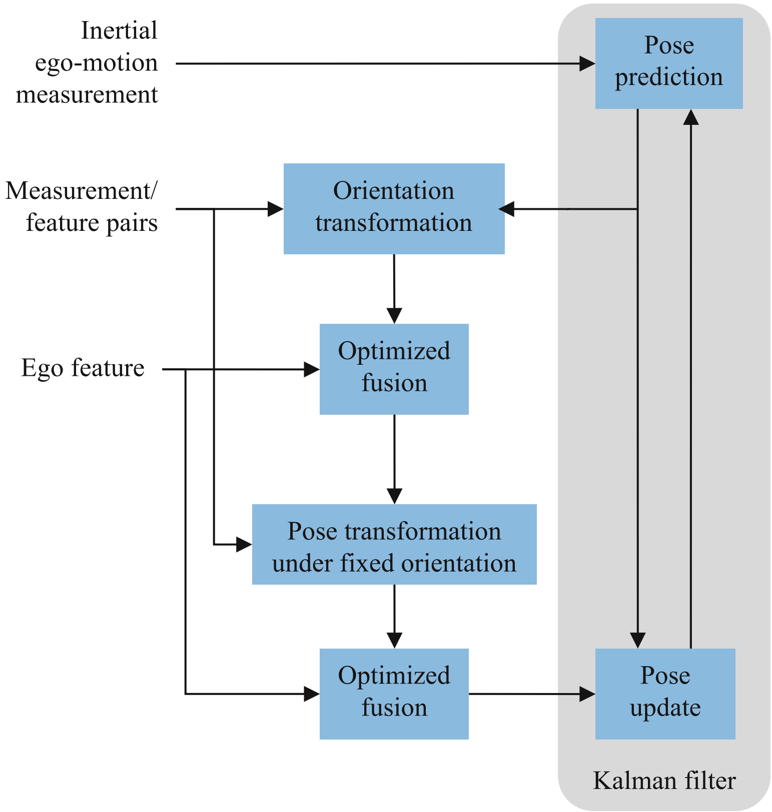

Fig. 2. System overview of the localization algorithm.

3.2 Pose Transformation

It is possible to obtain the ego-pose based on a single measurement/feature-pair. Therefore, we define the measured variables, represented in Fig. 3. A pose is composed of the two spatial dimensions and one orientation. The infrastructure sensors track the road-user poses in the global coordinate system. They are represented with the index F. The ego-vehicle tracks in the vehicle frame, represented with index M.

The global orientation of the ego-vehicle $\tilde{\varphi}$ is determined by the angle between the orientations in the global and local coordinate system of the road user. Following, the global position of the ego-vehicle is provided by shifting the global position of the road

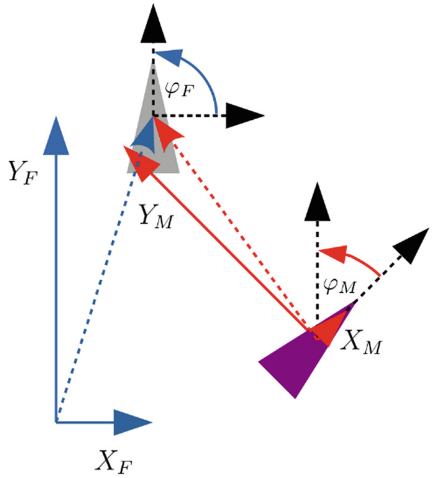

Fig. 3. Measurement definition: In this example, the gray road user is measured by the infrastructure in the global coordinate system (blue). The purple ego-vehicle measures the road user in the vehicle frame (red).

user along the relative measurement in the global frame. The relative measurement is depicted as the red dotted line in Fig. 3. For the correct shift, the relative measurement is rotated using the global ego-orientation. The entire transformation is therefore:

$$\tilde{\mathbf{x}}\begin{pmatrix} x_F \\ y_F \\ \varphi_F \\ x_M \\ y_M \\ \varphi_M \end{pmatrix} = \begin{pmatrix} x_F - \cos(\varphi_F - \varphi_M)x_M + \sin(\varphi_F - \varphi_M)y_M \\ y_F - \sin(\varphi_F - \varphi_M)x_M - \cos(\varphi_F - \varphi_M)y_M \\ \varphi_F - \varphi_M \end{pmatrix} := \begin{pmatrix} \tilde{x} \\ \tilde{y} \\ \tilde{\varphi} \end{pmatrix}$$

The transformation is non-linear due to the sine and cosine functions. For this reason, the transformed positions are dependent on the global orientation. As a consequence, the accuracy of the positions strongly depends on the accuracy of the calculated ego-orientation. If the calculated orientation is incorrect, the shift along the relative measurement will also be incorrect and the impact is bigger with greater distances. Therefore, the error of the orientation is propagated into the position.

To minimize the error propagation and the non-linearity we calculate the ego-orientation at first. If there are several measurement/feature-pairs, there is the possibility to minimize the error by fusing the resulting orientations of each pair together. Since the error propagates in one direction only, it is possible to avoid expensive methods like errors-in-variables models [21]. Split in two steps, the orientation and pose calculations are:

$$\tilde{\varphi} = \varphi_F - \varphi_M$$

$$\tilde{\mathbf{x}}\begin{pmatrix} x_F \\ y_F \\ x_M \\ y_M \\ \tilde{\varphi} \end{pmatrix} = \begin{pmatrix} x_F - \cos(\tilde{\varphi})x_M + \sin(\tilde{\varphi})y_M \\ y_F - \sin(\tilde{\varphi})x_M - \cos(\tilde{\varphi})y_M \\ \tilde{\varphi} \end{pmatrix} := \begin{pmatrix} \tilde{x} \\ \tilde{y} \\ \tilde{\varphi} \end{pmatrix}$$

With the resulting variances:

$$\sigma_{\tilde{\varphi}}^2 = \sigma_{\varphi_F}^2 + \sigma_{\varphi_M}^2$$

$$\mathbf{P}_{\tilde{\mathbf{x}}} = \mathbf{J}_{\tilde{\mathbf{x}}}\widehat{\mathbf{P}}_{\tilde{\mathbf{x}}}\mathbf{J}_{\tilde{\mathbf{x}}}^T$$

Using the linearization:

$$\tilde{\mathbf{J}}\begin{pmatrix} x_F \\ y_F \\ x_M \\ y_M \\ \tilde{\varphi} \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\cos(\tilde{\varphi}) & \sin(\tilde{\varphi}) & \sin(\tilde{\varphi})x_M + \cos(\tilde{\varphi})y_M \\ 0 & 1 & -\sin(\tilde{\varphi}) & -\cos(\tilde{\varphi}) & -\cos(\tilde{\varphi})x_M + \sin(\tilde{\varphi})y_M \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

3.3 Pose Fusion

The Covariance Intersection (CI) [22] allows fusion of contradictory information under unknown covariance. The result of CI fusion is suboptimal, but it provides an upper limit of error estimation and the result is consistent. Furthermore, the merged error-covariance matrix is always symmetric and positive-definite. The constraints are that the fusion weights **w** add up to one and each individual weight must lie within an interval of zero and one.

The optimal fusion weights can be found by optimization. We use sequential quadratic programming (SQP) [23], since the objective function and the constraints are twice continuously differentiable. The resulting orientation variance, resp. the determinant of the pose covariance is the objective function to be minimized. The resulting objective functions for the two different fusion steps are:

$$f_1(\mathbf{w}) = \left(\sum_{k=1}^{N} w_k \sigma_k^{-2}\right)^{-1}$$

$$f_2(\mathbf{w}) = \det\left[\left(\sum_{k=1}^{N} w_k \mathbf{P}_k^{-1}\right)^{-1}\right]$$

Since these are angles to be fused, the periodic space must be taken into account.

3.4 Optimized Pose Tracking

To include additional information in the localization, the vehicle's own pose is tracked. Thus, past estimates, the known vehicle dynamics and measurements of the inertial measurement unit (IMU) are included in addition to the transformed and fused poses. For this purpose, the Kalman filter [24] is used in this paper. We chose constant velocity as the dynamic model. The observation- and the state-space are the same, so there are no linearizations needed.

4 Experiments and Results

To evaluate the performance of the algorithm we tested it with simulated data and real-world data, gathered by the infrastructure of the MEC-View project.

4.1 Simulated Tracks

To generate the simulation data, two-dimensional trajectories in the global coordinate system were created using a map of the test crossing. In practice, often not more than three other road users are perceivable, as the others are hidden by buildings or by vehicles in front or behind the ego-vehicle, therefore the simulation is limited to four road users. The road users start at different points and enter the intersection at different times. They obey given right-of-way rules and behave according to the permitted speeds and possible vehicle dynamics. The speed is not constant, but is subject to fluctuations in order to simulate natural driving behavior.

The infrastructure uses cameras and LiDAR sensors to determine the poses of vehicles in the intersection area. In contrast to the infrastructure, the vehicle is additionally equipped with radar sensors and can thus measure the radial relative speed of other road users. The simulator transforms the reference trajectories of the road users observed by the ego-vehicle into the ego coordinate system to generate the ideal measurements of the ego-vehicle. To generate artificial measurements, the simulator adds a zero-mean, normally distributed noise to the ideal conditions. The standard deviations are listed in Table 1. The accuracy is distance independent. There are no objects that restrict the view. For the ego-vehicle an inertial measurement unit is additionally simulated. The simulated measurement noise of the infrastructure and the vehicle sensors differ, since we expect the infrastructure sensors to be cheaper than those installed in the vehicle. The standard deviations are listed in Table 1. The simulated measurements are tracked by a Kalman filter under assumption of a constant velocity model.

The simulation reveals a stable localization after the Kalman filter has settled. The filter does not diverge and the results of the estimation are consistent. The result of the localization of the simulated scene is shown in Table 2. It shows, that the calculated ego poses, obtained by transforming the measurement/feature-pairs, before fusion are inaccurate in relation to the ego feature. Although, the information can increase the accuracy of the ego-pose estimation. In detail, during the simulation the fusion mainly trusts the ego feature. The reason is the transformation adds a lot of noise to the calculated pose.

Table 1. Standard deviation of the simulated measurements

Dimension	Vehicle	Infrastructure
IMU		
Acceleration	1E-6 m/s^2	
Angular velocity	0.12°/h	
Measurement		
Position	1 m	2 m
Velocity	0.5 m/s	–
Orientation	3°	10°

Table 2. Error statistics of the simulated scene. Ego-feature is the tracked pose of the ego-vehicle by the infrastructure. The transformed poses are calculated by the measurement/feature-pairs of the road users.

	X-Position	Y-Position	Orientation
Ego-feature			
Mean μ	−0.12 m	−0.20 m	7.17E-3 rad
SD σ	0.79 m	0.64 m	62.96E-3 rad
Transformed poses			
Mean μ	0.19 m	10.52E-3 m	4.49E-3 rad
SD σ	5.69 m	3.31 m	73.16E-3 rad
Final result			
Mean μ	−8.74E-3 m	−45.00E-3 m	14.81E-3 rad
SD σ	0.76 m	0.45 m	8.12E-3 rad

4.2 Real-World Data

The real-world data was recorded by the test infrastructure of the MEC-View project. The AD vehicle is also used in the project. For the test scene, four road users are recorded, but not permanently visible during recording. The infrastructure and the vehicle were in an early experimental state during the recording. Table 3 lists the error statistics of the test scene. Figure 4 shows the result as tracks.

It stands out, that the result of the result is less accurate than the ego features at the input. The reason for this is that ego-features were not available at every time step. During the record, there are 3092 IMU measurements and 153 features, thereof 38 ego features. Taking that into account, the algorithm shows a significant improvement.

Table 3 Error statistics of the real-world scene. Ego-feature is the tracked pose of the ego-vehicle by the infrastructure. The transformed poses are calculated by the measurement/feature-pairs of the road users.

	X-Position	Y-Position	Orientation
Ego-feature			
Mean μ	0.68 m	0.60 m	−9.41E-3 rad
SD σ	0.33 m	0.42 m	68.38E-3 rad
Transformed poses			
Mean μ	−0.33 m	1.40 m	−45.33E-3 rad
SD σ	8.62 m	9.42 m	0.12 rad
Final result			
Mean μ	1.48 m	0.31 m	5.29E-3 rad
SD σ	1.28 m	1.16 m	82.46E-3 rad

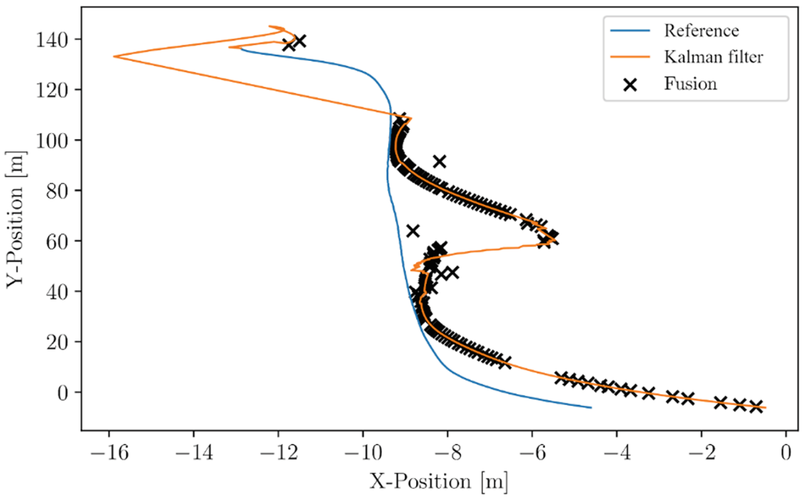

Fig. 4. Localization process with real-world data. Blue: Reference track of the Ego vehicle. Orange: Result of the localization after Kalman filtering. Black: Results of the localization after the fusion of the transformed poses.

In the middle part, the localization drifts away towards the positive x-position. During this time, the orientation of other road users was wrongly estimated. This error gets propagated into the position, see Sect. 3.1. The localization is therefore very sensitive to orientation errors.

Based on the accuracy of the experimental state of the infrastructure, this form of localization is not sufficient to guarantee AD functions. Thus, the test with real-world data confirms the strong dependence of infrastructure-sensor accuracy.

5 Conclusions

The method developed in this paper provides a consistent localization result despite little information about the structure of the infrastructure that the environment model transfers for localization. The environment model consists of tracked, dynamic road users. There is neither knowledge about the algorithms used in the infrastructure nor about possible relationships between the tracks.

The results of the simulation show that the localization algorithm, under the simulated measurement inaccuracies of the infrastructure and the vehicle, has a higher accuracy than the Global Positioning System [25]. Thus, applications using GPS data are possible. The two-stage transformation and fusion provides a significant improvement in the accuracy of the transformed pairs. The simulations show a strong dependence on the accuracy of the infrastructure sensors. Overall, the developed method provides a consistent estimate.

In the future, we plan to investigate the tracking of the ego pose, since the used Kalman filter is a rather simple solution for tracking the ego pose. Using different tracking methods or providing additional information, like wheel speed or steer angle, has the potential to increase the accuracy. In addition, the real-time capability requires attention. The algorithm was implemented in the programming language Python 3, because changes can be implemented and tested quickly. For a test of real-time capability, the implemented methods need to be translated into a high-performance language and tested on the target system. Since the Kalman filter estimates few dimensions, the optimizer will take up most of the computing time. There is potential for runtime improvement.

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Alternative Technologies for V2I Communication

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Abstract. A low cost communication alternative could allow better V2I communications. In this way, the alternative would complement the 5G technology, driving the reliability of the system up. For that purpose, a selection of low cost technologies, which cover a short/middle range, was carried out. Then, theirs capabilities were tested and compared by means of a test-bed, achieving knowledge about theirs strengths and weaknesses. The final goal is to apply the technology in a real proof of concept.

Keywords: Communication technologies · ZigBee · nRF24L01+ · Test-bed · Comparison · WiFi · V2I

1 Introduction

The full integration of V2I (Vehicle to Infrastructure) is the first step to achieve the V2X (Vehicle to Everything) communication on automated cars. It will provide real time road data, which will supplement data from sensors of the vehicle, as can be seen in Fig. 1. To establish network communication, technology with adequate performance is required.

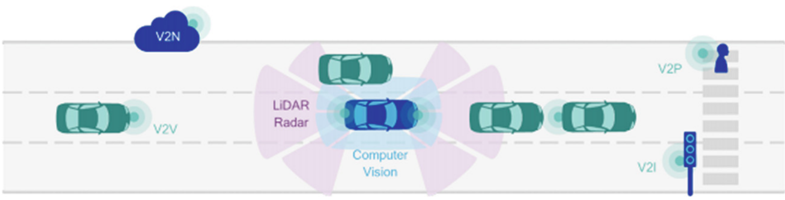

Fig. 1. Performance test

The European community has focused on the use of 5G instead 802.11p, the first one will be the main technology, once it is available. The reasons are its suitable performance for V2X and the reduced cost of its integration because it will use the existing 4G and LTE (Long Term Evolution) infrastructure. However, the cost of both technologies is too high for their broad application.

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In addition to this, possible problems in the operation of the technology or the lack of coverage in some places will be a serious problem, because the vehicle will be uninformed while the problem persists. The solution is a technological redundancy; in this way, two technologies working in parallel would increase the reliability.

The synergy between 5G and 802.11p will be an expensive solution, which could have interference problems. In order to cut down costs and facilitate further synergies, we looked for low cost short/middle range communication technologies, which have adequate performances for V2I communications in real world applications.

Lots of works have analyzed different technologies for V2I communications. Several studies [2–4] contrasted ZigBee with Bluetooth and Ultra-Wideband (UWB), and then carried out a V2I ZigBee prototype. They ensured ZigBee operability for V2I communications, but [3] highlighted that data rate of ZigBee is slower than that of Wi-Fi or Bluetooth technologies. Other works like [5] point out the better performance of nRF24l01+ than ZigBee. In [6], Visible Light Communication (VLC), which is an emergent technology, is analyzed for really short range (until 100 m) in V2I communications.

Previous related work shows the broad range of technologies. For this reason, an own preliminary comparative was carried out in order to make a selection tool of these technologies for this work. In Table 1 only low cost technologies have been compared, which was the first selection criterion.

Table 1. Low cost communication technologies

Technologies[a]	WiFi	LoRa	ZigBee	Z-Wave	Bluetooth	nRF24
Frequency Band	2.4- 5GHz	868 MHz	2.4 GHz	1GHz	2.4 GHz	2.4 GHz
Protocol	802.11 b/g/n/ac	LoRaWan	802.15.4	802.15.4	802.15.1	802.15.4
Data Rate	<867 MB/s	50Kb/s	250Kb/s	100 Kb/s	< 2Mb/s	< 2MB/s
Distance(m)	<1000	<5000	<1000	<30	< 100	<1000
Bus	Embedde d/SPI	USB/SPI	UART	UART	SPI	SPI
Network available[b]	Yes	Yes	Yes	Yes	No	Yes

[a] The colors show if the performance is suitable for our needs. Green= fit, Red= Unfit

[b] Possibilities for a network with more than 1 node, for instance, Point to Multipoint.

The next selection criterion is short/middle range, meaning that technology with a range cover higher than 100 m and a maximum covered range close to 1000 m. Therefore, ZigBee, nRF24 and Wi-Fi were chosen.

- **DIGI XBEE S2C:** Radiofrequency module from DIGI XBee, whose operation protocol is ZigBee, which is inside 802.15.4 radiofrequency protocol. Its technical specifications can be found in [7].

- **nRF24L01+:** Radiofrequency module with an integrated antenna amplifier. It operates inside 802.15.4 radiofrequency protocol. Its technical specifications can be found in [8].
- **WiFi IEEE 802.11 b/g/n:** WiFi module embedded in the Arduino Uno WiFi REV2. The technical specifications of the WiFi module can be found in [9].
- **WiFi IEEE 802.11 b/g/n/ac:** WiFi module embedded in the Raspberry Pi 3B+. The technical specifications of the WiFi module can be found in [10].

These technologies have been tested to have a better knowledge of their performance for V2I. The overall goal of this work is to build a proof of concept for two applications:

- **Variable traffic signs:** The aim is improve traffic flow, benefiting from green cycle of the traffic lights. If this application extends beyond vehicles, it reduces fuel consumption.
- **Variable traffic information:** It will give valuable information, which depends on the user profile or vehicle type. It will increase safety and will upgrade the old and expensive infrastructure, which currently is based on a portico whose message is generic and with no application for the driver.

The rest of this paper will describe the realized test bed (Sect. 2), its results (Sect. 3) and will discuss the results obtained (Sect. 4).

2 Experimental Tests

2.1 Materials

The different technologies work with low cost microprocessors: Raspberry Pi 3B+, Arduino UNO R3 or Arduino UNO WiFi REV2, depending on the technology. Meanwhile, carrying out the test bed, the additional material was a Toyota Auris Hybrid, a fork lift and a ladder of 2 m.

2.2 Tests Background

There is no standard comparison methodology for different communication technologies. For this reason, one was developed within this work. The critical parameters (latency of the messages, repeated messages rate and range covered) to control any V2X communication were highlighted in [11].

The different tests were designed to detail as much information as possible. Thus, the backbone of the tests is based on [12] and [13], where experimental data from 802.11p technologies and C-V2X (Celular- Vehicle to everything) technologies respectively is obtained. Although the main parameters neither are measured nor give a complete behavior of the devices. Thus, this methodology aims to define a comprehensive behavior of the devices, based on real scenarios, allowing a comparison between technologies. To achieve it, a sequence of static and dynamic tests was proposed.

2.3 Tests Bed Description

2.3.1 Screening Test

It was aimed to test the short/middle range, the right operation of the device and right performance for V2I communication.

Devices were separated 20 m and they were kept on with no movement during communication at height of 0.5 m. Latency was gathered during the communication.

After that, another test was carried out, where both devices were separated until the loss of the connection. Therefore, the range was measured.

2.3.2 Performance Test

It took place in the facilities of CIDAUT Foundation in Mojados (Valladolid, Spain). It was aimed to test the performance of the different technologies, analyzing the influence of different factors during communication. The track and the followed procedure is shown in Fig. 2.

Fig. 2. Performance test

The road has a length of 506 m, with enough open space at the beginning and end of the road for accelerating and braking to the desired speed. The OBU (On board Unit) was on the roof of the car, meanwhile the RSU (Road Site Unit) was placed at a fixed point on the road. Each test was set up as a sequence of 6 round trips in different operation conditions, data measurement was taken during the communication:

- Orientation: Different RSU orientation. Type of signal.
- Different speeds: 50, 70 and 90 km/h with the RSU at 2 m.
- Different heights: 50 km/h at a height of 5 and 10 m A Crane was used to lift the RSU

- Different data range: Change the data rate from 1 Mb/s (recommended by the manufacturer) to 250 kb/s and 2 Mb/s.

2.3.3 Obstacle Test

It took place in the facilities of CIDAUT Foundation in the Technological Park of Boecillo (Valladolid, Spain). This test was designed in order to test an operation close to a real case and evaluate obstacles influence. In Fig. 3 the route can be appreciated.

Fig. 3. Obstacle test

The test consisted of 6 consecutive rounds. The RSU kept the same position along the test meanwhile the OBU followed the white line trajectory. The speed of the car was at most 40 km/h, because it was the road limit speed. In the course of the test, the direct line of sight between the OBU and RSU was hindered by building and trees. The influence of obstacles was obtained by comparing results of communication with and without obstacles.

3 Results and Discussion

3.1 Screening Test

In Table 2, there is the main data performance. Latency, which is the needed time until the next message could be send and the range, which is the distance covered by the device.

Table 2 shows that nRF24l01+ performance is defined by a low latency with a broad range. Contrasting with ZigBee, which operates with bigger latency than nRF24L01+, although covers more distance.

The really short range of the WiFi is out of our constraints, so it was no further tested.

Table 2. Devices performance

Comparison of results			
Features	nRF24L01+	XBee (ZigBee)	WiFi b/g/n/ac
Range (m)	600	700	<100
Latency (ms)	40–350	1000–3500	14–100

3.2 Performance Tests

3.2.1 Orientation

6 data measurement were performed for each orientation. The results are displayed in Fig. 4.

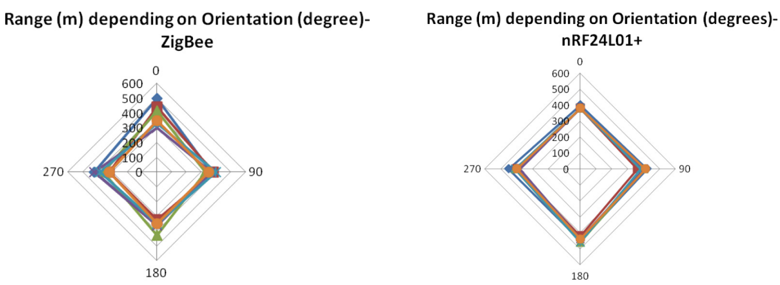

Fig. 4. Orientation results

As can be seen in Fig. 4, each technology covers the same distance regardless of the antenna direction, thus, the antenna is omnidirectional.

3.2.2 Different Speeds

Figures 5 and 6 show where communication begins to become progressively worse, the repeated messages are the points in different colours. There were 6 trips for each speed, 3 go trips and 3 back trips. The beginning of each rehearsal takes place at the RSU (purple panel in the Figures). The repeated messages take place when the car is moving away from the RSU (go trips) or is coming closer to the RSU (back trips). It is marked with a yellow square the distance at which there is a short number of repeated messages, on the right side of this mark, it is likely that the technologies are out of range. On the other hand, in Fig. 7 there is a comprehensive comparison of both technologies with different speeds.

The operational range of both technologies is displayed in Fig. 5 and 6 nRF24L01+ ensured an excellent signal until 200 m, being capable to cover up to 370 m. In contrast, ZigBee ensured 350 m, being capable to operate in a range of 400 m. However, ZigBee sent less messages than nRF24L01+ per second and ZigBee had more repeated messages

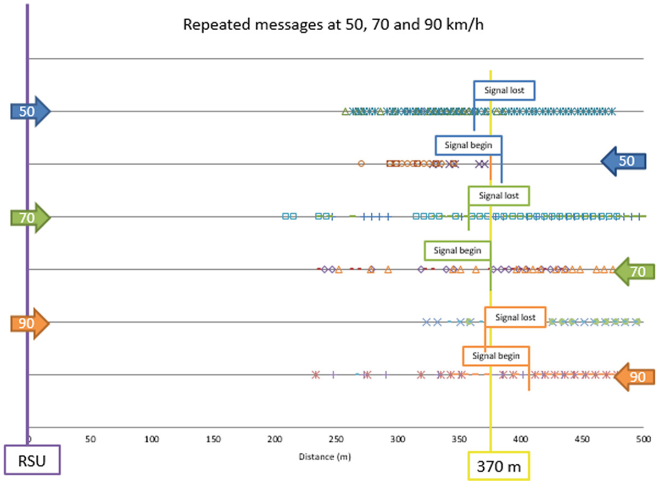

Fig. 5. Repeated messages at different speeds for nRF24L01+

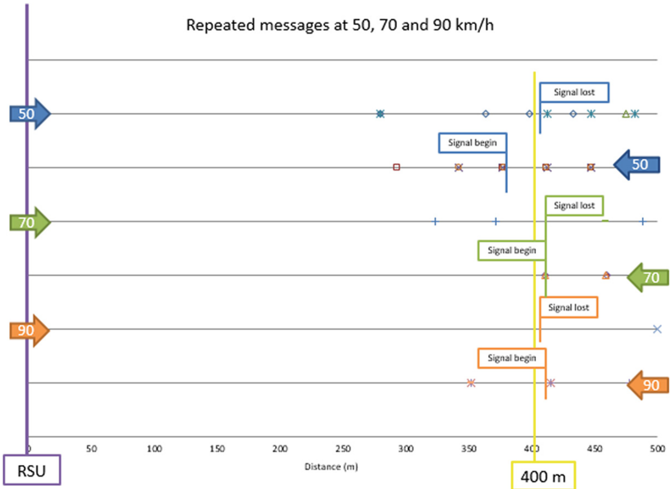

Fig. 6. Repeated messages at different speeds for ZigBee

percentage, as can be seen in Fig. 7. Both technologies offered stable operation with diverse car speed.

The reduction of the repeated messages with the speed in ZigBee (Fig. 7), is related to the fewer time for send messages in the test. Therefore, the speed does not have influence in the performance of the communication technologies. It will let us use the technologies in any kind of road.

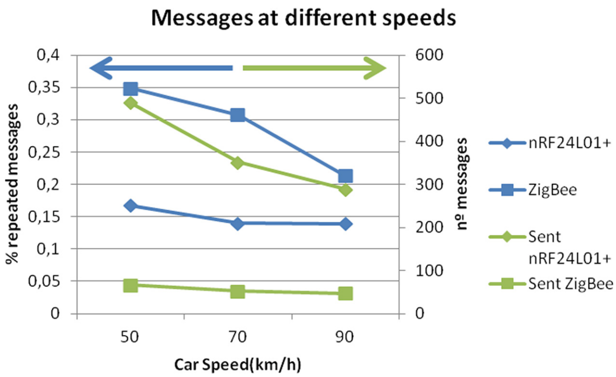

Fig. 7. Repeated messages at different speeds

3.2.3 Different Heights

The following figures show influence of different heights of RSU. The height at 2 m is the same as was used for the data obtained at 50 km/h in the previous Sect. 3.2.2.

At a RSU height of 5 m there was a better performance of both devices. Both devices extended their range, up to 400–450 m for nRF24l01+ and up to 500 m for ZigBee. However, as can be seen in Fig. 8 and 9, it did not longer improve with the height; the case at 10 m had the same results than at 5 m. In addition to this, the repeated messages percentage was cut down around a 15% according to Fig. 10, although it did not enhance in the case at 10 m. Therefore, If the RSU is placed in an elevated location, communication will be much better, reducing interferences.

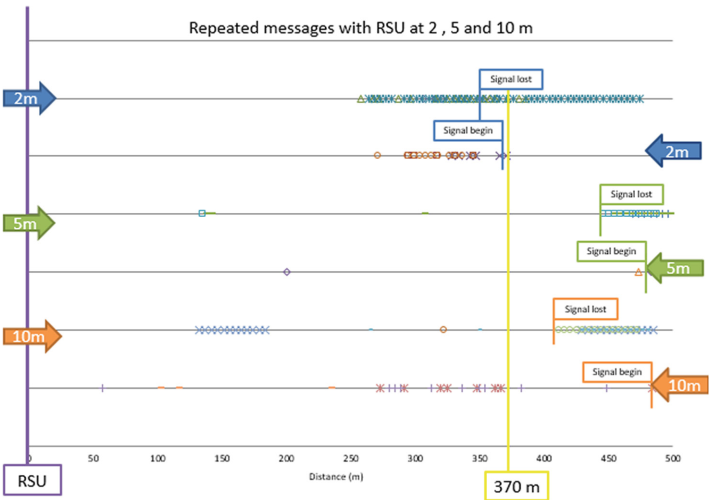

Fig. 8. Repeated messages for different heights of the RSU at 50 km/h for nRF24L01+

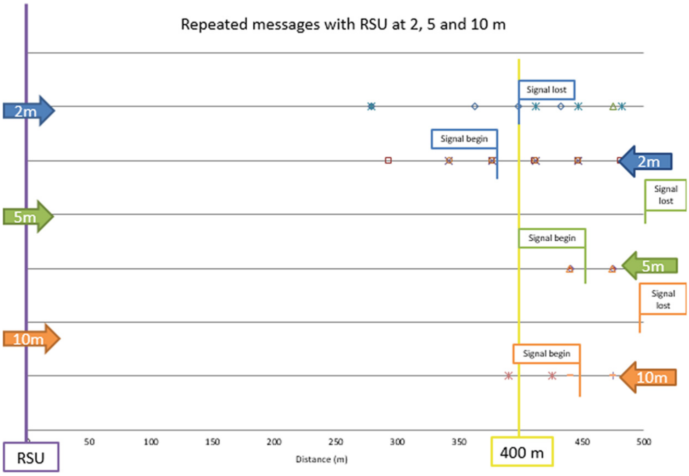

Fig. 9. Repeated messages for different heights of the RSU at 50 km/h for ZigBee

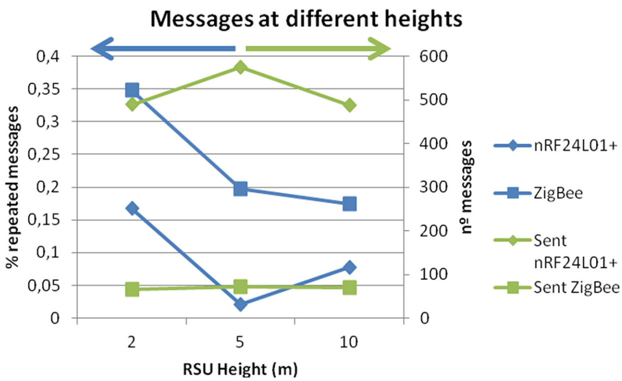

Fig. 10. Repeated messages for different heights of the RSU at 50 km/h

3.2.4 Different Data Range

Only the nRF24L01+ device has the choice of different data range: 250 kb/s, 1 and 2 Mb/s. The measured data in previous sections was made with 1 Mb/s, because it is the recommendation of the manufacturer. In Fig. 11 and 12 the obtained results can be seen.

nRF24l01+ had better performance at 250 kbits/s and 2 Mb/s, because at this data rate the device had different dBm sensitivity than at 1 Mb/s. Nevertheless, the manufacturer recommends using 1 Mb/s, because the device is more stable in the mixed operation with the microprocessor. Therefore, the data rate of the technology could have influence in the communication, thus it must be take into account in following works.

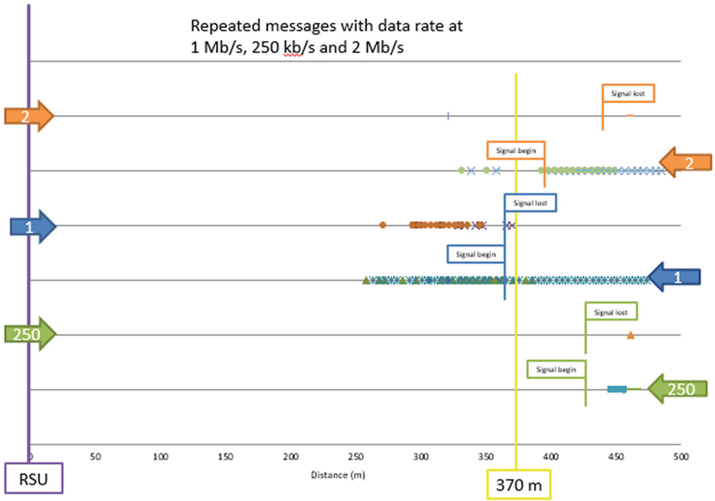

Fig. 11. Repeated messages in function of the data rate at 50 km/h for nRF24L01+

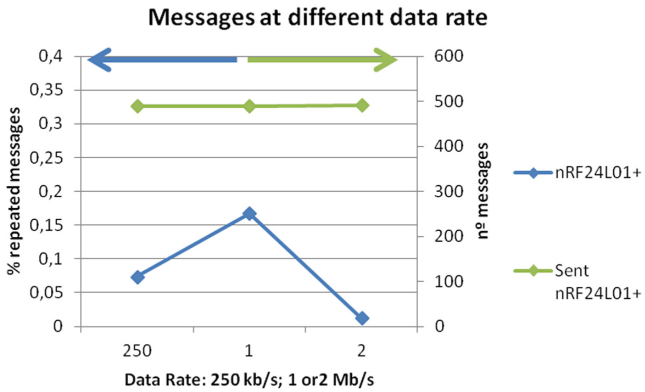

Fig. 12. Repeated messages in function of the data rate at 50 km/h for nRF24L01+

3.3 Obstacle Test

Figures 13 and 14 show the operation of both technologies. Red color means a insufficient operation which requires to resend the message, while green color means a good behavior.

By comparing Fig. 13 and Fig. 14, it can be seen that the operation of both devices varied during the route. In lack of a direct line of sight, nRF24L01 works worse than ZigBee. Buildings and trees have less influence in the right operation of ZigBee, although ZigBee operation is slightly worse. Thus, if there is not a direct line of sight between the communicative technologies, a malfunction is more likely.

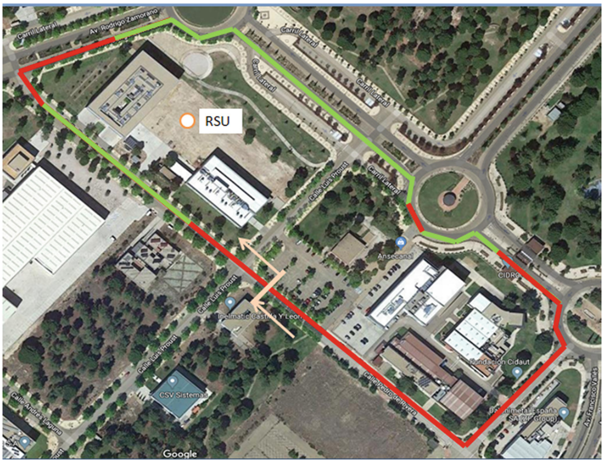

Fig. 13. Repeated messages for nRF24L01+

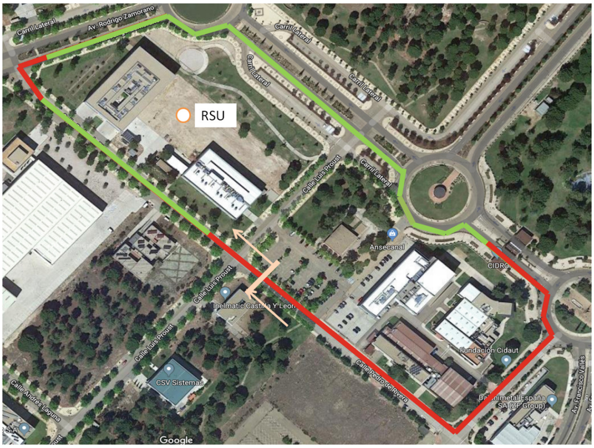

Fig. 14. Repeated messages for ZigBee

4 Conclusions

This paper has presented the comparison between nRF24l01+ technology and ZigBee technology. The aim was to look for a low cost technology for V2I communication. This comparison has offered the features and limitations of both technologies through a developed test bed based on real cases. This study has observed the improvement of the operation with the height, its independence with speed and the influence of the direct line of sight in their operation. It was also observed that ZigBee is not capable of sending many messages.

We tried to use low cost technologies for V2I communications (depending on their performance). Hereby, we observed that 5G could have some operation failures, which could isolate the vehicle from the rest of the infrastructure. Thus, a solution is required, which can improve communication reliability such that, if the 5G would fail, the short/middle range technology integrated will lead the vehicle with V2I communication. This integration would provide a reliable and strong solution by means of two technologies working in parallel.

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Application of Artificial Intelligence Techniques for the Creation of Novel Services Based on Connected Vehicles

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Abstract. New technologies have been progressively integrated into vehicles during the last thirty years. Commercial vehicles today can be seen as 2 tonne IoT devices on wheels that continuously collect high-quality information not only from the internal performance and behaviour of the vehicle but also from the external environment. The adoption of cutting-edge technologies like 5G, Edge Computing and Artificial Intelligence (AI) will be essential pillars for the actual implementation of new Intelligent Transportation Systems (ITS) leveraging Vehicle-to-everything (V2X) paradigm. This paper is focused on the design and implementation of a connected vehicle-based system to enable new services and applications to be developed, by exploiting high-quality data collected from onboard sensors and ECUs and leveraging state-of-the-art machine learning technologies.

Keywords: Artificial Intelligence · Connected vehicle · SUMO · V2X · CAN · V2V

1 Introduction

There has been an exponential increase in the integration of high-powered computing technologies in parallel with communication technologies inside modern vehicles. As such, these capabilities enable complex safety systems, contribute to smart cities and ultimately a more immersive and enjoyable driving experience. Solutions deployed by vehicle manufacturers are mainly proprietary and include limited connectivity features tightly coupled to brand-dependent applications. Ongoing efforts by governments, regulators, drivers' associations, research initiatives, and standardization bodies are trying to break these silos.

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In this case, the developed system relies on a flexible, independent, vehicle-agnostic Onboard Unit (OBU) that can be connected and adapted to vehicles. The OBU includes a variety of connectivity capabilities and specialized hardware to accelerate machine learning workloads. The developed software provides the first level of abstraction, to capture, aggregate and normalize vehicle data and apply standard data models before sharing any information with other vehicles, devices or cloud services. FIWARE open-source cloud platform has been chosen to implement the basic cloud infrastructure of the system. Generic Enablers (GEs) have been configured, interconnected and deployed to allow the exchange of information and control commands, to virtualize vehicles' attributes and to persist collected information. This latter aspect is absolutely essential in order to perform data analysis or to apply data-driven artificial intelligence techniques.

The possibilities of the system have been demonstrated with the development of two different applications: usage-based insurance and warnings on traffic and road conditions. In the first case, the use of high-quality vehicle data allows insurance companies to offer customized products. The application of supervised machine learning techniques is proposed to classify drivers' profiles which generates a customized insurance premium. Several datasets have been generated using different driving patterns to train the model. Then, a process of feature engineering has been followed to find the set that provides higher accuracy. The second application aims to support management, monitoring, and decision-making regarding urban traffic. In this case, as it is not possible to collect in real-time information from a big enough fleet of vehicles, an open-source urban traffic simulator has been integrated. A specific connector has been developed on top of the simulator to replicate the functionality of the OBU and inject data into the cloud platform. Thus, it is possible to analyse realistic traffic simulations considering thousands of vehicles and their interactions.

Finally, a web application has been developed as a front-end for the two services. It is built considering state-of-the-art security practices and it offers features in order to visualize real-time and historic information and to understand the outcomes of the underlying layers.

2 Innovation Beyond the State-of-the-Art

Prior to the connected car concept, a vehicle architecture was a closed network with no access to the outside world, other than an expensive (physical) service tool sold exclusively to vehicle maintenance garages. The modern vehicle is an assortment of interconnected ECUs (Electronic Control Units), running a variety of different closed and open-source OS (Operating Systems) and applications with specific purposes to support the driver's safety and comfort. In most of these cases, legacy architectures are used within the vehicle from robustness and low-cost point of view, however, the integration of state-of-the-art systems is questioning the overall security and as a consequence safety of the vehicle. There is a heavy focus on semi-autonomous safety features, or ADAS (Advanced Driver Assistance Systems), which uses a sophisticated camera and radar sensors to react in emergency situations, such as AEB (Autonomous Emergency Braking) which allows the vehicle (independent to the driver) to bring the vehicle to a standstill. Drivers and users are at the mercy of the robustness and resilience of these systems running inside the vehicle with the safety implications of compromising such systems becomes significant. There are also emerging markets in the area of ‘teleoperation’, such that a human operator can remotely drive a vehicle in the event of an emergency. While these capabilities have clear benefits in the mobility sector, the implementation of such systems enables a platform for detrimental consequences. For this reason, the rapid developments in communication technologies and integration of these systems in TCUs (Telematic Control Units) into a vehicle have proven that the reliability and robustness of the systems are questioned due to vulnerabilities exposed. Such vulnerabilities are discovered through misuse of a system not originally anticipated during the design phase, and in particular, the rapid availability of low-cost tools enabling such activities make this task much easier for hobbyists. Alternatively, pushing OTA (Over-The-Air) updates enabling updated features but exposing new vulnerabilities in other systems as a consequence. The industry has responded to this complexity with the development and validation of methodologies based on the risk evaluation, having a strong impact on the implementation of both software and hardware. However, reports in the media about third parties hacking vehicles are more rapid and have raised awareness in society.

Thanks to this modern approach of the in-vehicle technology, brand-new data sources appear, opening up space for applying AI techniques. Even though it is being implemented in several other areas, it is undeniable that the way AI is put into use in the automotive sector is evolving to new levels continuously. Notwithstanding that autonomous driving mechanics is the most known application, plenty of other practices are available for research and appliance. Throughout this research, some of these applications are presented, moving outside of the in-vehicle limits and targeting a wider range of operations in the V2V and V2X paradigms.

3 Technical Description and Methodology

3.1 Onboard Vehicle Unit (OBU)

Supporting such innovative developments require sophisticated and flexible development platforms. The IDAPT vehicle OBU has been developed specifically to support connected and autonomous vehicle R&D activities, by providing a single vehicle unit containing high-performance processing, legacy, and emerging automotive technologies and a collection of wireless communication technologies keeping in line with modern vehicle architectures.

This platform aimed to be vehicle-agnostic and provides a familiar Linux environment to developers with access to a number of complementary components such as CAN (Control Area Network), Ethernet, camera support, positioning/movement hardware (GPS/IMU), cellular modem (4G), a V2X module and an independent safety-microcontroller for high-integrity applications. IDAPT can then be developed on a bench and then quickly integrated into within a vehicle’s electronic architecture for validating applications.

Fig. 1. IDAPT OBU in vehicle

In the context of this work, the IDAPT OBU captures CAN data from the vehicle, comprising of strategic signals to support the 'usage-based insurance' scenario, such as vehicle speed, throttle position, braking information, steering information and RPM, along with data from other sensors, such as positioning (GPS) and transmitted ETSI ITS G5 V2X data. This data is then aggregated and processed in the IDAPT OBU and is periodically uploaded to the FIWARE IoT Cloud Platform (via a 4G cellular modem) that represents a 'snapshot' of the vehicle's state for a specific point in time. The sequence of these snapshots then reflects a detailed summary of how the vehicle's performance data has changed throughout the drive and is used to assess the driver's risk level (Fig. 1).

3.2 Cloud Platform for Connected Vehicles' Services

The cloud platform supports data reception, validation, and storage, thus enabling the vehicle's data exploitation by upper services and applications. A FIWARE-based implementation (Fig. 2) is proposed here to support data management features. It is composed of multiple FIWARE components, as known as Generic Enablers (GEs), each of them configured and integrated in order to support the different use-cases considered within the AI developments. In particular:

- Policy Enforcement Point (PEP) Proxy: Enforce authentication and authorization in the requests done by the edge components in a transparent way.
- Identity Management (IdM) KeyRock: Management of users, organizations, and applications. OAuth2.0 server to delegate authentication and authorization. Management of security policies.
- JSON IoT Agent: Interconnection of vehicles, translation of JSON information to NGSI standard format, bridge to Orion Context Broker.
- Orion Context Broker Virtualization of vehicles as context data sources. Management of real-time context information.
- Quantum Leap: Aggregation in a time-series format of context data coming from the vehicles. Persistence in CrateDB. NGSIv2 based API.

Data flows within are driven by the FIWARE NGSI v2 specification [1] which defines a set of context data management operations plus an evolving combination of data models to map heterogeneous devices and complex smart objects. FIWARE Vehicle data model [2], as part of the transportation models set, is used to represent data captured by real and simulated OBU devices.

Each one of these listed GEs is deployed as docker containers, using a Kubernetes deployment controller.

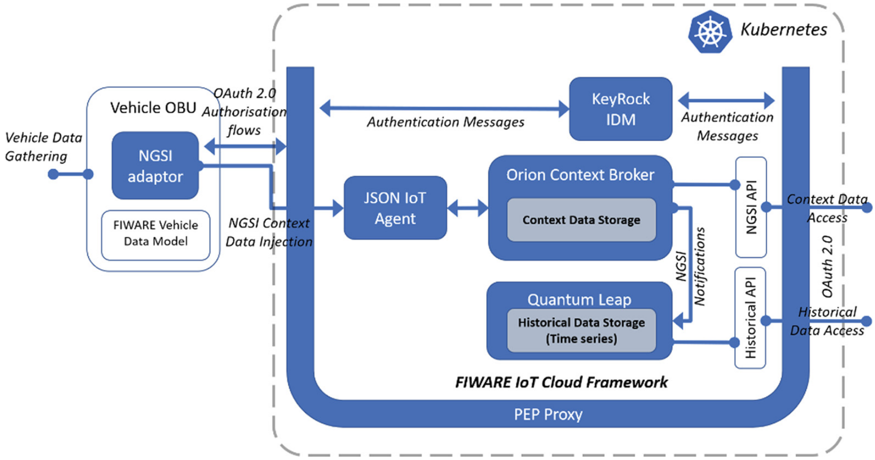

Fig. 2. FIWARE-Based IoT cloud platform implementation to capture, store and share vehicle's datasets

4 Artificial Intelligence for Connected Vehicles' Services

4.1 Usage-Based Insurance

Concerning the available data, the driver's vehicle usage-based insurance is the first application developed to exploit the connected vehicle possibilities. In this scenario, the objective is to assess the driver's behaviour during a trip, determining the risk of the driver to provide a tailored insurance premium. Information relating to the vehicle's circumstances, with complementary knowledge relating to V2X and GPS positioning, is uploaded to a cloud platform, where a machine learning (ML) classifier is trained. Each record is either labelled as "*normal*" or "*aggressive*", depending on whether the driver's behaviour follows a proper driving style, or a disturbing driving style, respectively. The results of the classification of new driver's data, when the ML model is deployed, can be used to determine which kind of allowance the insurance company should apply to the driver.

In order to train the classifier, a proper analysis of the available features of the data was first carried out, so that the most relevant ones are used during training, and the least relevant features are previously discarded. The total set of features consisted of: *time over limit* (time in seconds the driver was driving with a speed over the limit of the road), *throttle average* value (average use of throttle), *throttle standard deviation*, *throttle maximum* value, *breaks average* value (average use of breaks), *breaks standard deviation*, *speed over limit average* value (average speed of the vehicle when it was over the limit of the road), *acceleration average* value (average acceleration of the vehicle), *acceleration standard deviation*, *acceleration maximum* value, *acceleration minimum* value, *rpm* (revolutions per minute) *average* value, *rpm standard deviation*, *rpm maximum* value, *rpm minimum* value, *steering wheel angle standard deviation, steering wheel angle maximum* value, *steering wheel angle minimum* value, *total time* of the trip, and the label "*normal*"/"*aggressive*".

The selection of the relevant features was carried out in the Google Colab [3] workspace due to the friendly user interface and the ease of use of multiple Python libraries on top of it. In this regard, the Python library Scikit-Learn [4] was the selected one, as it provides tools for many data pre-processing procedures and lots of machine learning operations. A common approach to perform feature selection is to select one (or more) specific algorithm(s), like for instance a feature wrapper, run it on the dataset to select a subset of the whole feature set, and then test this feature subset with a machine learning classifier. Nonetheless, the approached resolution was to run several feature selection algorithms, each of them provided with a different feature discrimination style, leaving the Scikit-Learn library the task of testing against a built-in classifier the new feature set automatically. Eventually, the selection of the final set of features was done by isolating the features that appear in most of the algorithms' results.

The first technique used was *Univariate feature selection*, a procedure that selects the features with the highest scores computed with univariate statistical tests for each feature. These tests provide a value (called *p-value*) that represents the statistical relationship between the feature and the label. The resulting scores of each feature are computed with $-Log(pvalue)_{10}$ and are collected in Table 1 shows that there is a high correlation of the *acceleration, breaks,* and *rpm* related features with labelling as aggressive or normal the driver's behaviour. For instance, selecting the 60% of the features with the highest score, results in the set: [*'acceleration_min', 'breaks_std', 'acceleration_max', 'rpm_max', 'acceleration_std', 'total_time', 'rpm_min', 'rpm_std', 'throttle_max', 'str_angle_std', 'str_angle_min'*].

Table 1. Univariate feature selection scores per feature

Feature	Univariate score	Feature	Univariate score
time_over_limit	0.167909	acceleration_max	0.716232
throttle_avg	0.00251	acceleration_min	1.0
throttle_std	0.171322	rpm_avg	0.010138
throttle_max	0.333179	rpm_std	0.416174
breaks_avg	0.195417	rpm_max	0.718711
breaks_std	0.753736	rpm_min	0.432397
speed_over_limit_avg	0.064331	str_angle_std	0.299809
acceleration_avg	0.148537	str_angle_max	0.078069
acceleration_std	0.601208	str_angle_min	0.225012
total_time	0.447617		

The next feature selection technique used was *L1-based feature selection*, which penalizes each feature with a coefficient (the Manhattan Distance between the feature and the label), run along with a linear model that selects the features that have been granted a non-zero coefficient. The resulting set of features selected by this method was: [*'rpm_avg', 'rpm_max', 'rpm_min', 'str_angle_std', 'str_angle_max', 'str_angle_min', 'total_time'*].

Subsequently, development was proceeded with some feature wrapper methodologies, which work by iteratively removing features and testing the new feature set against a classifier. The first procedure was *backward elimination* tested with the *Ordinary Least Squares* model, which computes a value for each feature and, iteratively, removes the features with the highest ones. The resulting set of features after running this procedure was: [*'throttle_avg', 'throttle_std', 'acceleration_min', 'rpm_std', 'rpm_max', 'rpm_min', 'str_angle_std', 'total_time'*]. Another method run was the *Recursive Feature Elimination*, tested against a Linear Classifier, which resulted in this feature set: [*'throttle_avg' 'throttle_std' 'breaks_avg' 'breaks_std', 'acceleration_avg' 'acceleration_std' 'acceleration_max', 'acceleration_min' 'str_angle_std'*].

Some other variations of these procedures were additionally tested. The final set of features consists of [*time over limit*, *speed over limit average*, *breaks standard deviation*, *throttle standard deviation*, *acceleration minimum value*, *rpm maximum value*, *steering wheel angle standard deviation*].

Once the subset of features was selected, the Tensorflow [5] library was used to produce the machine learning classifier. Two different kinds of algorithms were examined: linear classifier and boosted trees classifier. However, the boosted trees classifier was elected because of several reasons: (i) decision trees classifiers have a background of great performance in many machine learning scenarios, (ii) it utilizes boosting methodologies to strengthen the resulting model's efficiency, giving us space for future model's improvements as new data arrives, and (iii) it resulted in a higher accuracy on the test set over the linear classifier. The final accuracy of our boosted trees model was 86%.

Finally, the model is exposed via Tensorflow Serving [6] and a dedicated software built with the Python library, which provides a RESTful API where the driver's profile data is sent and the model classification (whether the driver's driving profile is classified as "normal" or "aggressive") is responded back along with some additional statistics.

4.2 Warnings on Traffic and Road Conditions

Communications V2I (Vehicle to Infrastructure) and I2V (Infrastructure to Vehicle) constitute a collaborative scenario where the information collected from multiple vehicles can be exploited to provide specific (and relevant) services to the connected car. Having a set of cars with an OBU installed and managed from a control center can derive on periodical reports of the traffic status in concrete areas, e.g. lanes on the main streets of a city. Considering thousands of connected cars reporting to an AI-enabled control center allows building an accurate map of the whole road traffic in a city whilst on the other side, captures enough information to enable ML models to infer traffic behaviour. Depending on the information captured (and shared) by the OBUs built on the vehicles, the detected and forecasted traffic issues may vary, from e.g. traffic jams or accidents to noise and/or air pollution incidents.

Currently, having in mind V2X infrastructure deployments, this scenario is still not realistic. However, in order to explore ML techniques, there exist several tools that simulate data coming from virtual vehicles with OBU installed. In order to develop and train the AI models proposed in this text, Simulation of Urban Mobility (SUMO) [7] tool is used. SUMO is a versatile open-source road traffic simulation package, designed to handle large road networks. It also counts on a wide community of developers. The environment provides different (and configurable) scenarios[1] replicating realistic traffic behaviour in selected cities supported by specialized developers. For this research work, the city of Cologne [7] scenario was initially selected, providing data up to ten thousand simulated vehicles per iteration. All these vehicles are set up to drive along the city's roads and surroundings during the whole day, adapting their behaviour and routes according to configured real parameters. Thus, a simulation closest to the real city traffic is achieved. Vehicles' speed, acceleration, and angle (heading), linked to its GPS location and time are captured and registered, to feed AI models related to traffic analysis and forecasting.

As current embedded OBUs do not provide any link about the road or lane the vehicles are driving on, this information must be gathered from different external sources. Platforms like Google Maps tackle this issue but, focusing on open-source solutions, Open Source Routing Machine (OSRM) project [8], based on Open Street Maps (OSM) is used to map the closest road segment to the GPS data included in every observation. Thus, all the traffic information collected can be indexed to a concrete traffic road in each date and time.

ML technologies and AI models are powered by IoT frameworks that gather and aggregate information from heterogeneous smart objects. This research action relies on a FIWARE-based IoT cloud architecture (Fig. 2) to manage and direct traffic data. Figure 3 depicts the overall approach followed to capture, aggregate and store traffic data to feed ML components and AI models: i) SUMO tool provides vehicle's data (speed, acceleration, and angle) referred to a GPS location and a timestamp. The reported GPS data is used to obtain the corresponding road segment identification. The information ii) is mapped using the FIWARE NGSI Vehicle Data model [2] and injected as context information into the cloud platform. Last reported values are offered to the ML component, to compose the current traffic status, whilst, in turn, are classified and stored as historical information. The historical data is used iv) to train the developed AI models and enhance the accuracy of the traffic conditions reports and forecasts.

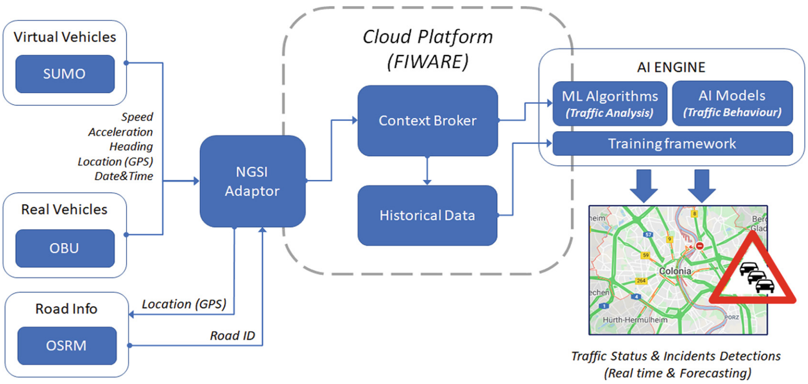

Fig. 3. AI & ML framework approach for traffic analysis and forecasting

[1] SUMO data/scenarios available via https://sumo.dlr.de/docs/Data/Scenarios.html.

In this sense, the framework studies ML techniques applied to traffic analysis, in two complementary lines: i) analysing average speeds associated with given road segments and linked to date and time coordinates and exploiting real-time captured speeds to detect and foresee possible traffic jams. This information would be later shared with connected cars to a) recalculate a specific car route to avoid an incoming bottleneck and improve its Estimated Time of Arrival (ETA), and b) propose alternative routes to most frequent destinations within the city, based on current and forecasted traffic status that relieve vehicles' traffic and reduce noise and air pollution. On the other side, ii) unusual acceleration/deceleration reports plus detected relevant reductions of average speeds may point out an incident. AI models will be trained on these patterns to quickly detect and even anticipate traffic incidents, so car connected routes can be modified to avoid them.

4.3 User Interface Applications

To support the presentation of such data, a user interface application has been developed and it contains several interfaces which are used to visualize and analyse the vehicles' data. One such interface is the "Driver behaviour interface", which illustrates the results of a Machine Learning classifier to evaluate a driver's risk, and subsequently calculate an insurance price relative to a combination of factors extracted from the vehicle as a source of information, such as driver aggressiveness, time of day and route taken. Moreover, the web interface can generate a graphical representation of specific data values from a driver. Additional elements used as features by the machine learning classifier (e.g., standard deviation, maximum revolutions per minute, speed over limit average) are also illustrated to highlight to drivers and insurance companies a more detailed understanding. An example of this can be seen in Fig. 4.

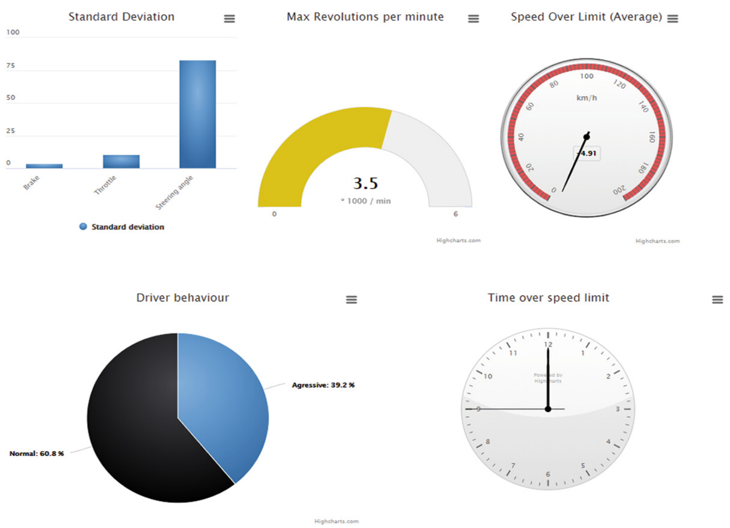

Fig. 4. Detailed information provided by the user interface

Furthermore, several other interfaces have been developed to illustrate and analyse historical data (generated by the vehicle during the trip) and real-time data that contains the latest vehicle information. In our case, the real-time data is updated every second due to terms of efficiency and consistency. Several interfaces have been developed to provide and show all the information required for this analysis:

- **Trips information interface:** A list of different trips of each vehicle is illustrated in Fig. 5 and a graph that shows when the trips have taken place is shown in Fig. 6.

Trip Number	Start Date	End Date		
1	2019-05-01 15:15:41	2019-05-01 15:15:41	Info	Driver Behaviour
2	2019-05-01 15:18:24	2019-05-01 15:31:52	Info	Driver Behaviour

Fig. 5. Trip information interface

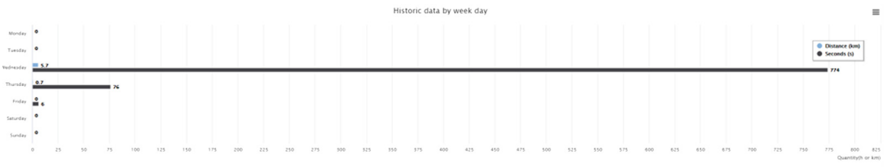

Fig. 6. Trip information interface (detailed view)

- **Specific trip information interface:** Individual trips can be visualized for assessment by the user. It plots the entire trip on a map with supporting graphs (e.g. speed variation, fuel use and distance over time) (Fig. 7).

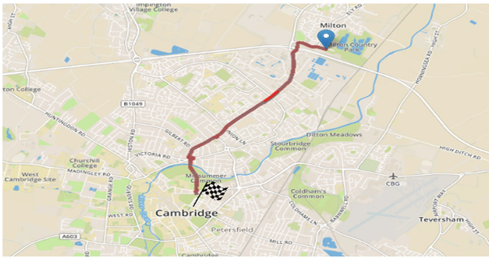

Fig. 7. Vehicle trip interface

- **Warnings on traffic and road conditions interface:** Visualization of data generated by SUMO. It allows the user to visualize the current position of every simulated vehicle. The position is reloaded every second. Using the combination of positional data (GPS), vehicle performance data (e.g. vehicle speed, braking conditions, throttle position), and frequency (e.g. morning and evening commuter traffic) it is possible to support the development of traffic detection algorithms (Fig. 8).

Fig. 8. SUMO vehicle visualisation

5 Conclusions

There are clear benefits for connected vehicles in a wide area of domains, such as a more immersive and informed driving experience, improved safety capabilities and the disruption of traditional business models and enablement of new such as vehicle ownership, and insurance in the MaaS (Mobility as a Service) paradigm.

Future transportation innovations will be pioneered with connected and autonomous vehicle research, producing innovative machine learning applications that consume data coming from the in-vehicle systems and the V2V and V2X paradigms. Although Artificial Intelligence has already demonstrated part of its potential with respect to natural language processing or robotics processing automation, the greatest impact is foreseen in vertical domains and among them, the automotive industry has huge possibilities. In this sense, there is an ongoing strategy by the European Union with initiatives like the Automotive Edge Computing Consortium[2] or studies with respect to intelligent transport systems[3] that aim to strengthen the European innovation capacity, competitiveness, and growth of companies.

This work goes beyond the state-of-the-art of commercial and research solutions by combining the potential of modern edge computing platforms and deep learning. This enables a new generation of cross-sectorial high-added-value services, independents of the vehicle brand or model, opening the door to huge market opportunities, business models and benefits, not only for big companies but also for small and medium enterprises and start-ups. In the case of the two proposed applications, the economic impact is expected for insurance, carmakers, ICT providers, drivers, and citizens. Also, security and safety will be improved thanks to the active promotion and rewarding of good driving practices, the early warning of hazardous situations or even the adoption of preventive actions relying on the predictive capabilities of deep learning models.

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Safety, Security and Validation

Validation and Verification Procedure for Automated Driving Functions Using the Example of the TrustVehicle Project

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Abstract. Automated driving is supposed to alleviate driver's workloads and improve traffic efficiency and road safety. In order to achieve these goals, it is crucial to test the automated systems thoroughly. Since pure testing on test tracks and public roads is highly time consuming and still cannot cover all critical scenarios, usage of simulation and driving simulators can speed up the testing process. The TrustVehicle project aims at improving SAE Level 3 automated driving (L3AD) functionalities, especially in critical situations and under harsh weather conditions. Therefore, co-simulations, driving simulators and real-world tests are used to test the trustworthiness and availability of the developed functionalities.

An overview of the approach used within the project is presented in this paper. Based on one of the four use cases, the used toolchain and corresponding workflow is described.

Keywords: Level 3 automated driving · Reliability · Driver-centric approach · Co-simulation · Driving simulator

1 Introduction

TrustVehicle aims at advancing technical solutions for automated driving to better assess critical situations in mixed traffic scenarios and even under harsh environmental conditions, hence increasing safety far beyond the current levels.

The project follows a user-centric approach and will provide solutions, which significantly increase reliability and trustworthiness of automated vehicles and contribute to end-user acceptance.

The output of the TrustVehicle project is extensively assessed in real-world operating conditions on three demonstrators representing three vehicle classes. Special focus is placed on the demonstration of fault-tolerant and fail-operational system behavior as well

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as on 24/7 availability. End-users of the technology are systematically and thoroughly involved to express their requirements, expectations, and concerns.

The success of TrustVehicle is based on the excellent combination of expertise from key industry players and research partners [1].

In TrustVehicle there are three different methods to verify the work in this project:

- Simulation
- Driving Simulator
- Real-World Demonstration (Fig. 1)

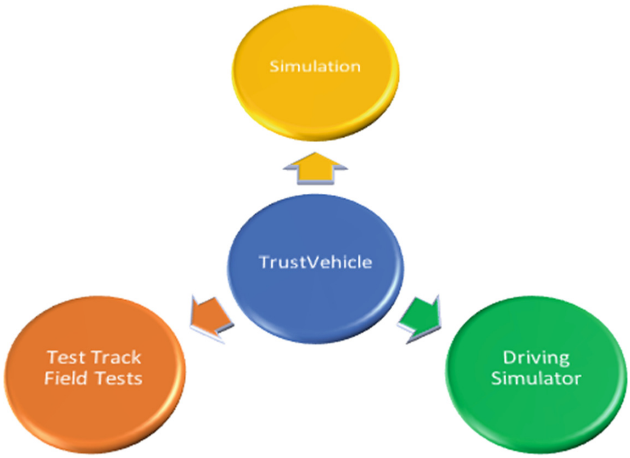

Fig. 1. Verification methods in TrustVehicle

Each method has its advantages and deficiencies, but combined they complement each other very well. Simulations provide the capability to test a wide range of scenarios and use cases. Furthermore, it is easily possible to make and test parameter adjustments without spending much money on demonstrator build-up and testing facilities. The focus is on functional development. The Driving Simulator is a good way to determine user acceptance and get feedback on the behavior and settings of driving functions. The Test Track/Field Tests are necessary to verify the simulation models, determine user acceptance and test the robustness of the demonstrators under real environmental influences, such as harsh weather and road conditions.

The following sections explain the work conducted in the TrustVehicle project for each of these methods. Section 2 starts with a brief overview of the workflow. In Sect. 3 all four TrustVehicle use cases are listed, followed by an introduction of the passenger car use case, which is the model use case presented in this paper. Sections 4, 5 and 6 sum up the modeling, driving simulator and field test stage in the verification procedure respectively. Finally, a short wrap-up is given in the conclusion in Sect. 7.

2 Workflow

The TrustVehicle workflow includes all aspects from the well-known V-cycle (see Fig. 2), starting with the examination of the use cases' aims and the specification of the different aspects. After the specification phase, modelling of the various vehicle parts is performed and combined with the newly developed automated driving functionalities. Simultaneous measurements of the real vehicles ensure close to real life parametrization of the used models and hence simulations can provide results usable to test the functionalities with respect to the specified key performance indicators (KPIs) and already improve the performance before testing it in the real vehicle. An important aspect of the TrustVehicle project is the integration of the end user during the development process of the driving functions. Therefore, additionally to collecting input already in the specification phase via questionnaires, feedback with respect to the developed functionalities is collected in a driving simulator study. This feedback is used to further improve the driving functions and related modules before, in the final step, integrating it in the real vehicle. Verification and validation in this last step are performed on proving grounds as well as on real roads.

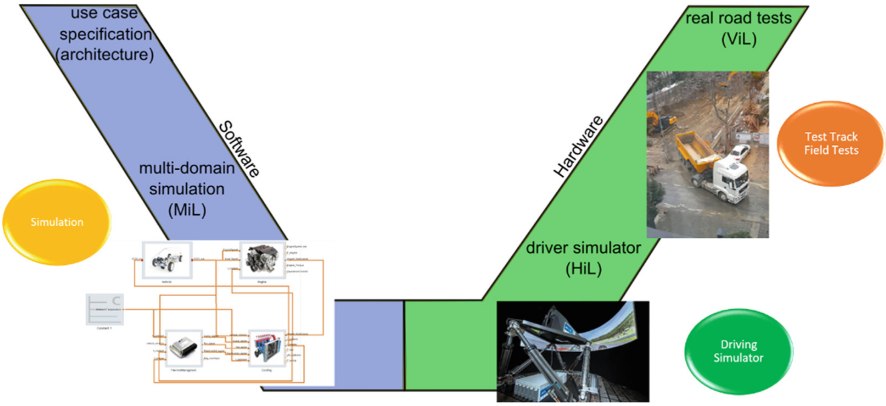

Fig. 2. Development V-cycle of the TrustVehicle project: use case specification, model in the loop (MiL), hardware in the loop (HiL) and vehicle in the loop (ViL).

3 Use Cases

Four use cases were defined as part of the TrustVehicle project to demonstrate the work done and to show that the project objectives were fulfilled. In three of the use cases real demonstrators were built. Table 1 gives an overview of all use cases. In this chapter, however, only the passenger car use case is presented to describe the verification process, since it is the only one that uses all three verification methods of this project (simulation/modeling, driving simulator and test track/field tests).

The purpose of this use case was to analyse the performance of different types of sensors used for perception and to use the learnings to develop a sensor monitoring module, a software component that provides information to sensor fusion algorithms about

Table 1. TrustVehicle use cases

Use cases	Scenarios
Truck/Trailer	*Reverse parking in a loading dock and construction site backing* [2]
Passenger car	*Degraded sensor functionality*
Electric bus	*Automatic approach towards electric charging points at bus stops* [2]
Light commercial vehicle	*Automated door-to-door delivery (back parking and narrow street manoeuvring)*

potential faults in the sensor data. By monitoring sensor performance, the trustworthiness of sensor output and consequently sensor fusion, which provides necessary information for decision and control, can be improved. The sensor monitoring module provides a confidence measurement to sensor fusion by monitoring real-time sensor data. The data is analysed with respect to parameters based on the expected performance of camera, radar, lidar and ultrasonic sensors, such as performance in different environmental conditions or their ability to detect and classify different types of objects. The following potential faults affecting sensor data were analysed:

- **Fault Scenario 1: Sensor health and communication quality**

Diagnostics of components, such as reporting heartbeat or signal quality, is already a vital part of sensor implementation. The sensor monitoring module use diagnostic information as a confidence value to measure the trustworthiness of the sensor outputs.

- **Fault Scenario 2: Environmental conditions**

The availability of vehicle sensor data is dependent on environmental conditions and different sensors react differently depending on these conditions. Conditions such as harsh weather or reduced visibility can highly degrade the sensor, which has to be reported to the sensor monitoring system.

The KPIs for the passenger car use case are mainly related to improvement of the availability of the used L3AD system in various environmental conditions. It is intended to decrease the number of take-over scenarios and therefore improve the user acceptance. A classification of the TrustVehicle KPIs is presented in Fig. 3. The chosen classes and dimensions are based on TrustVehicle's main aims (improvement of driving function reliability (technical) and end user acceptance (non-technical)) and the focus of the involved project partners (OEMs and Tier1).

Some of the KPIs that resulted from user surveys are: Perceived feelings of safety, Reliability, Expressions of trust, Perceived control, Perceived travelling comfort, Availability of L3AD during harsh weather conditions (rain, bad visibility), Sensor accuracy, Sensor robustness. The ranking of the KPIs was based on the conducted surveys.

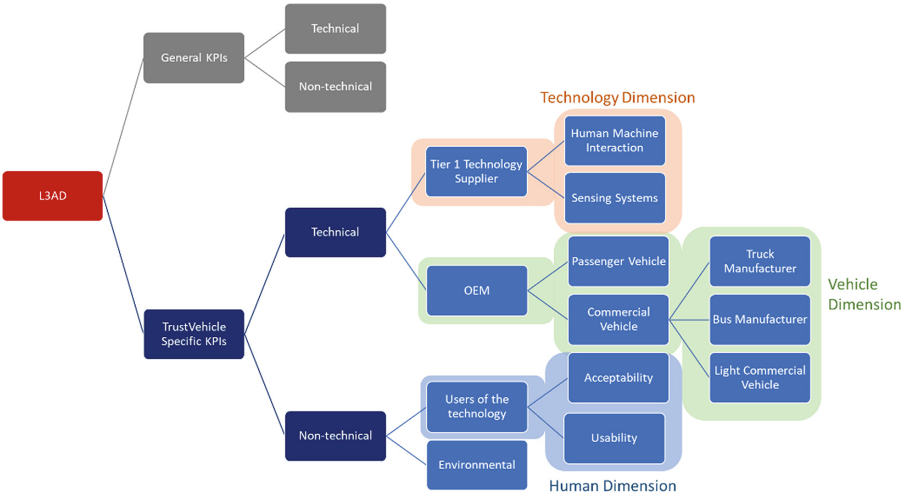

Fig. 3. Classification of the TrustVehicle key performance indicators (KPIs)

4 Simulation

For the simulation performed on the driving simulator the sensor fusion and automated driving functions were provided by Virtual Vehicle (VIF) (see Fig. 4). Both were replaced for the real world testing in the Volvo XC90 demonstrator vehicle by Volvo internal functions. Since the focus of the passenger car use case is on Volvo's sensor monitoring rather than on the driving function, this change is acceptable in the validation and verification procedure.

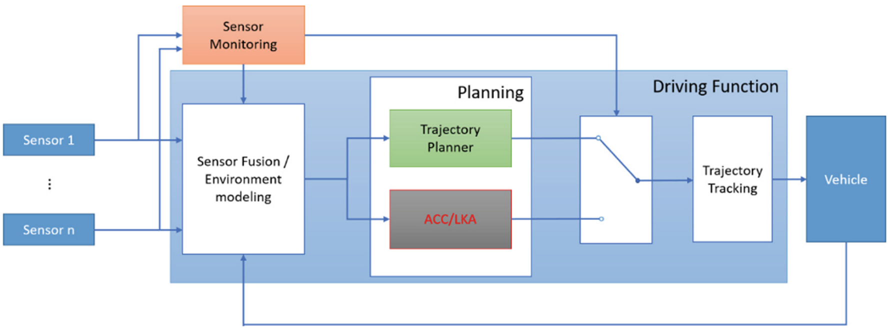

Fig. 4. Passenger car use case simulation setup

For the passenger car use case on the driving simulator, a multi-sensor multi-object tracking system from VIF, based on radar, lidar and camera sensors was used.

The automated driving function developed at VIF is a SAE Level 3 driving function, relieving the driver of longitudinal as well as lateral control responsibilities including adaptive cruise control (ACC), lane keeping (LK) and lane change (LC). It is based on work described in [3] and adapted for the passenger car use case in TrustVehicle. In order to achieve a fail-operational architecture, two sets of functionalities are executed in parallel as can be seen in Fig. 4. The primary driving function, including full longitudinal and lateral control in the ego vehicle's own lane as well as the adjacent lanes (lane change functionality), is the Trajectory Planner. A combination of ACC and LKA serves as Hot Standby. In case the sensor monitoring system detects a failure in the sensor system that affects the availability of specific functionalities (in this case lane change), the switch position changes and signals from ACC/LKA instead of from the Trajectory Planner are sent to the Trajectory Tracking.

The Trajectory Tracking component implements the feedback control of the vehicle's lateral and longitudinal motion with respect to the reference trajectories provided by the Trajectory Planning subsystem. Its implementation uses a separate control strategy for the vehicle's lateral and longitudinal motion. Since the vehicle's motion is planned within the Trajectory Planning, the resulting reference values for lateral and longitudinal control are always consistent. Depending on the rate of execution, repetitive re-planning also ensures consistency in the presence of unknown disturbances.

The driving function model is only one part of the Model.CONNECT^{TM} co-simulation setup. In Fig. 5 all components of the simulation setup for the passenger car use case are shown. The VTD block represents the connection to the environment simulation tool Vires Virtual Test Drive (VTD). This tool is working on a separate computer. The IP address and port number are stored in the block to enable the communication. The user can also select the scenario in this block. When the Model.CONNECT simulation is started, it starts also the scenario in VTD.

The green block with the white car is the VSM (Vehicle Simulation Model) block. It simulates the vehicle dynamics in a detailed way. Since it uses another coordinate system as VTD, a transformation block is connected between them. VSM is also connected to a small block that controls the function of the driving simulator motion platform.

The third major block is the MATLAB/Simulink model of the Driving Function (blue block) as mentioned above. Among other signals, the data of the LookAhead sensor from VTD is needed for the driving function. However, before these data can be used, they have to be prepared in another small block that is called LookAhead_Data.

The other blocks are for the functionality of the Time-of-Flight camera for driver monitoring (the top left subsystem block), for collecting data for AVL Drive (bottom) and some blocks that provide constant signals.

The simulation structure is a parallel one, i.e. all models are executed at the same time and provide the output signals for the other blocks at every time step simultaneously. To prevent unwanted behavior at the beginning of the simulation initial values are set.

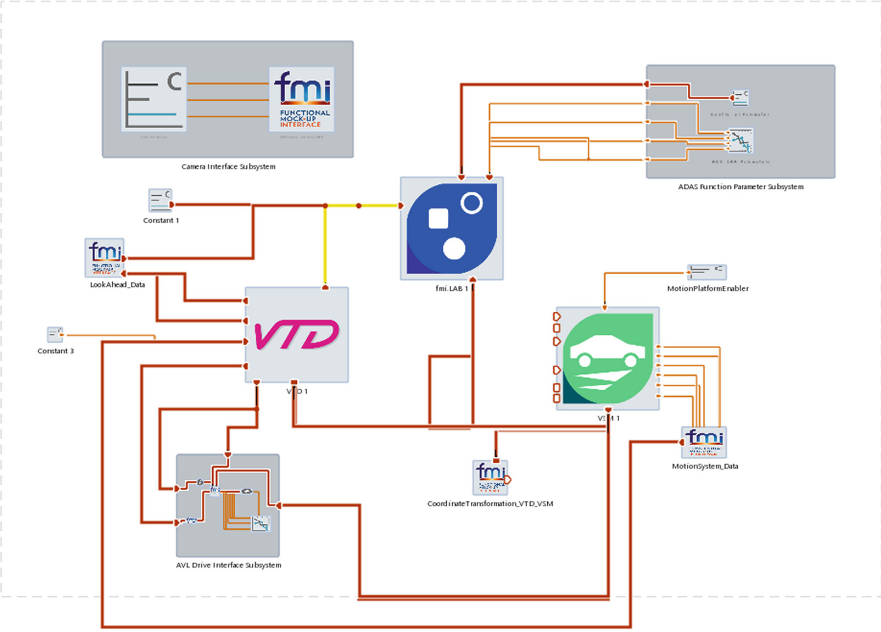

Fig. 5. Model.CONNECT^{TM} setup for the driving simulator study

5 Driving Simulator

The driving simulator used for the TrustVehicle study consists of an electromechanical six-degree-of-freedom motion system. With this platform, it is possible to simulate longitudinal, lateral, and vertical translational motion and rotational movement around each axis. The cockpit comes from a passenger car and for installation on a driving simulator only around a quarter of the real vehicle is used. The passenger seat can be electrically adjusted, the center console can be used to display different information and the steering wheel is still the original from the real vehicle which is connected to the SimSteering system to simulate steering feedback. The field of view is an important factor for the capability to recognize the current situation for the driver. Therefore, a 180°-degree canvas with a height of 1.5 m and a radius of 2.5 m is used for visualizing the environment. Two sideview mirrors are installed on the cockpit to increase the field of view and inform the driver what is going on behind the own vehicle (Fig. 6).

5.1 Driving Simulator Study

During the project, two studies on the driving simulator were conducted. A small one to test the hardware, scenarios and the testing method and a larger a year later. In this second study, 55 participants from different age groups took part.

Two main instruments have been used during the field test on the driving simulator – questionnaires and sensors. Several questionnaires were conducted before, during and

Fig. 6. AVL driving simulator [Source: AVL]

after the test to get the test persons' opinions and feedback. In addition, a set of sensors were used to get physical measurements from the participants:

- 2 Time-of-Flight cameras for driver monitoring
- Chest Belt and Wristband as heart rate sensors
- Eye Tracker

Before approaching the driving simulator, each participant was introduced to the study. An information sheet was given to the participants. Each participant had time to read it carefully and to ask for an additional explanation if something was not clear. After that they signed a consent form and were asked to complete a pre-simulation questionnaire on trust in automation. Then they were equipped with the physical sensors and got an instruction on the driving simulator part of the study. In the simulator, they were first asked to drive a "test ride" of 10 min on rural roads and a highway with mixed traffic, where they were in complete control of the vehicle. To introduce the participants to the scenario/sequence questionnaires, they had to fill a test questionnaire after the "test ride". Then the simulator was switched into automation state to start the scenario-based part of the study. After each scenario, they were asked questions about their driving experience. The questionnaire was digitalized on a tablet embedded in the cockpit. Throughout the simulation, the participants were asked about how they were feeling, if they were feeling unwell or had any questions to the researcher. At the end of the simulation, their physical sensors were removed, and they were guided to another researcher to complete the final questionnaires.

5.2 Scenarios

Ten scenarios, chosen to represent a diverse set of critical situations, were presented to the participants of the study. Thus, it was possible to build up a large data set. Each scenario was limited to a maximum of two minutes in order to not overly extend time in the simulator for the participants. The ten scenarios consisted of four different maps with variations in controllers or parameters. In this chapter, only the two scenarios regarding the passenger car use case will be described as examples.

- **Scenario 1: "Sensor Cleaning"** (Fig. 7)

Fig. 7. Screenshot of scenario 1

The focus of the first scenario was on sensor degradation and cleaning. The ego car drives on a street with two lanes both in the same direction. The weather is cloudy and the underground wet.

The focus in this scenario is degradation of a sensor due to dirt that is caused by a car passing by on the left lane. The participant receives a message on the dashboard that the lane change functionality is temporarily not available. Therefore, the car has to brake behind a slower car in front of the ego car. After 15 s the participant is informed that the sensor is cleaned, and the ego car performs the lane change to overtake the slower car.

This scenario was used two times with different controller settings. The first one was a comfortable controller with a moderate acceleration rate, where the vehicle starts to break earlier and keeps a bigger distance to the vehicle in front of the ego car. In addition, the takeover process starts earlier. The second controller was a sportier controller, where the acceleration rate is considerably higher as for the comfortable controller. The vehicle does not break as early and the distance to the vehicle in front of the ego car while following is smaller.

To adjust the setting of the driving functions, feedback of the participants regarding preferences in controllers and used parameters were collected.

- **Scenario 2: "Reduced Visibility"** (Fig. 8)

Fig. 8. Screenshot of scenario 2

The second scenario covers the reduction of L3 functionality due to harsh weather conditions. The ego car drives through a village with a speed limit of 50 km/h. The street has one lane in each direction and oncoming traffic. The scenario starts with light rain and good visibility but then the rain picks up and the visibility is reduced. Therefore, the speed of the ego car is adjusted by the driving function according to the visual range of the sensor.

This scenario has been used two times with the two different controller settings mentioned above.

6 Proving Ground/Field Tests

Representing real-life traffic scenarios is one of the most critical methods used by the automotive industry for verification and validation processes. It becomes essential if verified or validated attributes are related to the safety measures. Since the main purpose of the TrustVehicle project is to develop L3AD autonomous functions to enable safer and more reliable products, validation of these developed functions with the traffic scenarios is of vital importance.

6.1 Demonstration Setup

Volvo Cars' use case, using a passenger vehicle, is based on degradation and its effect on the overall function availability. The tests will take place in two different environments – Volvo's proving ground in Hällered and in real traffic conditions. Two different demonstrator setups will be used for these environments:

a) **Proving ground**

The test location is the Volvo Cars multipurpose test facility. If the environmental conditions are not met on the day of testing, the conditions can be manually simulated, e.g. watering the driving path for road spray conditions and using a water spray system for the sensors for rain conditions. Scenarios in the test environment will focus on how well each sensor performs in different environmental conditions and thereafter how well the complete perception system, e.g. sensor fusion software, performs in the same environmental conditions. The test in this scenario will be carried out according to the EuroNCAP scenario "Car-to-Pedestrian Nearside Child" [4].

Both the vehicle and the pedestrian in the test scenario will be operated by robotic installations that control the vehicle actuators such as acceleration, steering and braking (Fig. 9).

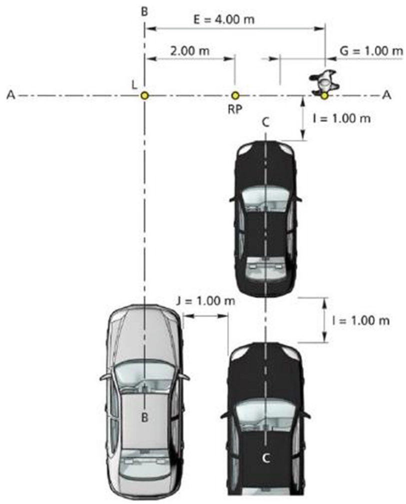

Fig. 9. EuroNCAP scenario "Car-to-Pedestrian Nearside Child" test scenario [4]

b) **Field Tests**

Scenarios in the real environment will focus on how well the complete perception system, i.e. sensor fusion software, performs in real traffic situations in different environmental conditions. The test scenario will be carried out on a driving route outside the central parts of Gothenburg, Sweden. This route is specifically chosen to reduce complex situations such as oncoming vehicle, pedestrians and traffic lights. The vehicle will be operated by professional test drivers, employed and educated to operate tests by Volvo Cars. The vehicle will be equipped with the complete system solutions including sensors and cleaning systems; however, the vehicle will be fully controlled by the driver.

7 Conclusion and Outlook

In this paper, the full verification and validation procedure used in the TrustVehicle project is described. Basis for every validation and verification procedure is the thorough specification of requirements and KPIs. This has been done by both, experts and end-users, using multiple rounds of questionnaires. The second stage is testing in simulation. Using real-world data to parameterize the developed models this stage is intended to reduce the amount of real-world testing needed to cover every critical driving situation. To add the driver into the mix, a testing stage on the driving simulator was performed. Especially for the sensor monitoring system developed in the described use case, end-user feedback is essential and can be obtained at an early stage in the development process. Finally, real-world testing is performed. Realistic traffic scenarios are tested on real roads and are supplemented by testing on proving grounds, where harsh weather conditions and specific critical driving scenarios, which cannot be staged on real roads, can be constructed.

Based on the outcome of the real-world tests, driving functions and sensor monitoring system will be further adapted and improved. These improvements will on the one hand concern functionality issues, e.g. precision regarding maneuvering, and on the other hand acceptance issues reported by the test drivers. In the end, these advancements will sustainably increase the acceptance of L3AD vehicles embedded in complex environments, independent of ambient weather conditions and contribute to quicker market take-up.

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Advancing the Design of Fail-Operational Architectures, Communication Modules, Electronic Components, and Systems for Future Autonomous/Automated Vehicles

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Abstract. The paper presents the concepts behind the developments of technologies, electronics components, communication concepts, embedded systems modules for designing fail-aware, fail-safe, fail-operational (HW and SW redundancy) electronic components and systems architecture that enable the introduction of autonomous/automated driving capabilities of level 4 and 5 future vehicles categories. Focus is given to the automotive standards such as ISO 26262, ISO/PAS 21448. The paper is based on findings of the AutoDrive ECSEL project [1] and gives examples of safety use case scenarios for heterogeneous V2X low latency communication between the autonomous vehicle and the environment.

Keywords: Autonomous vehicle · High automated vehicle · Safety · Fail-operational · Fail-aware · Fail-safe · ISO 26262 · ISO/PAS 21448 · V2X connectivity · ITS-G5 · NR-V2X · C-V2X 5G · IoT

1 Introduction

Today, the entire traditional transportation and mobility ecosystem is going through significant changes. Several key trends are accelerating this transformation: new mobility modes, multimodality and behaviours, electrification of powertrains, connectivity, penetration of autonomous driving technologies, the development and the use of digital features that are impacting industry and consumers, as well as the introduction of AI techniques and methods for implementing intelligent solutions and components.

In this context, building future ECAS (Electric, Connected, Autonomous, Shared) vehicles is particularly challenging owing to stringent performance requirements necessary to address these trends, making safe operational decisions, tackle real-time

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processing issues, sharing data, and integrating stakeholders' heterogeneous ecosystems. The new electronic systems enabling autonomous driving are required to include fail-operational capabilities of electronics, control and software to meet dependability requirements and satisfy the system constraints considering that several functions and attributes are assigned to the maximum safety-critical categories.

Current automotive electronic systems are fail-safe and require the driver to take over and drive without Advanced Driver Assistance Systems (ADAS) and active safety systems in case of problems. At the same time, the increased level of automation pushes the need for fail-operational behaviour.

The AutoDrive project addresses the design and development of fail-aware, fail-safe, and fail-operational integrated electronic components, Electrical/Electronic (E/E) architectures as well as embedded hardware/software systems for highly and fully automated driving to make future mobility safer, more efficient, affordable, and end-user acceptable.

Advancing towards fail-operational systems requires increased reliability and availability of components, new redundancy schemes as well as architectures, and methodologies to manage appropriately and balance complexity, cost, robustness, and flexibility. A holistic perspective, from electronics to systems is considered for automated vehicles. AutoDrive focuses on urban and rural road scenarios as well as mixed traffic.

The aim is to provide fail-operational capabilities for automotive electronic systems with maximum reliability, multiple but minimum redundancy at low cost and low power by addressing the system architecture (mixed-criticality cyber-physical systems), the system and the semiconductors components (systems-on-chip, component level) along with the entire development and value chain.

In this context, the paper is organised as follows. Section 1 introduces the topic by presenting the requirements for new electronic systems enabling autonomous driving to provide fail-operational capabilities and increased safety functions. A short overview of the AutoDrive project and its main objectives are given in this context. Section 2 discusses the levels of automation and the role of fail-operational systems for intelligent driving systems that must take full responsibility for traffic safety and fault management. Section 3 highlights the functional safety concepts and introduces two functional safety standards ISO 26262 and ISO/PAS 21448 as the baseline for the assessment of autonomous vehicle and the underlying electrical/electronic (E/E) control architecture. The fail-operational design for autonomous vehicles is presented in Sect. 4. The approach addresses system redundancy, fail-operational concepts for V2X systems, and presents the safety use case scenarios for heterogeneous V2X communication. The conclusions and discussions are summarised in Sect. 5.

2 Levels of Automation

Autonomous vehicles must make a "correct" operational decision at all times to avoid accidents [2]. For this purpose, they use fail-operational systems, advanced machine learning (ML), computer vision, and robotic processing algorithms. Autonomous vehicles have to provide fail-operational behaviour, maintaining certain functions for a specific time even in case of particular faults [3], while having to process a large amount of information and react to traffic conditions in real-time under a given power budget to avoid negative impact on the driving range, energy efficiency, and passengers' travelling experience.

SAE International (SAE J3016) defines six levels of automation [10, 11]. Automation levels 1 and 2 address driving assistance, where the human driver still always handles a substantial portion of the driving tasks under all conditions. Autonomous driving functions take driving responsibility at automation levels 3–5 under certain driving conditions; these are typically referred to as the highly automated vehicle (HAV) functions. This paper focuses on HAVs at levels 3–5.

The SAE classification of driving automation identifies the autonomous functions and driver's role during vehicle operation. This classification uses environmental monitoring as an element for differentiation. A human driver is responsible for perceiving the environment for partial or no automation (levels 0–2), whereas, for higher degrees of automation (levels 3–5), the vehicle is responsible for these tasks.

In this respect, fail-operational systems are critical for intelligent driving systems (levels 4 and 5) that have to take full responsibility for traffic safety and fault management; they are less critical for automated vehicles (levels 1–3) that require a human driver to take control in case of any fault.

Autonomous vehicles need to understand their surroundings, localise their position and that of other vehicles and objects, and plan a path to travel. RADARs, LiDARs, cameras, IoT devices are used to facilitate scene understanding, while global positioning systems (GPSs), inertial measurement units (IMUs), high-definition maps (HDMs), wheel odometers are used for vehicle localisation. The in-vehicle platform needs to process the data generated by these sensors in a power-efficient manner in real-time without reducing the vehicle range.

The SAE autonomous driving capabilities for level 4 and 5 autonomous vehicles need to be addressed in terms of computing, control, cognition, and connectivity for sensing/detection, perception, processing, thinking/decision, control, propulsion/actuation functions (Fig. 1) to ensure that vehicles "see" (sense/locate) the surroundings, perceive obstacles and act safely following their perceptions.

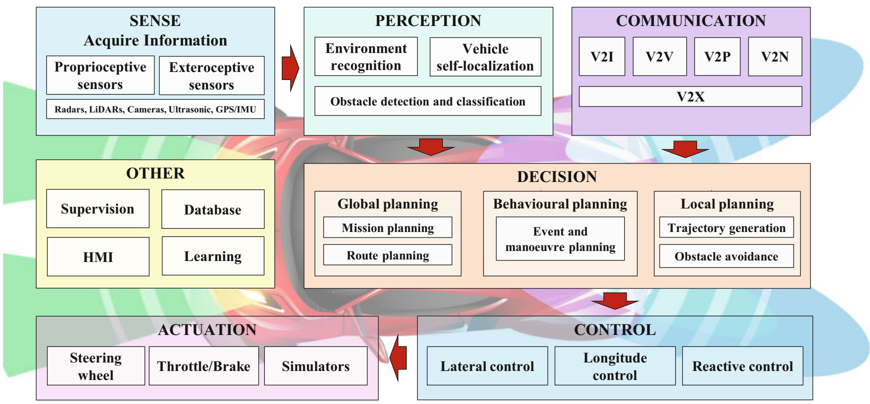

Fig. 1. Autonomous vehicle functions

The complex integration of multipurpose in-vehicle platforms and the distribution of functions between automated vehicles, other vehicles, infrastructure, edge/cloud platforms, and high-performance computing data centres must accommodate solutions for over-the-air (OTA) updates, predictive maintenance, and vehicle-to-everything (V2X) connectivity features as autonomous or highly automated driving requires vehicles to be aware of their surroundings, like traffic situations in the vicinity and road and weather conditions.

To move automated vehicles from research prototypes to commercial products, European vehicle manufacturers and suppliers have committed to enabling fail-operational electronic technologies for environmental sensing, sensor fusion, communication, high-performance processing, by-wire actuation, and other functions. All these electronic component and system (ECS) technologies must be optimally designed in terms of performance, size, cost, power requirements, reliability, availability, and support. Furthermore, automated vehicle control systems have to be scalable to accommodate a multiyear evolution as car models change and data loads increase with additional features and improved sensors.

The ECS technologies developed for HAVs that enhance automated driving rely on technical advancements in semiconductor technologies, electronic components, and systems to enable and ensure operation in particular featuring [1]:

- Fail-awareness (e.g. self-diagnostics, health monitoring)
- Fail-safety (if fail-operational fails)
- Fail-operational functionalities (fault-tolerance and hardware/software (HW/SW) redundancy)

3 Functional Safety Concepts

In such respect, the autonomous vehicles need to be designed to function in various operational conditions such as rain, snow, freeway, urban roads, and the system safety is critical for all these situations, while stringent automotive safety standards are applied to all electronics components and systems.

It is critical to building redundancy into all elements of the design and development process chain for the electronic components and systems, while it is of primary importance to manage the autonomous vehicle electronic system's safety (HW/SW) throughout its life cycle, from the concept/design phase to the end of the life cycle.

In this context, two functional safety standards ISO 26262 and ISO/PAS 21448 (Safety of The Intended Functionality - SOTIF) are the baseline for the assessment of any autonomous vehicle and the underlying electrical/electronic (E/E) control architecture. The V-model is a process model created for software development that has been established for the development of complex safe-critical systems in the avionics and the automotive domain. The V-model of ISO 26262 and ISO/PAS 21448 (SOTIF) is presented in Fig. 2.

ISO 26262 defines a process to ensure the functional safety of electric and electronic (E/E) systems in passenger vehicles before putting them into operation. The process is applied for vehicles that are exclusively operated by human drivers and for vehicles

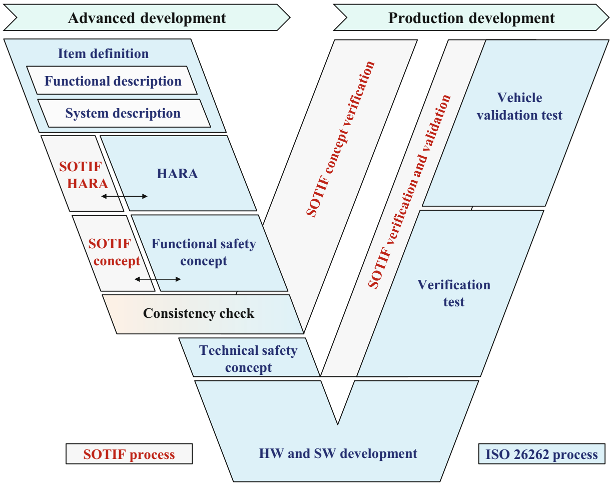

Fig. 2. The V-model of ISO 26262 and ISO/PAS 21448 (SOTIF) [7, 8, 12, 18]

equipped with advanced driver assistance systems, and it does not address the nominal performance of the E/E systems. The ISO/PAS 21448 (SOTIF) provides guidance on the applicable design, verification and validation needed to archive the safety of the intended functionality for SAE level $\leq$2, does not apply to faults covered by ISO 26262 and is used where the situational awareness is critical to safety.

The developments of highly automated driving functions require extensions of standards and safeguarding processes to include interaction with other human traffic (mixed traffic) scenarios, operation in highly complex and hardly predictable environment (open world), loss of human driver as a fallback (fail-operational instead of fail-safe), changing safety-critical functional requirements during product life and intensive use of machine learning techniques.

3.1 ISO 26262

ISO 26262 standard was derived from IEC 61508 [6] and both standards address the safety analyses, like Fault Tree Analysis (FTA), Failure Modes and Effects Analysis (FMEA) and quantified analysis. ISO 26262 standard is dedicated to on-road vehicles, such as passenger cars, trucks, busses and motorcycles, covering the safety concept through production stage for electrical/electronic systems. As defined in ISO 26262, functional safety includes the absence of unreasonable risk owing to hazards caused by malfunctions of E/E systems [7, 14]. Risk reduction is the basic principle of functional safety, where risk is defined as the aggregation of the probability of occurrence of harm and the severity of that harm. Each E/E system has an initial risk based on its function. The associated risks can be reduced in the following ways [7, 14]:

- Reduction of risk occurrence through appropriate safety measures in the product (e.g. watchdog monitoring microcontroller malfunctions) and the process (e.g. by extensively testing the embedded SW/HW).

- Reduction of risk severity. This option is challenging to realise and seldom applied.

The concept of functional safety implies that there is no absolute safety. Residual risk is always present even in the safest systems, and if this residual risk is below the continuously shifting acceptance limit, the products are considered safe.

Functional safety focuses on failures of safety-related ECSs that need to be prevented and/or controlled appropriately. ISO 26262 defines faults and failures as follows [7, 8, 14]:

- Fault: Abnormal condition that can cause an element or an item to fail.
- Error: Discrepancy between a computed, observed, or measured value or condition and the right, specified, or theoretically correct value or condition.
- Failure: Termination of the ability of an element to perform a function as required.
- Failure mode: A way an element or an item fails.

Error events can either occur systematically or randomly. Systematic HW/SW error events are deterministic and can be eliminated by improving the design/manufacturing process [4]. Random error events omit SW reasons, but random HW error events can be caused by component ageing or environmental factors.

Fail-operational systems require redundancy, for example, homogenous redundancy (element duplication) against HW error events or diverse redundancy against systematic HW/SW error events [4]. A fail-safe is considered if one or more failures occur, and the system or HW/SW elements are possibly brought into an active or passive safe state and avoid using the unreliable systems/elements.

For autonomous vehicles, we can consider that fail-operational systems remain functional if the failure is tolerated, and the component remains active [4]. This considers that HW/SW elements showing fail-operational behaviour continue to execute specific functions at a satisfactory performance level for a given time.

An automotive-specific risk management framework is provided by the ISO 26262 standard in order to determine different risk classes called Automotive Safety Integrity Level (ASIL). The ASIL definition replaces the concept of (1) Likelihood from the safety risk definition with (2) Controllability to enforce how well a potential failure can be managed inside the system and not how likely it is to occur [5, 7].

$$Risk = Severity\ x\ (Exposure\ x\ Likelihood) \tag{1}$$

$$Risk = Severity\ x\ (Exposure\ x\ Controllability) \tag{2}$$

ISO 26262 standard and its "V-model" framework reflect accepted practices for ensuring automotive safety. The autonomous vehicles (levels 4 and 5) present challenges in mapping the technical aspects of the vehicle to the "V-model" approach. One of the challenges is that in a fully autonomous vehicle, the "driver" is no longer actually driving the vehicle and can no longer be counted on to provide control inputs to the vehicle during operation [7, 8]. An approach to fit autonomous vehicle safety assurance within an ISO 26262-based V framework is presented in [9] where five major challenge areas in testing according to the V model for autonomous vehicles are identified: driver out of the loop, complex requirements,non-deterministic algorithms, inductive learning algorithms, and fail-operational systems.

ISO 26262 strictly follows the concept of requirement-based development. The hierarchy of the safety requirements is shown in Fig. 3 [4, 7]. This requirement-based approach is essential of the V-model used on the different abstraction levels [4]. Appropriate requirements are required to perform the verification and validation activities properly.

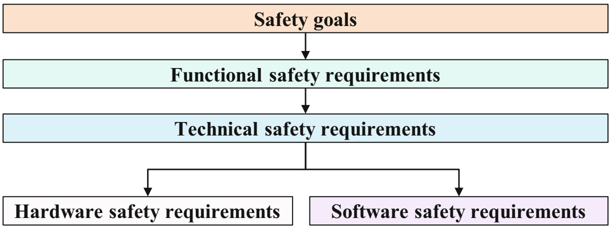

Fig. 3. Requirements abstraction levels of the ISO 26262 [4, 7]

There are no agreed quantifiable dependability measures based on which HW and embedded SW can be qualified to achieve SAE autonomous driving capabilities of levels 4 and 5.

Safety concepts for autonomous vehicles are and in the last years are extended beyond the functional safety intent of ISO 26262.

3.2 SOTIF

ISO/PAS 21448 "Safety of The Intended Functionality (SOTIF)" is the follow-up of ISO 26262 with the aim of defining what should happen at the system level when non-systematic or random error initiators occur in terms of software and ML as well as through mistreatment/misuse or environmental factors. Safety concerns are not by definition determined by system failures; they could be determined by scenarios that were not considered in the design of the autonomous driving systems.

An example is driving on an icy/slippery road; SOTIF requires that these kinds of conditions be included for threat modelling and risk mitigation. The SOTIF risk identification and evaluation steps determine whether plausible harm may result from hazardous events. PAS 21448 defines hazardous events as a mixture of a potential system hazard and a specific operating situation.

The flowchart of SOTIF elements used for the evaluation of the use cases, starting from the functional and system specifications to the standard verification and validation for identifying the accepted risk is presented in Fig. 4 [12, 17].

ISO 26262 defines operating situations as scenarios that can occur during a vehicle's life. An example of a hazardous event is provided by PAS 21448 as the following [12]:

- Hazard: Unintended automatic emergency brake activation at 80 km/h for 1 s
- Operation situation: Operating on a highway

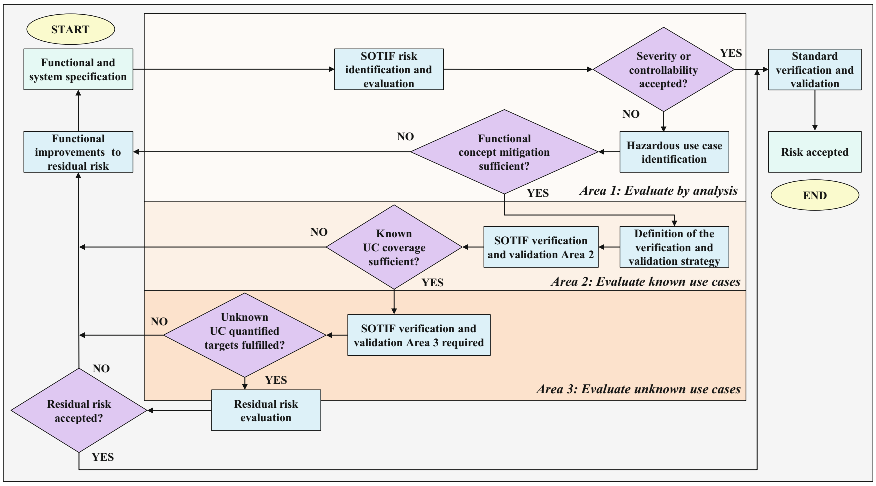

Fig. 4. SOTIF use case (UC) evaluation flowchart [12, 17]

After identifying hazardous events, the SOTIF process [12] focuses on identifying triggering events that may lead to unintended system behaviour and, ultimately, one or more of the identified hazardous events. The standard defines triggering events, including foreseeable misuse scenarios, as driving scenarios with specific conditions that serve as an originator for a subsequent system reaction. The triggering events analysis intends to identify weak system points and the possible related scenarios that could lead to an identified hazardous event. Triggering events can be divided into two types [12, 15]:

- Events that exceed the performance limitations of the system and components. Both sensors and algorithms limitations are included in this category. For example, a highly automated driver system may be operating within their intended operating domain (e.g. highway, rural roads, suburbs, urban streets, good weather, normal landscape) but then the vehicle encounters a new roadway configuration with different driving, lighting, environmental conditions, visibility - day, night, fog, haze, smoke, rain, snow, etc. The new lighting conditions may be beyond the technical specifications of the autonomous vehicle camera sensors or the training data of the ML and neural network algorithms.
- Events that contain human factor limitations, particularly in relation to the driver-vehicle interface. This category covers several human factors elements. For example, the driver is failing to keep their hands on the steering wheel; driver's understanding of the system capabilities and limitations, driver's responsibilities; and driver's ability to understand and react to warnings and alerts. The human factor limitations do not cover intentional misuse of the autonomous system (e.g. driver's takeover requests are deliberately ignored, or products intended to override the system limitations are explicitly used).

PAS 21448 defines the scenarios in which triggering events occur as a sequence of scenes (e.g. photos of the environment) starting with the initial scene and progressing to a succession string of events and actions (e.g. triggering events and system responses). As a result, the captured “landscape” has several characteristics, such as dynamic/static elements, terrain topography, scenery, and self-representations of actors and observers.

PAS 21448 classifies scenarios as known-safe or known-unsafe depending on whether the mitigation strategies sufficiently reduce the SOTIF risk [12, 15]. Another category, called unknown-unsafe, includes scenarios that are not known at the time of system design and that are identified through long-term vehicle tests, simulations, random input testing, and other measures.

PAS 21448 does not demarcate between temporary and permanent elements of the scene and includes “environmental conditions” as part of the scenery element, while for autonomous vehicles the environmental conditions (e.g., weather, visibility, lighting) should include further dynamic elements, such as traffic, objects, and pedestrians [15]. In the case of level 4 autonomous vehicles that need to transfer the control back to the driver, it helps to distinguish the permanent variables in order to identify elements of the scenario that a system could predict with increased confidence. In order to transfer control to the driver with enough time for the driver to regain situational awareness, these variables may be linked to geocoding or mapping information.

The work in the AutoDrive project derived triggering events through analysis of the physical limitations of sensors/communication components and probabilistic nature of algorithms and for a triggering event, initial scenes were considered by connecting the triggering event to a potentially hazardous event to construct a SOTIF scenario.

3.2.1 Scenarios Examples

The work performed in the AutoDrive project has considered hazardous events and triggering events to constrain the development of scenarios. One example can be considered for the lane centring manoeuvre of the highly automated vehicle. This manoeuvre attempts to keep the vehicle centred in the travel lane. A relevant hazard identified is “lane/roadway departure while the system is engaged”.

This use case starts developing scenarios by identifying hazardous events and corresponds to the second step in the SOTIF process. For developing the operating situation for the hazardous event, the use case was defined for the permanent-regional variables shown in the following example where the hazardous event was derived through this process [12, 15]:

- Hazard: Lane/roadway departure while the HAV is engaged.
- Operating situation: Operating in a lane on a two-way highway (e.g., restricted access on a lane).
- Potential crash type: Sideswipe (same direction of driving).

Permanent-regional variables define the overall context of a vehicle journey and maybe the only variables that last throughout the section of the journey in which the autonomous vehicle is actively involved. Permanent-regional variables are aligned with the examples of operating scenarios provided in the PAS 21448 standard. Worst-case assumptions can be made upon other conditions when assessing the hazardous event at this level.

In certain operating situations, several variable categories may not be relevant to the scenario (e.g. shoulder type - paved/gravel or dirt). Leaving out several variables is compensated by making sure that all relevant cases considered are included as subsets of the stated operating situation.

Triggering events are developed independently from hazardous events and considering the autonomous system limitations and potential driver misuse. In the project initially only SOTIF Type I triggering events were considered. Examples of triggering events developed for highly automated driver system are presented below [12, 13, 15]:

- The lane model incorrectly establishes the lane lines.
- The road model is wrongly established in the absence of clear lane markings.
- The cameras missed detecting landmarks due to inadequate contrast between the landmarks and the environment.
- V2X communication fails to interact with other vehicles due to weather and road conditions.

3.2.2 Applications Beyond SOTIF

The system safety strategy for Highly Automated Driving (HAD), described in SOTIF, is illustrated in Fig. 5 that considers the functional safety for overall autonomous system robustness, including the elements defined by SOTIF for overall system performance.

Propulsion
SOTIF: defines limits in control authority
Functional Safety: defines the system architecture robustness

Connectivity
SOTIF: extend analysis
Functional Safety: SOTIF scenarios developed using the framework could translate into scenarios where V2I may improve vehicle operation.

Cognition
SOTIF: decouple the safety from the comfort aspects.
Functional Safety: defines the system architecture robustness

Perception
SOTIF: defines detection requirements, analyse sensor limitations.
Functional Safety: drives the sensor architecture robustness

Fig. 5. System safety strategy for HAD

The framework used in the project goes beyond the SOTIF prescriptions that present a general classification of challenging scenarios for autonomous driving systems. The framework helps to characterise scenarios for vehicle-to-infrastructure (V2I) and improved GPS mapping (e.g., for geofencing) by separating permanent-regional and permanent-local variables depending on the frame of reference,

Applying a common framework for defining operating situations and scenarios in the development of autonomous vehicles and for implementing infrastructure capabilities helps provide consistency between analyses (e.g., types of situations where autonomous vehicle- based systems may rely more heavily on V2I).

Moreover, the AutoDrive project advances the current level of safety and reliability by driving forward the fail-safe systems, which switch to a safe state when they cannot operate, towards fault-tolerant systems that avoid service failure when faults are introduced to the system and fail-operational systems that continue to operate when one of their control systems fails until the vehicle is brought into a “safe state”. For the SAE autonomous driving capabilities of level 4 and 5, “safe state” means approximately 7–15 s for conditional autonomous driving and several minutes (<5 min), depending on the situation, for high and full autonomous/automated driving to perform an autonomous “safe stop” (coming to a standstill at a non-hazardous place).

The concepts used in the AutoDrive ECSEL project [1] enable the introduction of autonomous/automated driving capabilities of level 4 and 5 future vehicle categories are presented below. Particular focus is given to the embedded system design for secure, safe and low-latency communication between the autonomous vehicle and the environment.

The building blocks for defining predictive functional safety for autonomous vehicles are illustrated in Fig. 6.

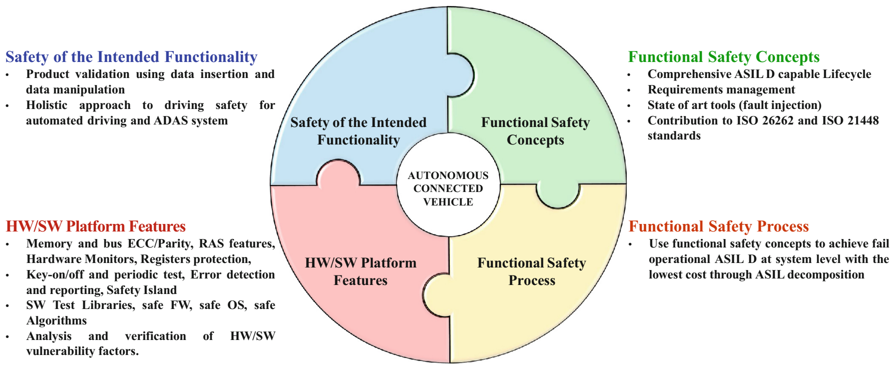

Fig. 6. Predictive functional safety building blocks

Predictive functional safety is intended to be applied to different autonomous driving use cases that include Artificial Intelligence (AI), ML software and algorithms that require testing according to standards designed to ensure the safe operation of AI-driven autonomous systems and further including virtual reality simulators and virtual validation.

4 Fail-Operational Design for Autonomous Vehicles

A system is considered fault-tolerant if it can perform its intended function also in the presence of faults. Fault tolerance is always based on some sort of redundancy since single-channel systems are prone to single-point failures. There are various ways to enhance the fault tolerance of a system [4]:

- Fault masking is a technique where it is ensured that the system produces correct outputs only, even in the presence of a fault. Majority voting is a typical example of this.

- Fault detection with subsequent fault containment ensures that the fault is isolated and cannot propagate. Fault detection can be based on various diagnostic principles, like cross-checks, plausibility checks, etc.
- Alternatively, fault detection with subsequent fault recovery ensures that the system recovers appropriately after a fault, to continue normal operation.

Typical domains where redundant designs are applied [4] are listed below:

- Hardware and systems
- Information redundancy
- Communication redundancy
- Time redundancy
- Software

The autonomous vehicles require support from infrastructure in order to enhance the fail-operation functions and to improve the security, reliability, trustworthiness. The inclusion of scenarios for V2I, improved GPS mapping and Global Navigation Satellite System (GNSS) is important for defining scenarios for fail-operational functions supporting V2I. The digital information provided by the V2X systems should be treated together with the safety and security aspects to ensure proper integrity while considering that the autonomous vehicle should operate safely in conditions where V2X is not available.

4.1 System Redundancy

A fault-tolerant V2X communication topology must ensure that the failure of one communication channel does not affect the communication of the others. For level 4, it is assumed that immediately after the first fault of the V2X communication system, the driver must be warned. It is then the driver's decision to seek assistance with a professional service or to continue the driving cycle.

Advancing towards fail-operational systems requires increased reliability and availability of components, as well as new redundancy schemes, architectures and methodologies to appropriately manage and balance complexity (e.g. software complexity [18]), cost, robustness and flexibility.

The domains of interactions between the autonomous vehicle and the environment through communication and sensing capabilities are covered under the descriptor of V2X. They consist of communication and sensing interactions between the autonomous vehicle and the dynamically changing environment (e.g., other terrestrial vehicles, pedestrians, cyclists, aerial and naval/maritime vehicles, different types of IoT devices, etc.), the communication and sensing interactions between the vehicle and its static environment (e.g., charging stations, traffic signals, street lighting, tolling systems, electronic parking, roads, buildings, home, IoT devices, etc.), communication and sensing interactions with different service providers (e.g., network communication providers, cloud/edge service providers, etc.) and communications with the owners, users and mobility service providers (e.g., vehicle owners, users, vehicle fleet owners/operators, vehicle producers, IoT service providers, maintenance providers, etc.).

The activities addressed at the current ITS-G5 capabilities for vehicle-to-vehicle (V2V) and V2I, designed to allow vehicles in the intelligent transportation system (ITS) to communicate with other vehicles or infrastructure technologies. The following section explores the challenges for next-generation V2X based on cellular connectivity (fifth-generation (5G) of mobile communication systems and beyond).

The methods and techniques presented are advancing hardware/software redundancy concepts along with approaches for self-diagnosis and health monitoring, self-configuration and self-adaption of electronic components and systems and communication modules for increased stability, reliability, robustness, fault tolerance and functional safety.

These electronic components and systems technologies are optimally designed in terms of performance, size, cost, power requirements, reliability, availability and support, while considering that autonomous/automated vehicle control systems need to be scalable, resilient, and maintainable.

4.2 Fail-Operational Concepts for V2X Systems

Implementing fail-operation concepts for V2X systems includes challenges that have to take into account the surroundings that influence the autonomous vehicle's decisions and are governed by thousands of parameters, regarding conditions such as:

- Traffic conditions.
- Pedestrian conditions.
- Weather conditions.

When V2X communication is established, an autonomous vehicle needs to examine and scrutinise the information being transmitted by other autonomous vehicles and smart infrastructure in the area.

Fail-operational architectures are in the development phase for autonomous vehicles where fail-operational behaviour is required. For the V2X systems used in future autonomous vehicles, it is important to consider the attributes of fail-operational architectures and the optimal type, degree and range of fault tolerance. The degree of required fault tolerance has an impact on cost, weight and required packaging space for connectivity systems. It also impacts the trade-off for the allowed functional and performance degradation of fail-operational components after the first failure, in order to identify which functions remain active and which performance elements they must provide in order to stay safe and provide fully functional parts and emergency functions for the V2X system. In autonomous systems, the number and type of faults that are accepted, need to be defined, before the vehicle shall enter a predefined emergency mode or stop completely.

For fault-tolerant systems that rely on incoming and/or outgoing communication signals, fail-operational communication channel systems are needed along with redundant communication channels using an appropriate autonomous vehicle V2X connectivity architecture that addresses:

- Degree of fault tolerance

- Time- or event-triggered processing
- Fault tolerance protocols
- Worst-case execution time
- Error handling
- Topology

A fault-tolerant V2X communication topology has to ensure that the failure of one communication channel does not affect the communication of the others. For level 4, it is assumed that immediately after the first fault of the V2X communication system, the driver must be warned. It is then the driver's decision to seek assistance with a professional service or to continue the driving cycle.

Ensuring the decisions made by the self-driving vehicle are safe is the hardest part of reaching level 5 autonomy. Safeguarding fail-operational safety requires to test, redesign and validate decision-making software algorithms over many driving scenarios, including virtual validation ones.

The testing of the V2X systems includes testing V2X for conformance, interoperability quality of service (QoS); testing for functionality and performance and testing for V2X security conformance.

Advancing HW and SW redundancy concepts along with approaches for self-diagnosis and health monitoring, self-configuration, and self-adaption of systems-on-chip and ECS are key for increased stability, reliability, robustness, fault-tolerance, and functional safety.

The challenges to design and implement fail-operational solutions for V2X systems is related to the changing landscape of V2X communication technologies and their coexistence (e.g., ITS-G5 [in Europe], WAVE-DSRC [in US] based on the IEEE 802.11p Wi-Fi [WLAN] IEEE 802.11a standard protocol, the V2X long term evolution [LTE] cellular V2X standard [LTE-V2X] introduced by 3rd Generation Partnership Project [3GPP]). These technologies are addressing basic safety use cases, e.g. road work and emergency brake warnings, traffic light information and emergency vehicle notifications. In order to address several more advance use-cases, the specifications of both technologies are further developed in the standardisation working groups of 3GPP and IEEE 802.11. The IEEE 802.11 next-generation V2X (NGV) task group was established to create a new amendment IEEE 802.11bd. The next cellular V2X standard based on 5G is included in Release 16 of the standard and is referred to as new radio V2X (NR-V2X).

The advanced V2X use cases are aiming to improve road safety, assist in better traffic management and provide the infotainment needs of passengers. The applications are divided into four main categories: advanced driving, remote driving, extended sensors and vehicle platooning. The QoS requirements for these use cases are presented in Table 1 [19].

For all fail-operational V2X communication, automotive systems developers need to handle signals from multiple suppliers, with protocols and requirements that cover different global regions using positioning data from multiple satellite systems (Galileo, GPS, GLONASS, BeiDou, regional networks and future cellular networks).

Table 1. QoS requirements of advanced V2X applications [19]

Use case group	Max. latency (msec.)	Payload size (Bytes)	Reliability (%)	Data rate (Mbps)	Min. range (meters)
Vehicle platooning	10–500	50–6000	90–99,99	50–65	80–350
Advanced driving	3–100	300–12000	90–99,999	10–50	360–500
Extended sensors	3–100	1600	90–99,999	10–1000	50–1000
Remote driving	5	–	99,999	UL: 25 DL: 1	–

(UL – Uplink, DL – Downlink)

4.3 Safety Use Case Scenarios

In the AutoDrive project, the heterogeneous V2X communication platform establish connectivity between vehicles (V2V) by the onboard units (OBUs); connectivity between the vehicles and the infrastructure (V2I) like traffic lights and lighting poles established by the OBUs and roadside units (RSUs); and through the use of GPS signals as illustrated in Fig. 7 [1]. In addition, some internal communication links are used for sensor readouts, user interfaces etc.

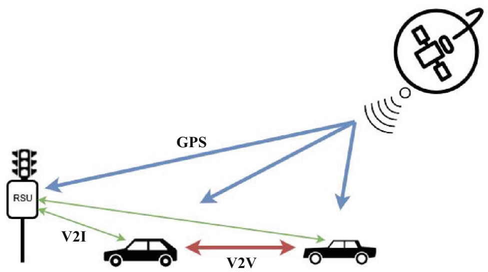

Fig. 7. Connectivity scheme (simplified) [1]

A modular V2X platform is used as an open development environment for prototyping advanced autonomous/automated driving [1]. The safe, secure and low latency communication requirements enable the intended use case scenarios through vehicle connectivity to back-end servers, road infrastructure and other vehicles or moving objects on a common platform.

The V2X platform is based on ETSI ITS-G5 vehicular networking technology focusing on safety use case scenarios [1]. Communication entities provided by the platform assure the communication among the moving vehicles, between the vehicles and the fixed infrastructure (e.g. traffic lights and lighting poles). The platform supports the integration of safety functions that rely on data also coming from other vehicles and could provide active safety with the low latency of the V2X network.

Typical use case scenarios covering both V2V and V2I communication are; vulnerable road users warning (VRUW), intersection movement assist (IMA), and green light speed advice/time to green (GLOSA/TTG) as illustrated in Fig. 8 [1], but also emergency electronic brake light (EEBL), forward collision warning (FCW), blind-spot warning (BSW), and lane change assistant (LCA).

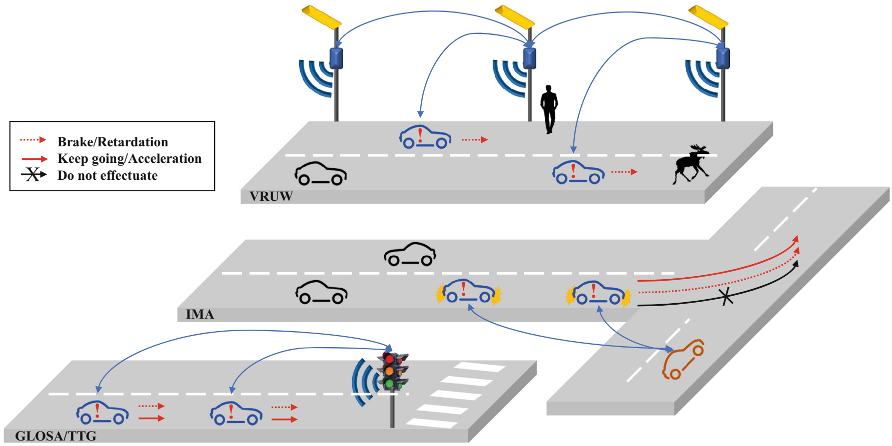

Fig. 8. Safety use case scenarios (VRUW, IMA, and GLOSA/TTG) [1]

The vulnerable road users warning scenario transmit a warning signal by V2I communication from the RSU enabled lighting poles to the host vehicle (OBU) when VRUs are located in or nearby the road [1]. The VRUs like pedestrians (or wild animals like a moose) are detected by a radar which communicates with the RSU. Additional functionality for maximum safety and the minimal energy consumption is moving from time-based to motion-based dimming. The streetlights are automatically activated as soon as vehicles and/or VRUs are detected in the area. The general flow goes from sensing motion by the RSU enabled lighting poles, to sending data to the vehicles in the area. Display warnings appear in the host vehicles along with the location on the map.

The intersection movement assist scenario transmits a warning signal by V2V communication to the host vehicle (blue) when it is going to enter an intersection and a remote vehicle (orange) is driving in the perpendicular direction, and a high collision probability situation occurs [1]. The general flow goes from receiving data if a remote vehicle is moving perpendicular to the host vehicle and a risk of collision occurs, through the calculation of relative positions together with paths calculations, to sending an alarm.

The green light speed advice is based on time to green information transmitted by V2I communication between the traffic light (RSU) and the host vehicle (OBU), plus the distance between the host vehicle and the traffic light given by GPS coordinates [1]. Based on the sensing of the traffic light status by the RSU and the sending of data to the vehicles approaching the intersection and through relative position and optimal speed calculations, speed advice are given to the host vehicles.

The safety use cases will be further explored by IEEE, 802.11 next-generation V2X (NGV), and new radio V2X (NR-V2X) or C-V2X, technologies for mission-critical services providing ultra-low latency, high reliability, availability and strong security.

These technologies are expected to have better coverage, lower latency (e.g. less than 10 ms) enabling real-time alerts upon accidents, notification on weather and risky road conditions.

5 Conclusion and Discussions

To move automated vehicles from research prototypes to market launch, the vehicle manufacturers and suppliers depend on enabling fail-operational electronic technologies for surround sensing, sensor fusion, communications, high-performance processing, by-wire-actuation, and other functions. All these ECS technologies have to be optimally designed in terms of performance, size, cost, power requirements, reliability, availability, and support. Furthermore, automated vehicle control systems have to be scalable to integrate the next generation of fail-operational ECS that extend the autonomous functions of the vehicles.

The paper presented an overview of the main automotive standards ISO 26262, ISO/PAS 21448 that address the functional safety and the concepts behind the work in AutoDrive to increase the reliability and robustness of automated driving systems by applying the proposed framework to different use cases, identify the need for HW, SW, communication redundancy and provide the safety use case scenarios for V2X in cooperative manoeuvres with autonomous vehicles.

The components and systems developed in the AutoDrive project are supporting the advancing of HW/SW and embedded systems redundancy concepts along with approaches for self-diagnosis and health monitoring, self-configuration, and self-adaption of systems-on-chip, electronic components and systems for increased stability, reliability, robustness, fault-tolerance, and functional safety to provide the next level of fail-aware, fail-safe, fail-operational, and novel vehicle architectures.

The development of concepts for fail-operational autonomous vehicles, support the adoption of autonomous vehicles that help to reduce CO_2 emissions, improving air quality, traffic efficiency and safety while advancing towards an accident-free mobility scenario ("Vision Zero").

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Ongoing Cybersecurity and Safety Standardization Activities Related to Highly Automated/Autonomous Vehicles

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Abstract. Highly automated/autonomous vehicles using extended features like Vehicle to Vehicle (V2V) or Vehicle to Infrastructure (V2I), cognitive systems for decision taking, needing extensive perception features and sophisticated sensor functions, cause a considerable shift in safety and cybersecurity (trustworthiness) co-engineering and assurance. To achieve trust of the public/users, standards and certification/qualification are challenged, not comparable to conventional "singular vehicle only" issues. The paper highlights the necessary evolution in the automotive and related standardization landscape, including ethics guidelines and recent activities, and the consequences from upcoming UNECE (United Nations Economic Commission for Europe) regulations. An Overview on ongoing work in large European ECSEL projects, SECREDAS and AutoDrive, including standardization, is provided.

Keywords: Automated driving · Autonomous vehicles · Functional safety · Cybersecurity · Standardization · Trustworthiness · Ethics guidelines · SotiF (Safety of the intended Functionality) · Ethics guidelines

1 Introduction

Autonomous vehicles and even assistive features of highly automated vehicles area causing a shift in the basic control paradigm of vehicles. In the past, the main task of vehicle systems was to capture the driver's control command and transmit it to the actuators without misinterpretation. The main focus was functional safety, e.g. the protection against failures in the electronic, electric and programmable electric systems (E/E/PE) related to this task. This was addressed in ISO 26262 [1], a domain specific adaption of the generic functional safety standard IEC 61508 [2]. The first version was published in 2011, the second version in 2018.

With the change towards assistive features, the role of the E/E/PE-systems also changed towards an optimization of driver's control command and even autonomous decision making. While increasing driving efficiency and road safety, the potential for adverse effects are also increasing. Manipulated E/E/PE systems are no longer restricted to an incorrect reaction to driver's control command but can also trigger completely new actions. In a similar way, systems, which perceive and react on their environment to

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optimize actions or take decisions, need a certain level of guarantee that the perceived environment represents the real environment.

The automotive industry and research field reacted on these new challenges and developed methods and approaches, which resulted in standards, collecting the best practice and industrial accepted and proven engineering processes.

Noteworthy results are ISO PAS 21448 "Road vehicles—Safety of the intended functionality" [3] which focuses on novel parts of safety aspects beyond nominal performance, as introduced by automated and autonomous vehicles, and ISO/SAE DIS 21434 "Road vehicles—Cybersecurity engineering" [4], a joint effort by ISO and SAE to standardize automotive cybersecurity engineering.

In the following chapter, we will present an overview about ongoing developments towards highly automated and autonomous vehicle systems and their impact on society. This will be followed by an overview about automotive standardization, status and content. Finally, we will conclude with an overview about the SECREDAS and AutoDrive research projects referencing some key results, and the activities in addressing novel automotive challenges.

2 Automotive Standardization Activities

2.1 Automotive Standardization Landscape

There does exist a huge landscape of automotive standards with respect to electric, electronic and programmable electronic (E/E/PE) systems. Most are covered by ISO TC22, "Road vehicles", and the associated subgroups. Other areas relevant for highly automated/autonomous systems are covered e.g. for ITS (Intelligent Transport Systems) in ETSI and ISO TC 204, or by ISO/IEC JTC1 for IoT (Internet of ThingsSC41) and Artificial Intelligence (ISO/IEC JTC1 SC42), particularly concerning trustworthiness of such systems (technically, but also from the ethics viewpoint) (see Fig. 1).

We focus here on standardization for dependability. Dependability summarizes the ability of a system to be trusted by its users, e.g. to perform its mission as intended. This notion was introduced in [5], and the different dependability attributes, threats and means were introduced:

- Safety and security requirements can be incompatible.
- Requirements can be derived from the other domain (safety requirements, which cause a security requirement and vice versa).

Historically, a major focus of the automotive domain was on functional safety as the subset of safety which was focused on risks due to failures in the E/E/PE-systems (ISO 26262 [1]). Due to the rising number and complexity of sensors, communication and decision taking systems, and the increasing security risks endangering safety, this was extended to include automotive cybersecurity and safety of the intended functionality (SotiF) [3].

Figure 2 gives a view on these attributes. Important are the cross-relations between all these attributes. One of the first systematic analysis of this has been done in [6], identifying the following relations:

Fig. 1. Standardization landscape for (highly automated) automotive systems

- Requirements can be incompatible
- Requirements can be derived from the other domain (safety requirements which causes a security requirement)

In order to identify these interdependencies a conflict resolution and integration of requirements was proposed in [6].

Based on this, newer standards (one of the additions in the 2018 version of ISO 26262 [1], compared with the 2011 version) required communication channels for such interactions between different dependability related disciplines. The approach in the automotive domain was to require such communication channels and give guidance from the respective standard towards other domains. As an example, ISO 26262:2018 requires communication channels and contains guidance on the interaction from functional safety towards cybersecurity (particularly in Part 2 and Annex F of Part 2).

2.2 Safety of the Intended Functionality

The SotiF process [3] is based on ISO 26262 [1] and it is assumed that the lifecycle is enhanced with additional activities to ensure that the likelihood of a hazardous event is

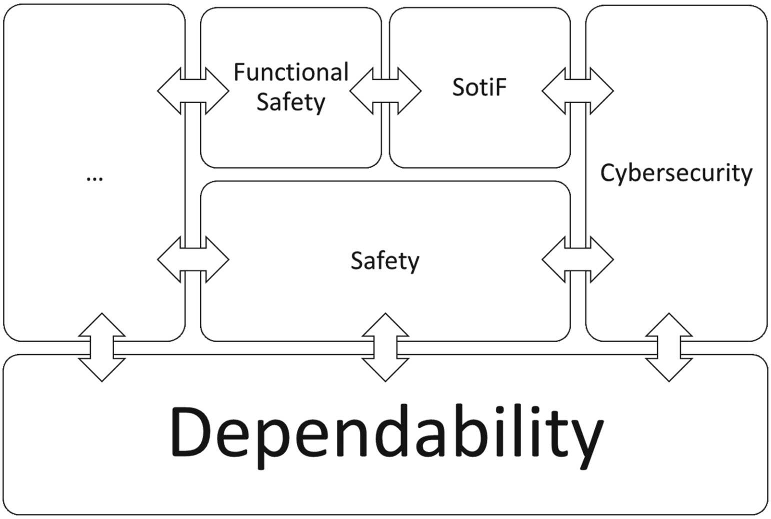

Fig. 2. Automotive dependability with the focus on safety and cybersecurity

sufficiently low. The assumption is, that, compared to ISO 26262, which scope does not include nominal performance issues, a certain amount of unsafe behavior is not known, (e.g. of sensors and their intended functionality which may not be sufficiently known).

Figure 3 gives an overview of the concept and approach of SotiF. This is based on the assumption that, compared to functional safety, not all situations are known for SotiF, since SotiF is based on a perception and reaction of the real world.

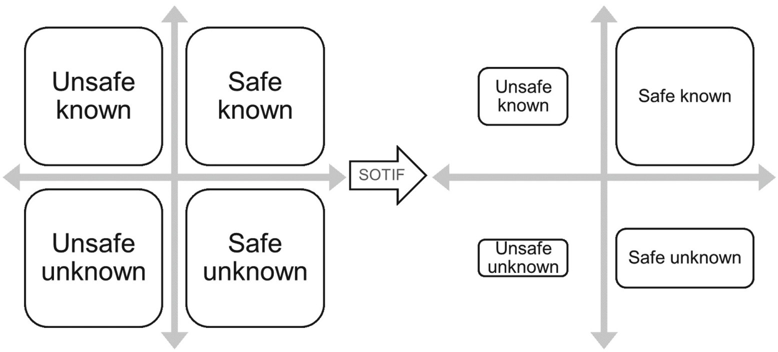

Fig. 3. Overview of the SotiF approach

The goal is therefore not only a reduction of the risks of known hazards to a tolerable level but also a reduction of the unknown. Examples for this are the difficulties Volvo's self-driving cars had with the detection of kangaroos [12]. This was based on the different manner of movement (e.g. hopping) compared with other, and especially with native large animals from Sweden. This reduction of unknowns includes also a learning of the engineers about the later application environment to understand potential difficult scenarios and situations.

Based on this a test and verification plan can ensure that the vehicle has a sufficient rate of "safe" reaction, even on difficult scenarios and under problematic circumstances. This is supplemented by real world evaluation of the system. UL4600 was especially developed for testing and evaluation [13]. This document describes an approach to ensure safe self-driving cars based on an extended safety-case and with a focus on highly-automated and edge-case analysis [14].

Nevertheless, the topic on how to ensure sufficient testing and assurance is still not completely addressed. A sufficient combination of "testing in the loop" (based on simulation, safe, cheap but only pre-defined scenarios), "testing in controlled environments" (test-tracks, safe but environment does not contain surprises) and "real world testing" (safety risks, costly) needs research.

2.3 Automotive Cybersecurity and UNECE Draft Regulation

The first official guideline regarding automotive cybersecurity was SAE J3061 [7]. This document was intended as a first step, collecting engineering methods and approaches, which could be applicable to the automotive domain. This was not an international standard, but a first step as guidebook. Work with this guidebook demonstrated applicable methods, but also still existing gaps [8, 9].

Based on this, ISO and SAE decided to cooperate on the development of an international standard regarding automotive cybersecurity engineering. Here an additional driver of this development was the parallel development of a new UNECE draft regulation [24] regarding cybersecurity for the type approval. Currently the draft international standard (ISO/DIS 21434) was published and the publication of the international standard (IS) is planned for end of 2020.

The standard offers requirements and guidance on four topics. Processes for cybersecurity on organizational and project level define a framework for cybersecurity engineering and the integration of cybersecurity with other disciplines. This is followed by an automotive specific approach towards risk management, based on the generic risk management approach from ISO 31000. The last two parts are on cybersecurity engineering, including production, and post-production with a focus on maintaining cybersecurity of the system.

2.4 Software Update (Over the Air) and UNECE Draft Regulation

Similar to the topic of cybersecurity, UNECE developed a draft regulation on software update [25]. This time standardization lagged behind and the standardization process started after the draft regulation was available. The focus of the draft regulation is on requirements for the update system in vehicle and backend and on organizational processes. The goal is to a) ensure updates while mitigating safety, security and other risks and b) controlling the versions of software on a vehicle for regulatory processes.

Since regulatory requirements are on a very high level there was a need to collect the interpretation and state of the art. For this a standardization project was started last year, which will develop a standard on software update engineering (ISO 24089). Here we have also a strong linkage between technical work and standardization. The topic of fail-safe/fail-tolerant update systems is important for the overall AutoDrive objective of fail-safe/fail operational automated vehicles, and security topics are the main focus of SECREDAS. There is a overarching activity with multiple project partners to develop an implementation of "IEEE-ISO 6100.1.0.0 Uptane Standard for Design and Implementation".

Besides implementing the standard on a relevant environment to demonstrate the technology, an additional goal is to extend the focus from secure updates towards safe updates. This includes an update framework which

- ensures before the update that the vehicle is in a status where an update is possible (vehicle state, usage of systems, available energy, consent from vehicle user),
- controls and restricts vehicle operations during the update in order to avoid undefined situations (usage of a half-updated ECU),
- and ensures safe operation after the update (self-tests and monitoring, inform the vehicle user about success/failure and changed features)

The main challenge here with a remote update, compared to an update during regular maintenance is the unreliable connection, missing trained staff and restricted control about the vehicle environment and state.

2.5 Ethics Guidelines and Rules for Autonomous Driving

Several organizations from standardization, governmental advisory groups, professional and scientific associations have already produced guidelines and recommendations on how ethical principles should be considered in taking up new technologies, particular when applying cognitive systems in automation (not only automotive for highly automated/autonomous driving).

A few examples (not exhaustive) are [10, 11]:

- Informatics Europe and ACM Europe [18] "When Computers Decide"
- The IEEE Global Initiative for Ethical Considerations in Artificial Intelligence and Autonomous Systems (AI/AS) (April 2016)
    - Ethically Aligned Design: A Vision for prioritizing human wellbeing with artificial intelligence and autonomous systems
    - Identification and recommendation of ideas for standards projects focused on prioritizing ethical considerations in AI/AS.
    - IEEE ECAIS "Ethics Certification for Autonomous and Intelligent Systems" (Industry Connections Activity Initiation Sept. 2018).
- IEC/SMB Ad-hoc group on autonomous systems and ethics (AHG 79), recommendation "…*assessing the role of IEC and standards in addressing ethics, trust and values particularly in autonomous systems, and making recommendations. The review should consider the work of JTC 1/SC 42 (Artificial Intelligence), ACART (Advisory*

Committee on Applications of Robot Technology), ACOS (Advisory Committee on Safety), TC 59 (Performance of household and similar electrical appliances), TC 100 (Audio, video and multimedia systems and equipment), SyC AAL (Systems Committee on Active Assisted Living), SyC Smart Cities, IEEE, ISO etc."

- ISO/IEC JTC1 SC42 (Artificial Intelligence): Technical Management Board resolution 53/2018: *Approval of the inclusion of certain aspects of 'societal concerns' in the ISO/IEC JTC1/SC 42 programme of work.*
- ISO TC241 Road Traffic Safety (RTS) – new work item under discussion: "Ethical considerations for driverless vehicles" (IEC 39003), which had to be redrafted because of criticism from other automotive-related TCs (e.g. TC22).
- EC: "Ethics Guidelines for Trustworthy AI" [19]
- German Federal Ministry of Transport and Digital Infrastructure (June 2017), "Ethics Commission – Automated and Connected Driving" [20]

The document of the German Ethics Commission for Automated and Connected Driving defined 20 principles to follow for an ethical and human-centered approach to approve autonomous vehicles. This ethics commission was the first of its kind and the approach was the initiator for the EC to start their ethics task force, leading to high level structural dialogues under German leadership, with members (according to the report of June 2018) Germany (Chair), Austria, Luxembourg, United Kingdom, European Commission, ACEA, CLEPA (automotive associations). The report is available (see [19]). Most principles are also reflected in the draft discussions to ISO DTR 4804 ([16], derived from [15]) and the NHTSA (National Highway Traffic Safety Administration, US) (shortened):

- The primary purpose of partly and fully automated transport systems is to improve safety for all road users, to increase mobility opportunities and to make further benefits possible. To preserve personal autonomy, which means that individuals enjoy freedom of action, is another principle
- The protection of individuals takes precedence over all other utilitarian considerations. The licensing of automated systems is only justifiable in case of a positive balance of risks.
- The public sector is responsible for guaranteeing the safety of the automated and connected systems introduced and licensed in the public street environment. Driving systems thus need official licensing and monitoring.
- The personal responsibility of individuals for taking decisions is an expression of a society centered on individual human beings, with their entitlement to personal development and their need for protection.
- Automated and connected technology should prevent accidents wherever this is practically possible. This includes dilemma situations, where they have to drive in a defensive and anticipatory manner, posing as little risk as possible to vulnerable road users.
- A statutorily imposed obligation to use fully automated transport systems or the causation of practical inescapabilty is ethically questionable.

- In unavoidable hazardous situations, the protection of human life enjoys top priority in a balancing of legally protected interests, e.g. to accept damage to animals or property in a conflict.
- Genuine dilemmatic decisions, such as a decision between one human life and another, depend on the actual specific situation, and cannot be clearly standardized, nor can they be programmed such that they are ethically unquestionable. It would be desirable for an independent public-sector agency (e.g. a Federal Office for Safety in Automated and Connected Transport) to systematically process the lessons learned.
- In the event of unavoidable accident situations, any distinction based on personal features (age, gender, physical or mental constitution) is strictly prohibited. It is also prohibited to offset victims against one another. General programming to reduce the number of personal injuries may be justifiable. Those parties involved in the generation of mobility risks must not sacrifice non-involved parties.
- In the case of AD systems, the accountability shifts from the motorist to the manufacturers and operators and to the bodies responsible for taking infrastructure, policy and legal decisions.
- Liability for damage caused by activated automated driving systems is governed by the same principles as in other product liability.
- The public is entitled to be informed about new technologies and their deployment in a sufficiently differentiated manner.
- The complete connectivity and central control of all motor vehicles within a digital transport infrastructure is ethically questionable.
- Automated driving is justifiable only to the extent to which conceivable cybersecurity attacks do not result in such harm as to lastingly shatter people's confidence in road transport.
- Autonomy and data sovereignty of road users: The vehicle keepers and vehicle users decide whether their vehicle data that are generated are to be forwarded and used.
- No abrupt handover of control to the driver ("emergency"): To enable efficient, secure human-machine communication and prevent overload, the systems must adapt to human communicative behaviour.
- It must be possible to clearly distinguish whether a driverless system is being used or whether a driver retains accountability with the option of overruling the system. This applies especially to the human-to-technology handover procedures.
- In emergency situations, the vehicle must autonomously, i.e. without human assistance, enter into a "safe condition". Harmonization, especially of the definition of a safe condition or of the handover routines, is desirable (standardization).
- Learning systems that are self-learning in vehicle operation and their connection to central scenario databases may be ethically allowed if they generate safety gains. Self-learning systems must not be deployed unless they do not undermine the safety requirements. It is advisable to hand over relevant scenarios to a central scenario catalogue at a neutral body in order to develop appropriate universal standards, including tests.
- The proper handling of automated driving systems should be taught appropriately during driving tuition and tested (part of general education).

In "My agenda for Europe" [21] of Ursula von der Leyen, the President of the European Commission, one chapter is dedicated to "A Europe fit for the digital age".

It focuses on AI, IoT, 5G, and ethical and human implications of these technologies, empowering people through education and skills, and protecting ourselves with respect to the risks of these technologies. This is a strong indication, that efforts to considering ethical aspects in time will be continued.

3 Standardization Towards Autonomous Vehicles

The increased use of automated support functions (ADAS, Advanced driver assistance systems) led to an substantial increase in standardization in related areas for road vehicles (ISO TC22, TC 204 Intelligent transport systems, TC 241 Road safety, each with many subcommittees – some evolving standards do already contain a phrase like "for automated driving (functions)"), and other standardization groups like SAE (US), ETSI ITS, CEN/CENELEC, and UNECE WP.29 (UN Economic Commission for Europe, who sets the regulatory framework valid in most countries of the world).

Looking at the structure of ISO TC22 SC31 (Fig. 4) indicates already, that some topics concern automated driving functions, but outside SC32, e.g. WG6, WG9 and WG10, but there are also overlaps with other subcommittees (e.g. JWG1 with SC37, electrically propelled vehicles, and also with SC32 WG 12, Software update and ExVe functions, if communication is done over the air).

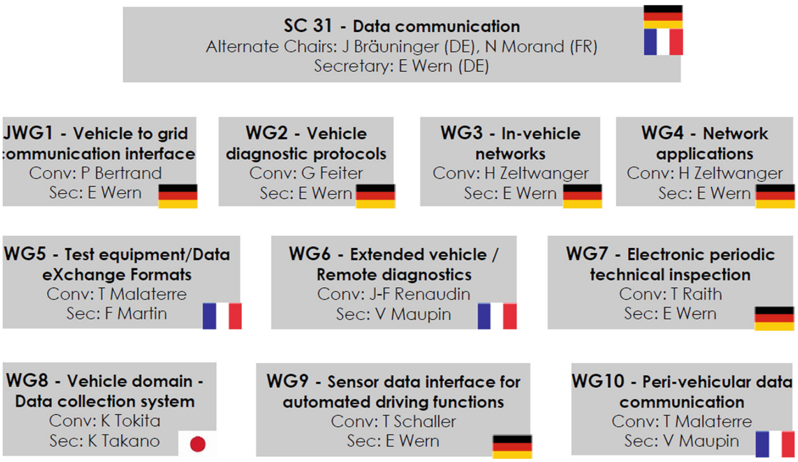

Fig. 4. Structure of ISO TC2 SC31 – AD-relevant WGs (WG6, WG9, WG10) (source: ISO TC22 SC31 report to TC22 ADAG on Automated Driving, 2018)

Being aware of the risk that competing standards in particular (sub-)areas might arise, ISO TC22 SAG (Strategic Advisory Group) initiated AG1, an Ad-hoc group for automated driving (ADAG) for a mid-term roadmap task in this field. This resulted in a report ISO/CD TR 4609 "Road vehicles – Report on standardization prospective for automated vehicles (RoSPAV)" [23]. It provides an overview over all relevant standards from ISO TC22 SC 32 (Electrical and electronic components and general aspects), SC31

(Data communications, including Sensor data interface for automated driving functions, Extended vehicle (ExVe) and ExVeS time-critical applications), SC33 (Vehicle dynamics and chassis components), SC 39 (Ergonomics), SC37 (Electrically propelled vehicles), and TC204 (ITS) WG 14 (Total system functionality and behavior).

Additionally, the report provides an outlook on future needs, opportunities and recommendations for standardization. These recommendations will be considered (e.g. by the authors working in EU-research initiatives and projects (ECSEL, Horizon)) in context of the standardization objectives of these work programs.

Key issues identified are concerning (addressed also in the ethics guidelines):

- Driver monitoring systems (define globally addressed metrics).
- Internal HMI (particularly for take-over, drivers' inactivity, on/off s, urgency buttons, maneuvers information, police orders, …).
- Reaction of the car (minimal risk conditions, fail operational or degraded, environmental conditions, communication with VRUs).
- Perception (common requirements for assessment of sensor functionality, independent of technology, quantification of performance and other dependability/trustworthiness attributes)
- Infrastructure signs (worldwide standard for design for perception)
- Connectivity (for cooperative intelligent transport systems, interoperability V2V, V2I (complementary to ETSI, ITU, SAE, TC204).
- Digital mapping system (reliable geolocation, interoperable platforms)
- Data storage system for AD (DSS-AD) (Event data recorder, plus DSSAD complementarity)
- Specific aspects for electrical vehicles (EV) (electrical safety, etc.)
- Validation (SotiF, validation based on test scenarios (SC33/WG9))

A key document for future standardization for automated driving is the "White Paper" [15]. This document provides an extensive overview over all relevant state-of-the-art safety by design, validation and verification methods, focusing on the challenges of automated/autonomous driving. The goal is to ensure the requirement of all existing ethical and technical guidelines to achieve a "positive risk balance", as compared with the situation of human driving. It takes into account the existing road vehicle standards, precision maps and navigation standards (ISO19157:2013, ISO/TS 16949:2009), and system and software engineering standards (ISO/IEC/IEEE 15288:2015). Cybersecurity and required capabilities of automated driving are described in detail as well as their elements (technologies and rules) for implementation. The document is positioned around the "Twelve Principles of Automated Driving" as a baseline for safe automated driving:

- Safe operation (dealing with degradation (performance related), Fail operational (limited to safety-related function or component).
- Vehicle operator-initiated handover (explicit, high confident intent).
- Operational design domain (typical situations that can be expected shall be managed; odd determination: system reaches its limits and compensates or issues/requests a handover in a sufficient time frame).

- Security (cybersecurity threat protection ensured).
- User responsibility (user state monitoring, responsibility of user always clear, driving mode awareness all time).
- Vehicle-initiated handover (if failing in time, vehicle must perform a minimal risk maneuver; request should be clearly understandable and manageable).
- Safety assessment (V&V used to ensure that safety goals are met, consistent improvement of overall safety achieved).
- Passive safety (crash scenarios and vehicle layout and automation; alternative seating and interior shall not reduce occupant protection).
- Data recording (record status data for event or incident tracking compliant with privacy laws).
- Behavior in traffic (applicable traffic rules obeyed by automated vehicle, behavior easy to understand, predictable and manageable for other road users (VRUs)).
- Safe layer (the system shall recognize its limits, and react to minimize risks, particularly if safe transition is not possible).

Most of these conditions fit well also to the ethical rules, which address the user and public acceptance issues.

This document is now the basis for the evolving standard ISO TR 4804 [16], "Road vehicles – Safety and security for automated driving systems – Design, verification and validation methods" (a technical report). The kick-off meeting was February 19–21, 2020, in Paris, the author took part in the discussions. The working document follows the white paper, the parts on motivation and general challenges, was removed because these parts are not required in a standard. Details on some technologies and issues handled already in existing standards are either shortened (with references) or put into an informative annex (e.g. use cases as examples). There were extensive discussions on terms and definitions, which is crucial, because important clauses refer to them and common understanding is required (e.g. "fail degraded" will be used, "fail operational" was removed, the issue of performance has to be separated between planned performance degradation because of bad weather conditions, or degradation because of failure or uncertain decision situation). The DTR 4804 will be soon distributed for comments to the national committees, taking into account the results of the Paris meeting.

4 Ongoing Research and Conclusions

Effective work is done in many European and national projects. Two examples are the ECSEL JU projects SECREDAS (grant agreement 783119-2, started 2018, https://secredas.eu/) and AutoDrive (grant agreement 78119-2, started 2017, https://autodrive-project.eu/). AutoDrive is the corner-stone project of the ECSEL Lighthouse cluster "Mobility.E" (https://www.ecsel.eu/mobilitye), SECREDAS is also a partner project in Mobility.E.

SECREDAS stands for "Product Security for Cross Domain Reliable Dependable Automated Systems". The high-level goal of SECREDAS is to develop and validate multi-domain architecting methodologies, reference architectures and components for autonomous systems, combining high security and privacy protection while preserving functional-safety and operational performance. This should increase consumer trust in connected and automated transportation (major focus automotive, but also railways), and in medical industries.

SECREDAS will be making a first important step into the direction of developing "trust"-building components and (sub-)systems for the European industries of tomorrow. Four main directions are taken: Reference Architecture, Powerful Components, Common Approaches, Scenarios & Pilot Tests.

The approach taken is to study a number of relevant use cases with specific requirements of safety, security, and privacy. Together with current state-of-the-art reference architectures, the use cases will lead to a next generation of reference architecture and common elements for multiple application domains. On top of that, several domain-specific solutions will be built to work out domain-specific and common demonstrators for the different application domains.

In SECREDAS, a number of relevant user scenarios with specific requirements of safety, security and privacy are studied in detail. A set of "Common technology elements" for achieving the overall goal of safe and secure automated systems was defined. Vehicle sensing, vehicle connectivity (particularly addressing ITS standards mentioned before), and in-vehicle networking are the key "abilities" for safe and secure automated systems. Demonstrators are foreseen for health, rail and "common demonstrators" (automotive). Standardization, qualification and certification is an important work package in SECREDAS. Particularly the new evolving standard ISO 4804 on "Road vehicles – Safety and cybersecurity for automated driving 4 systems – Design, verification and validation methods" should benefit from SECREDAS work. The outcomes of the work (technologies and use cases) are taken over for contribution to standardization by partners, who are members of standardization groups. The authors themselves are involved and leading this work package. The result of the first standardization deliverable, a survey on the applicability of safety, security and privacy standards in the three domains (with most contributions from the automotive sector) was published in a paper at the DECSoS Workshop at Safecomp 2019 [22], considering additionally the needs and reasons for certification according to these standards. The key result of this work were the answers to the following research questions (RQ1 – RQ4):

- RQ1. What standards are applicable and is there any difference between the availability of safety, security and privacy standards?
  "Safety standards for specific industrial sectors are available, as specializations of one basic standard IEC 61508 [2]. Security standards with different origins address different themes, while few are targeted to specific industrial sectors. There are fewer privacy standards than for safety/security, and there is no privacy standard targeted to specific sectors."
- RQ2. How are the Sa/Se/Pr (Safety/security/Privacy) standards practiced?
  "ISO 2700X and ISO 15408 are the most applied standards among all the studied standards. The application of safety standards is significantly more often imposed by customers and regulators than that of security/privacy standards. The conformance to safety standards is slightly more rigorously evaluated than that of security/privacy standards."

- RQ3. Which methodologies are applied for Safety/Security/Privacy evaluation? - *"Among safety analysis methodologies, FMEA [6], FTA [7] and HARA (Hazard Analysis and Risk Assessment) [8] are commonly used. Security analysis methodologies most commonly used are STRIDE [9] and Common Criteria [10]. The usage of security analysis methodologies is less convergent than of safety ones."*
- RQ4. Which tools are employed in Sa/Se/Pr engineering?
  MathWorks Simulink and IBM Rational DOORS kit are more used for safety and security engineering than the other tools. On privacy engineering, only very few tools are available and applied in practices.

The SECREDAS survey reveals as a result that security/privacy standards are gaining popularity in safety-critical industrial sectors, though both their development and their practices are less mature than that of safety standards. Standards linking safety and security engineering are not widely used, indicating that a multi-concern point of view for Sa/Se/Pr co-engineering is not yet widely adopted.

AutoDrive stands for "Advancing fail-aware, fail-safe, and fail-operational electronic components, systems, and architectures for highly and fully automated driving to make future mobility safer, more efficient, affordable, and end-user acceptable". The project is centred around the key attributes "fail safe", "fail aware", and "fail operational" of autonomous systems in the automotive and aircraft domain. The project is organized around so-called 10 supply chains, which are

- SC1: Fully automated driving (AD) and flying systems (bus, electrically propelled aircraft) targeting SAE level 5.
- SC2: Highly automated driving (SAE level 4; driver/system transition, V2V and V2I, dynamic planning)
- SC3: Cooperative active safety for AD (fail-operational collision avoidance, connectivity, critical situation handling)
- SC4: Fail-operational 800 V automotive powertrain
- SC5: Safe, secure and low latency communication
- SC6: Acquisition, 360° sensing, perception, environmental awareness
- SC7: Embedded intelligence (reasoning, decisioning, planning and controlling) and systems for AD
- SC8: Fail aware systems and components health prediction (weakness aware systems)
- SC9: End-user acceptance, certification and standardization of AD systems (includes societal and ethical aspects as described before)
- SC10: Impact on vehicle and road safety (Vision zero)

SC4–SC8 are the "technology enablers", the core of the research. The results are validated in the "output enablers" SC1–SC3. SC9 and 10 are reflecting the economic, societal and European impact.

One quasi-standards related key result was the computer vision benchmark WildDash https://wilddash.cc/ [26], which was incepted in the project. It enables better comparison of computer vision algorithms and, in the future, will help in certifying computer vision based automotive components. It is a key element to verify and validate "fail operational" behavior of autonomous systems, a key target of AutoDrive. The approach of an algebraic framework for runtime verification can be used to do predictive monitoring and detecting trends in a system. Early detection of upcoming problems is an enabler to build fail operational systems, because counter measures can be taken before the actual fault hits. The application to AutoDrive use cases is presented in a paper for Safecomp 2020 "Weakness monitors for fail aware systems" [27].

Several partners play an important role in standardization in ISO TC22 committees, particularly in the field of safety, cybersecurity and the new committee working on ISO DTR 4804, but are also active in ISO/IEC JTC1 SC41 (IoT) and SC42 (Artificial intelligence), with focus on trustworthiness issues for decision taking cognitive systems as the basis for autonomy. Most issues addressed by international standardization to keep pace with the developments in the domain of highly automated/autonomous systems/vehicles are tackled in these projects.

Although many details of the evolving system concepts and the implementations to build trustworthy highly automated/autonomous vehicles, being at the same time ethically and socially beneficial or at least tolerable, are still unclear, the approaches taken by the scientific community are looking promising.

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Enabling Trust for Advanced Semiconductor Solutions Based on Physical Layout Verification

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Abstract. With growing connectivity in consumer and industrial applications, the need for security rises proportionally. Compromises in security design of e.g. autonomous driving systems endanger not only material goods but may threaten personal life of humans. Besides the demand for functional safety of complex, connected systems, cyber security is paramount. As the traditional verification flow is only dealing with functionality, reliability and safety aspects, a trusted design flow extends this by adding aspects of hardware vulnerabilities in verification and certification. Consequently, without full trust in the globally distributed development and production process, semiconductor manufacturers need to check that no malicious modifications are inserted. Physical layout verification is achieved via a comparison of the recovered chip layout extracted from an application against the design data. To enable trust, a comprehensive figure of merit has been defined to evaluate the correlation of the layout extraction to design data. Using this figure of merit (FoM), it is shown on a 40 nm sample that ultra-high scanning speeds still deliver adequate image quality.

Keywords: Reverse engineering · Physical layout verification · Hardware security · Polygon comparison · Hardware trojans · Process enhancement

1 Introduction

The progressing digitalization covers all aspects of our daily life. Ranging from possibly intrusive smart home devices to connected autonomous vehicles. Comprehensive silicon based microelectronic solutions are the key technology in every field. As vehicles initially started to be equipped with electronic control units and sensors, the number and complexity of devices significantly increased. Mainly, the reason is the execution of software solutions including artificial intelligence (AI) functionality, the support of new interfaces like 5G or electric charging of batteries. For automotive applications, there are dedicated requirements on the silicon design, concerning lifetime and quality. These also affect the design of printed circuit boards (PCBs) as a next higher level of system integration and subsequently whole vehicles.

Recent reports show that counterfeit components are a major concern, which reportedly affect the industry by several billion dollars, threatening health, safety and security [1–3].

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Providing trustworthy solutions based on microelectronic devices is a major target for their acceptance [4]. This trust must be maintained over all different abstraction layers as shown in Fig. 1 where the top layer application is the interface to the product user. The lower layers describe the physical implementation of the product on a silicon substrate. The implementation depends on the used manufacturing technology, whereas its impact on the trust in the full product needs to be considered as well.

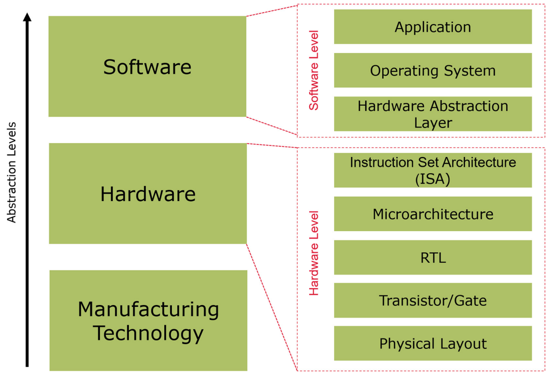


Fig. 1. Illustrates hardware and software abstraction layers.

The implementation of hardware-based security requires resistance to secret extractions, which can be classified as manipulative, semi-invasive, or observing attacks [5]. The use of encryption and authentication protects the processed information and blocks the recovery of communication. For hardware-based security devices, trust is generated through an extensive certification process which evaluates the devices performance against a publicly available security target, based on the appropriate protection profile (Common Criteria [6]).

An increasing complexity in electronic devices results in an ever more globally distributed development and production process. Consequently, without complete trust, semiconductor manufacturers need to check that the used products in the field is in the correct design state and no malicious modifications occurred.

This requires an improved verification and certification process for integrated device manufacturers and designers. The approach outlined in this paper extends the functional and security verification flow by a physical verification on the layout level. The verification is accomplished through a comparison of the original design layout against the via reverse engineering retrieved layout.

Figure 2 shows all the stages of a reverse engineering process. The search for malicious manipulations is based on a comparison of the extracted layout against the reference gold design. Based on the analysis of the differences between both layouts a semiconductor manufacturer can verify the absence of any modifications. The verification of the used manufacturing technology can also be done during the sample preparation process. While major differences, like the number of used metal layers will be easily detected, a fab identification will require a very detailed analysis and recovery of the manufacturing process.

Similar approaches are shown in [7, 8], or [9], the current state-of-the-art is expanded by presenting real analysis data on advanced semiconductor nodes. The imaging of large integrated circuit areas has been enabled by the usage of an ultra-fast scanning electron microscope.

Based on a successful extraction of the layout, a following netlist interpretation can target the understanding of a design. The recovered functionality can be compared against the product specifications; in a broader context, the target is to enable the detection of unspecified functions or possible malicious modifications by the product user.

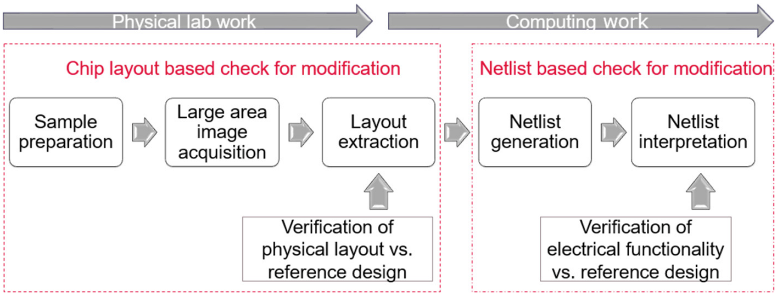


Fig. 2. Shows the physical and functional verification flow.

2 Security by Physical Verification

Figure 3 shows main stages of the complete production flow. The initial integrated circuit design stage handles an electrical description of the product where manipulation might be inserted directly, via third party components, or via compromised development tools [10–12], and [13]. Finally, the electrical description (netlist) is converted into a geometrical description (GDSII). During the fabrication, the geometrical layout is stored on masks and used for the manufacturing step. Fabrication time attacked describe the possibility to modify the layout information and add a malicious modification. Finally, test steps need to be bypassed in order to deliver the modified product to the field.

Independent of the concrete insertion point, the impact of the modification to the existing layout will be essential for the detection strategy [14–16] and define the requirements of the applied reverse engineering process.

A small example of such a modified inverter is illustrated in Fig. 4 and Fig. 5. Here the functional correctness of a CMOS (complementary metal-oxide-semiconductor) inverter has been compromised by intercepting the output and consequently setting the logical output of the inverter to *true*, disregarding the input. The related schematic and layout is observable in Fig. 5.

The only necessary changes are two minor alterations in the GDSII layout, or alternatively a direct edit of the mask of the metal layer. The aim of this work is the detection of these changes in the physical layout of advanced semiconductor solutions. Accordingly, the contributions of this paper are:

Table 1. Truth table of a maliciously modified CMOS inverter gate.

In	Out
0	1
1	1

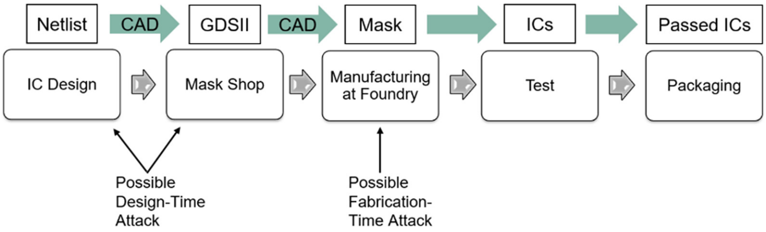


Fig. 3. Illustrates the integrated circuit design flow with different design steps in the rounded rectangles. The corresponding output of each step is shown in the cornered rectangles. Possible attack vectors within the process are indicated.

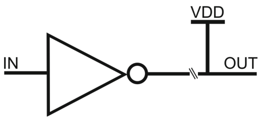


Fig. 4. Depicts the schematic of a maliciously modified inverter gate.

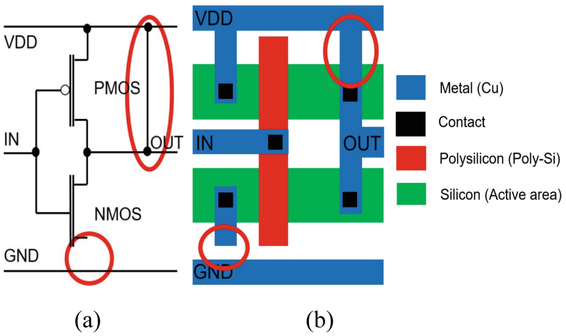


Fig. 5. Shows the schematic (a) and physical layout (b) of a maliciously modified CMOS inverter resulting in the truth table shown in Table 1.

- **Sect.** 3 provides a brief overview of the flow for semiconductor reverse engineering and is addressing the requirements for the analysis of modern technology nodes and complex silicon solutions.

- **Sect.** 4 introduces a figure of merit (FoM) for the reverse engineering process in order to evaluate the precision of the recovery layout data, to feedback results to improve performance and to estimate the detection probability for malicious modifications.
- **Sect.** 5 shows experimental results of a 40nm technology node sample with an emphasis on extraction performance and a comparison of two scanner types.

3 A Hardware Reverse Engineering Process

In this section a destructive hardware reverse engineering process - as shown by Lippmann *et al.* [17] - provides the capabilities to extract large-area chip-layouts is outlined. These extracted layouts are the basis for the detection of malicious modifications. The overview of the entire integrated reverse engineering flow consisting of sample preparation, image acquisition, image stitching, image segmentation, and netlist routing as shown in Fig. 6 is elaborated in this section.

Sample Preparation. The first step is the physical preparation of the packaged integrated circuit. That process step can be split into two sub-processes: First, in the *decapsulation* step, the bare silicon die is removed from its package.

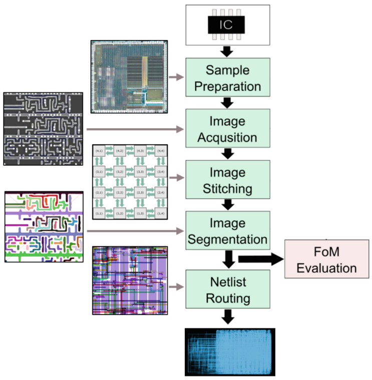


Fig. 6. Represents the hardware reverse engineering process flow with subsequent process-steps in the green boxes and related illustrations for each step.

This is followed by a *delayering* of the die. In the course of this, all layers of the die are individually prepared for imaging. To allow a sufficient preparation the planarity of each layer must be kept far below the layer thickness. Various chemical and mechanical etching techniques must guarantee a thickness variation far below 100 nm to process advanced technology nodes of 40 nm.

Image Acquisition. Subsequently, each layer is scanned with an ultra-high resolution scanning electron microscope (SEM) [18]. Due to large scanning areas, several thousand images are necessary, each with up to billions of pixels. Each pixel needs a certain dwell time to scan. With billions of scanned pixels, this will result in a very large scanning time and amount of data. Therefore, the SEM needs to have a high scanning speed, while retaining accuracy. In Sect. 5.1 the results of two different SEMs are presented and their performance regarding scanning time and image quality is compared.

Image Stitching. After scanning an entire layer, a geometrically-undistorted mosaic is reconstructed. By using overlapping portions of adjacent images, an area-based feature extraction algorithm creates one mosaic from up to several thousand single SEM images.

Image Segmentation. Afterwards, the physical layout is extracted from the mosaic by classical threshold-based and machine learning image processing algorithms. The result after this step is a near perfect vector-representation of the layout data of the original integrated circuit, segmented into vertical interconnect accesses (VIAs), wires, contacts, and standard cells.

Netlist Routing. To obtain an electrical flat netlist, standard cells and electrical devices are connected by following overlapping conductive tracks (i.e. VIAs, wires, and contacts).

The flat netlist can be interpreted e.g. by structural graph-analysis [19] or structural block analysis [20]. An extensive overview of interpretation techniques can be found in [21].

4 A Figure of Merit for Physical Verification

To provide a proactive countermeasure against hardware Trojans on layout level, a comprehensive figure of merit (FoM) is defined in this chapter. This FoM consists of two basic components, one based in pixel- and the other in vector domain. The basic idea is an overlay of the design layout and the extracted (reverse engineered) layout, as shown in Fig. 7.

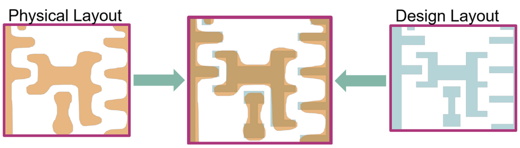


Fig. 7. General idea of the physical verification where the design layout is overlaid with the extracted reverse engineered layout.

Both layouts have to be to a mutual database, whereas the process of flattening the nested design layout files and parsing it into that database, has been described by Singla *et al.* [22]. Finally, the corresponding layers are aligned into a common coordinate system.

4.1 Definition of a Pixel-Based Metric

The design and extracted polygons are written to a grid of pixels is shoswn in Fig. 8. The pixels of this grid have the same physical dimensions as in the original SEM images. In Fig. 8 the dark green pixels are those, where both design and extracted layout are overlapping. The light green and red colored pixels are those, where only one layer is present and are defined as error pixels.

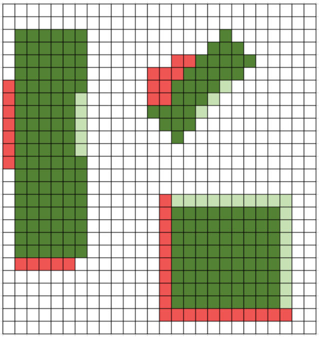


Fig. 8. Visualizes an example of the pixel-based metric. The dark green pixels are those where both design and extracted layout pixels are overlapping. The red pixels are only present in the extracted layout, while the light green pixels represent the design only. White pixel have no layout information at all.

Table 2 provides an overview of how the pixels are assigned using the *exclusive or* operator.

Table 2. *Exclusive Or* truth table with Boolean comparison of design and extracted pixels.

Design	Extracted	Design ⊕ Extracted
0	0	0
0	1	1
1	0	1
1	1	0

After performing the *XOR* operation on all pixels, the formal metric definition is shown in Eq. 1. It is the fraction of wrongly extracted pixels divided by the number of total pixels in the image.

$$XOR = \frac{\varepsilon}{M \bullet N} \tag{1}$$

where:
M = Number of pixels in x-direction.
N = Number of pixels in y-direction.
ε = Number of correctly predicted pixels.

4.2 Definition of a Polygon-Based Metric

The second metric is based on the properties of polygons [23] which is hierarchically the least abstract in the physical domain of the Y-chart [24, p. 660]. For this metric the properties of polygons are used, as visible in Fig. 9. First, the centroid is numerically calculated from the tuples of vertices in every polygon.

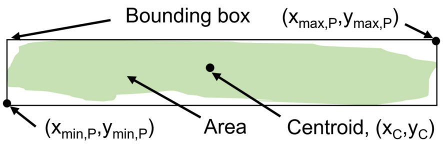


Fig. 9. Visualization of the utilized properties of polygons.

$$Centroid = (x_C, y_C) = \frac{1}{N} \cdot \sum\nolimits_{i=0}^{N-1} (x_i, y_i) \tag{2}$$

Equation 2 results in the coordinate tuples of the centroids. The centroids of polygons of the retrieved layer and the design layer are compared against each other. A Euclidean distance close to zero (see Eq. 3) of the centroids of two polygons (P_1, P_2) in both layers does not necessarily result in a match of the two polygons. Still, the shape of the polygons can be completely different.

$$d_c(P_1, P_2) = \sqrt{\left(P_{1,x} - P_{2,x}\right)^2 + \left(P_{1,y} - P_{2,y}\right)^2} \tag{3}$$

Therefore, as a second criterion whether a retrieved polygon matches a design polygon, the bounding boxes (BB) of all polygons (P) are calculated. The bounding boxes yield coordinate tuples of the outer border of the polygon and are shown in Eq. 4 and Eq. 5. For the x- and y-direction the differences between every polygon in each layer are additionally calculated. Finally, the Euclidean difference of the centroids and the difference of the bounding boxes in x- and y-direction are accumulated (see Eq. 8).

$$BB(P) = \left(x_{min,P}, x_{max,P}\right) \times \left(y_{min,P}, y_{max,P}\right) \tag{4}$$

$$\begin{aligned} x_{min,P} &= \min_x (x, y) | (x, y) \in P, \\ x_{max,P} &= \max_x (x, y) | (x, y) \in P, \\ y_{min,P} &= \min_y (x, y) | (x, y) \in P, \\ y_{max,P} &= \max_y (x, y) | (x, y) \in P \end{aligned} \tag{5}$$

$$d_{BBx}(P_1, P_2) = \left| \left(x_{max,P_1} - x_{min,P_1}\right) - \left(x_{max,P_2} - x_{min,P_2}\right) \right| \tag{6}$$

$$d_{BBy}(P_1, P_2) = \left| \left(y_{max,P_1} - y_{min,P_1}\right) - \left(y_{max,P_2} - y_{min,P_2}\right) \right| \tag{7}$$

$$\Delta(P_1, P_2) = d_c(P_1, P_2) + d_{BBx}(P_1, P_2) + d_{BBy}(P_1, P_2) \tag{8}$$

To determine which retrieved polygon is related to which design polygon, all polygons are compared in a distance matrix as shown in Eq. 9. The related polygons do have very small absolute numbers in comparison to unrelated polygons. When being below an empirical threshold, they get assigned.

$$CM_P = \sum_{i=0}^{N-1} \sum_{j=0}^{M-1} (\Delta(i,j)) = \begin{bmatrix} \Delta_{0,0} & \cdots & \Delta_{0,M} \\ \vdots & \ddots & \vdots \\ \Delta_{N,0} & \cdots & \Delta_{N,M} \end{bmatrix} \tag{9}$$

where:
N = Number of reverse engineered polygons.
M = Number of design polygons.
Δ = Distance function of centroid and bounding box.

After determining the polygon-pairs, the correctly extracted polygons, undetected, and additionally detected polygons can be written to a confusion matrix (CM), as shown in Fig. 10. Correctly, extracted polygon-pairs are assigned to *True Positive* field. Undetected design polygons are written to the *False Negative* field. Extracted polygons with no assignable design polygon are assigned to the *True Positive* field. In this case, there are no *True Negative* polygons, which represent non-existing polygon where no polygons are found.

		Design Polygons		
		p	**n**	
Extracted Polygons	**p′**	**T**rue **P**ositive	**F**alse **P**ositive	P′
	n′	**F**alse **N**egative	**T**rue **N**egative	N′
		P	N	

Fig. 10. Confusion matrix [25] applied to polygon extraction process.

From the confusion matrix, we can derive three different metrics: *Precision*, *Recall*, and the F_1 *Score*. That F_1 Score is the harmonic mean of precision and recall, which subsequently takes an under- and over-sensitivity of polygon extraction into account.

$$Precision = \frac{TP}{TP + FP} \tag{10}$$

$$Recall = \frac{TP}{TP + FN} \tag{11}$$

$$F_1 Score = \frac{2}{Precision^{-1} + Recall^{-1}} \tag{12}$$

In Fig. 11 a trivial example of how the polygons are assigned can be found. Whenever there is an extracted polygon (red) matching a design polygon (green), that polygon-pair

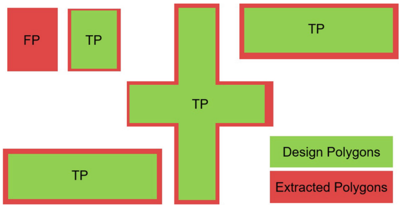


Fig. 11. F_1 score example where green polygons depict the design polygons and the red underlying polygons show the extracted polygons.

is added to the list of true positives. The additional extracted polygon is a false positive. The complete FoM consists of both metrics and provides a comprehensive taxonomy for the detection of possible malicious modification and an evaluation of the performance of the shown reverse engineering process.

5 Results of the Figure of Merit on a 40 nm Sample

In the following section, the comparison of two different SEM generations and additional variation in the scanning time will be shown. Furthermore, the continuous improvement in layer evaluation is shown. Finally, an artificial hardware Trojan on layout level will be added to the GDSII layout, where the detection methodologies are elaborated. The technical properties of the two scanners are listed in Table 3 and the scanners will be referred as CS150 Two and eSCAN 2018.

5.1 Comparison of Two Scanner Generations and Varying Dwell Times

Table 3. Comparison of last chip scanner generations [17].

Scanner feature	CS150 Two	eSCAN 2018
Detector speed	100 ns	25 ns
Scan generator speed	20 MHz	50 MHz
Deflection principle	Electromagnetic	Electrostatic
Scan generator - PC interface	Copper–SCSI	Glass fibre–PCI-E
Typical image overlap	0.2%	0.1%
Typical FoV	20 µm to 50 µm	20 µm to 100 µm
Dynamic corrections	Distortion	Distortion, focus, stigmator
Typical stitching error	10 nm to 50 nm	10 nm to 30 nm
Typical pixel dwell time	200 ns to 2000 ns	25 ns to 100 ns

Rising die areas of semiconductor solutions are paired with continually shrinking technology nodes. To maintain the ability to scan large chip-areas in acceptable time spans the requirements towards chip scanners have sharply risen. We will show that the eSCAN 2018 enables ultra-fast scanning while maintaining the necessary performance to extract the layout. The evaluated sample is shown in Fig. 12, which is a metal layer scan of the 40 nm sample and used for the following experiments.

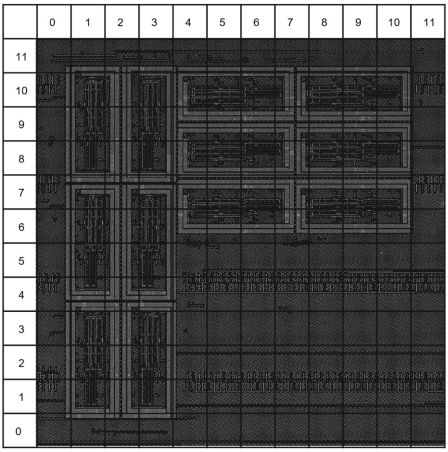
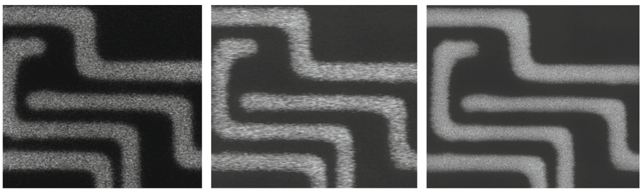


Fig. 12. Shows stitched large-area mosaic of discussed layer of the evaluated 40 nm sample.

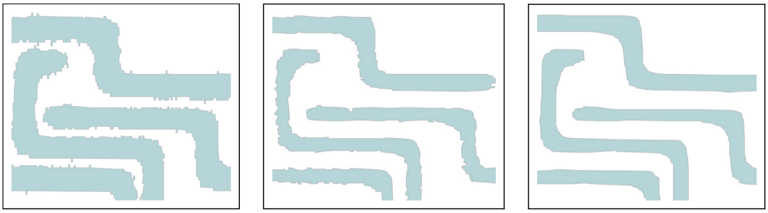
This layer is scanned with three different parameter sets (these were particularly selected for presented use-case and can strongly vary for different samples) that are visible in Fig. 13 with the extraction results visible in Fig. 14. These are:

(a) Scan with CS150 Two using minimum pixel dwell time of 500 ns with a pixel averaging of 12. This results in an overall time of 6 µs per pixel.
(b) For the image in the center, the eSCAN 2018 was used, and the pixel dwell time has been drastically reduced to merely 30 ns per pixel.
(c) The right image is Fig. 13a



(a) (b) (c)

Fig. 13. Series of images showing different scan parameters. (a) shows a scan with CS150 Two with a pixel dwell time of overall 6 µs per pixel. (b) depicts a scan of the eSCAN 2018 with an expeditious dwell time of only 30 ns. (c) is an excerpt from eSCAN 2018 with a dwell time of 500 ns.



(a) (b) (c)

Fig. 14. Series of images showing different extraction performances based on the input from Fig. 13. (a) shows a scan with CS150 Two with a pixel dwell time of overall 6 µs per pixel. (b) depicts a scan of the eSCAN 2018 with an expeditious dwell time of only 30 ns. (c) is an excerpt from eSCAN 2018 with a dwell time of 500 ns.

To enable the scan and extraction of large areas, the reduction in pixel dwell time is necessary as following formula of the calculated overall scan time (T_{Total}) shows:

$$T_{Total} = k \bullet \frac{Die_x}{Res} \bullet \frac{Die_y}{Res} \bullet t_{dwell} \tag{13}$$

The factor k in Eq. 13 describes the overhead caused among others by stage shifting and data processing. Large scans lead to a relatively small overhead, due to reduced stage shifting. Via empirical observations, the factor can be set between 2 and 10. Via Eq. 13, the scan time for large-area semiconductor products is estimated. For example taking an automotive microcontroller with five metal layers and a chip-area of 16 mm^2. The die has a quadratic aspect ratio with a 4 mm in x- and y- direction. The scan resolution is 4 nm/px in a 40 nm technology node. The approximated scan time for one metal layer is k·8.33 h with a pixel dwell time of 30 ns. On the contrary, the 6 µs pixel dwell time of the CS150 Two result in layer scan time of k·69.5 days. To still be able to ensure a comprehensive physical verification, not only the scan time is vital. Furthermore, the scan quality still has to be on a level where adequate extraction performance is achieved. Figure 15 shows the FoM results of those variations and additionally an increase in the pixel dwell time of the eSCAN 2018.

As shown, the small dwell time of 30 ns had no negative impact on the extraction performance and the F_1 score is even slightly increased, with only a minor drop in the XOR-Error. The 500 ns scan has the best yield, yet the two other scans achieve a comparable quality. Consequently, large-area semiconductor samples can be scanned in reasonable time frames for physical verification, while maintaining adequate image quality.

5.2 Detection of a Malicious Layout Modification

To enhance the evaluation time and effort, the basic approach is the exclusion of polygons through their functional relevance. Exemplarily, an additional polygon is inserted as illustrated in Fig. 5. This polygon connects two electrical nets and subsequently compromises the functional correctness of the whole IC. In a best-case scenario, this is discovered before shipping and results in economic damage. In a worst-case scenario, the modification is not detected and the product is shipped (Fig. 16).

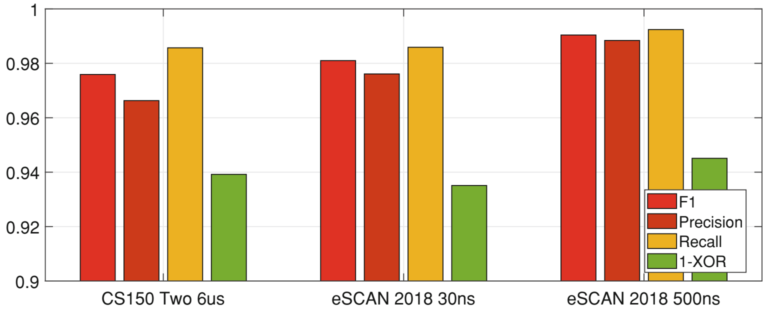


Fig. 15. Comparison of the results between the CS150 Two (left) and the eSCAN2018 (center and right). Additionally, the dwell times of the eSCAN 2018 are varied.

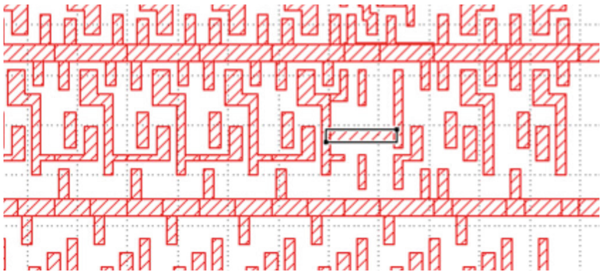


Fig. 16. Injection of an artificial Trojan that has been inserted to metal layer (via the open- source *kLayout* [26] design viewer).

By this point, the security of the integrated circuit (IC) cannot be appropriately checked. Therefore, the integrity of the entire system might be compromised which could lead to personal endangerment.

For the detection of possibly inserted malicious layout modifications, it is not feasible to inspect all tiles manually. To reduce the number of tiles, which might contain layout modifications, the F_1 score is calculated for every single tile. As shown in Fig. 17 the F_1 score is not equally distributed of all tiles but varies between 86% and 100%. Each tile with a score below 100% is eligible for further analysis.

To further minimize the discussed evaluation time and effort, the number of suspect polygons is reduced as illustrated in Fig. 18.

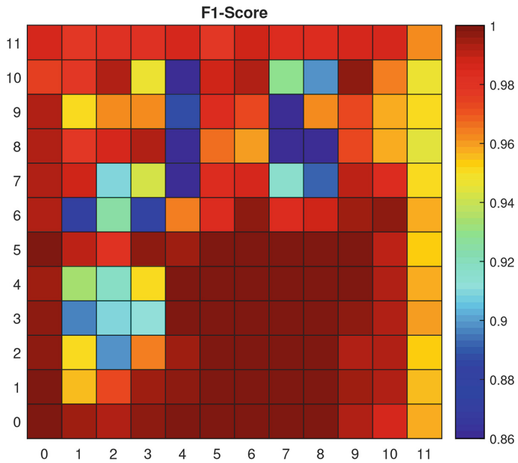
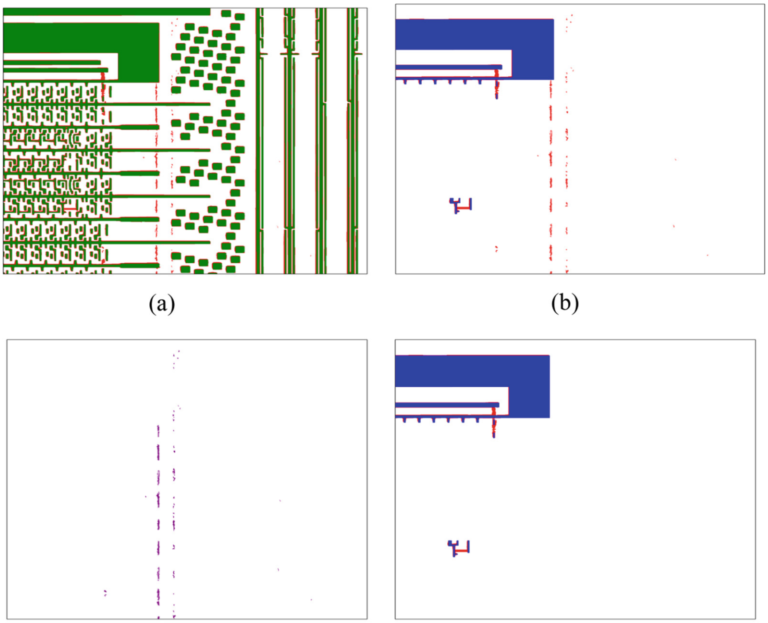


Fig. 17: Shows the F_1 score of the 30 ns scan from eSCAN 2018, where dark red shows a good yield and dark blue a low yield

First, extracted polygons, which are assigned to design polygons and classified as true positives are removed from the list of possible layout modifications as shown in Table 4. It results in an F_1 score of only 89.0% and in total 57 extracted polygons need to be tested whether or not they constitute in a malicious modification. Next, all polygons that are geometrically unconnected to design polygons are classified as *particles* (Fig. 18c) and therefore removed.

Mostly, these polygons are *particles*, dents, or other defects originating in sample preparation. In any case, these defects are irrelevant regarding the electrical netlist and can be disregarded from further analysis.

The resulting confusion matrix is shown in Table 5. Hence, the F_1 score increases to 98.8%, while the absolute number of remaining extracted polygons is decreased to merely three. These three remaining polygons must be inspected visually and verified whether they yield a hardware Trojan or just an electrically relevant reverse engineering defect.



(a) (b) (c) (d)

Fig. 18. (a) shows red pixels where only one layer is visible, while in green both layers are present. (b) true positive polygon-pairs are removed and only non-assigned polygons are shown. (c) shows all polygons classified as particles. (d) depicts the remaining polygons with functional relevance.

Table 4. Confusion matrix before particle removal.

		Design	
Extr.		p	n
	p	283	57
	n	6	X

Table 5. Confusion matrix after particle removal.

		Design	
Extr.		p	n
	p	283	3
	n	6	X

6 Conclusion

In this paper a figure of merit for the verification of physical chip layouts using GDSII design data was shown. An advanced reverse engineering process for very large scale integrated circuit layouts using dedicated, effective, and efficient tools for sample preparation, image acquisition, and layout extraction was presented. For a systematic evaluation of the layout extraction quality, a pixel- and polygon-based metric was developed. This metric was evaluated on a 40 nm IC sample. The results of the evaluation show that the ultra-high scanning speed of eSCAN 2018 enables the image acquisition for physical verification of large-area automotive semiconductor solutions in less than three days. Moreover, the FoM was evaluated on a small scale case study regarding the detection of malicious modifications. Thereby, 99% of the existing structures are either classified as design structures or as electrically irrelevant particles and subsequently eliminated from consideration.

7 Future Work

The verification of the physical layout of advanced semiconductor designs for autonomous driving requires continuous improvement on sample preparation, as well as image acquisition and processing in order to address shrinking feature sizes and the large chip areas. An efficient search for hardware Trojans or other malicious modifications in real physical layouts will only be possible by using a reverse engineering process with high performance. To improve the rating and interpretation of this performance a future task will be the extension of the presented figure of merit by higher level metrics. For the electrical integrity of the IC can be verified by a netlist based metric. Furthermore, not only the verification of single devices but the inspection of complete application boards will become an additional task in providing appropriately secure systems.

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Intelligent Mobility Systems

CPS Road Network Scenarios Analysed for Dependability and Standardization

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Abstract. Infrastructure planning of transport and mobility is a very complex and challenging issue for planners and decision-makers. Cooperative Intelligent Transport Systems (C-ITS) allow here not only improved information and planning in singular vehicle but optimization of the overall traffic and consideration of special needs. Understanding the design, structure and integration of the necessary infrastructure and other road users must become an integral part of developing modern vehicles and modern infrastructures. There are already existing concepts for special service permission for accessing road and traffic services which can improve public safety, decrease the environmental impact and improve the overall traffic flow. In this work, we analyse a CPS road network scenario, with both general and emergency processes, where vehicles and infrastructure are able to communicate with each other concerning dependability. We highlight challenges and propose building blocks towards a holistic system engineering method. Furthermore, we give a short overview of state-of-the-art methods proposed by standards and discuss their shortcomings concerning the raised dependability issues.

Keywords: Intelligent Transport System · Road network · Dependability · Safety · Security · Emergency use case

1 Introduction

From its early beginnings, the automotive industry has always been known for creating innovative new solutions and concepts. The automotive sector of Europe today is securing 12.2 million jobs, producing 22% of vehicles worldwide [12] and impacting different major societal challenges. These challenges are mainly related to the reduction of pollutant emissions, reduction of traffic fatalities, or increased mobility for an aging population. Advanced Driver Assistant Systems (ADASs) and Autonomous Driving Functions (ADFs), with the purpose of taking over specific driving manoeuvres and finally eliminating the demands for driver intervention, are sturdy provisions for tackling the societal challenges.

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These technologies are strongly supported or even enabled by embedded systems. Modern vehicles are equipped with more than 100 Electronic Control Units (ECUs) communicating through multiple networks within the vehicle and interacting with each other to handle the necessary controls for vehicle operation. The complexity of these embedded automotive systems has become more demanding in recent years, due to the integration of external services. Before the introduction of wireless connections and automated driving functionalities, vehicles were physically isolated machines with mechanical controls. The emergence of cyber-physical automotive systems over the last few decades has affected the development of vehicles, promising to support new applications and altering the customer added value of the passenger car. This is enabled through the availability and integration of information (e.g. powertrain control strategy, traffic information, as well as infotainment and connectivity features) and further opens new markets.

The contribution of this work is the analysis of future issues by using an emergency scenario where regular vehicles and emergency vehicle communicate with each other and with the infrastructure. A scenario, which will yield to an automatic traffic and emergency case management in the longer term. We use the emergency case, because while this is a special use case, the generic approach of road users with special permissions and active interaction with the traffic management is not only relevant for emergency but also for other public services, such as public transport. In addition, such use cases will contribute to increased public safety and in the case of public services increased level of service quality and usage. In Sect. 3 we enumerate and discuss the technical challenges of the presented scenario. Section 4 briefly presents state-of-the-art methods for tackling these challenges and their shortcomings. Finally, Sect. 5 concludes this work.

2 A CPS Road Network Scenario

A Cyber-Physical System (CPS) road network provides the platform to integrate Car2X communication for advanced traffic management. This is expected to make the streets safer by reducing the number of traffic jams and accidents. Additionally, it has the potential of making traffic greener by reducing fuel consumption and subsequently limiting the pollutant emissions. Building the necessary infrastructure for CPS road networks and integrating the vehicles, however, raises challenging problems for researchers and the industry. In this section, an extract of those challenges is discussed based on the scenario shown in Fig. 1. In the given setting, the traffic lights, cameras, and traffic signs execute their locally deployed control plans and publish the observed traffic situation to their assigned area traffic management station. Road vehicles publish information such as their Global Positioning System (GPS) position, velocity trajectory, live video streams, or information about the scene interpretation computed on board (e.g. pedestrian recognition, traffic jams, obstacle recognition).

The communication channels between vehicles, vehicles and the infrastructure, and the infrastructure itself can be either established via Dedicated Small Range Communication (DSRC) channels, the 4G/5G network or for permanent installations, via cable wiring. The area traffic management stations collect, pre-process, and forward the information received to centralized and global traffic management systems, which allow the

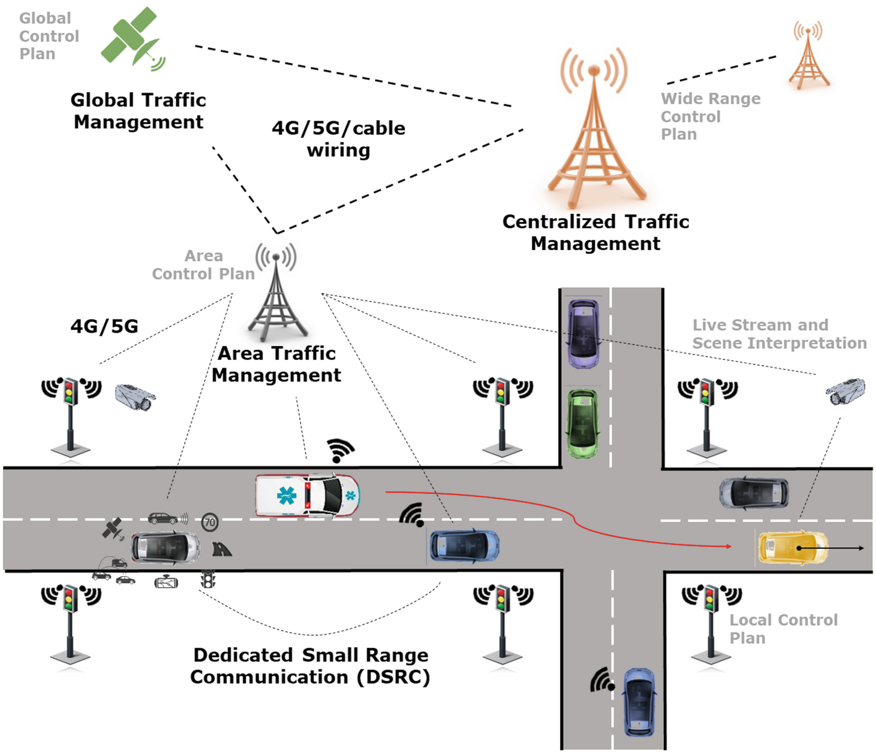

Fig. 1. A CPS road network scenario

cloud-based computation of a wide range, or even global, traffic density in real-time. This information can be used by the infrastructure and vehicles to optimize the local traffic density by calculating appropriate navigation routes. In normal operation mode, the management systems and stations treat all traffic participants equally and serve as information sources for them. Furthermore, the management system can be used for software deployment and update processes. Only in exceptional cases (e.g., accidents or emergency missions) the traffic management system might take over the control of traffic lights, traffic signs, and even road vehicles. In the following two subsections we analyse this representative scenario with two use cases. First, we present the default case where a driver is assisted by the traffic management systems. The second case examines what happens if an emergency occurs and how the overall system needs to communicate.

2.1 Typical Vehicular Communication Cases

One recurring every-day scenario in traffic is the need for a vehicle to stop at a precisely defined location at a precisely defined time; for example, when approaching a red traffic light or to give way for an emergency vehicle. Some human drivers with an anticipatory driving style may follow an approach not needing to perform a complete vehicle stop, but an intelligent vehicle equipped with automated driving functions, sensor fusion, and Car2X communication installed, typically can gather and process far more data (especially concerning information outside the line of sight) about the surrounding than a human driver would be able to. Thus, instead of stopping the vehicle completely, a requirement to not overstep a precise location before a specific point in time often allows more efficient and safe handling of various driving situations. An example here is the automated interaction between infrastructure, automated vehicles and emergency vehicles to build an emergency corridor. Smart traffic lights take into account the current traffic density at an intersection and switch the signals depending on the current number of vehicles [21]. In the event of danger, such systems can also stop traffic. The following paragraphs enumerate communication possibilities between vehicles and infrastructure.

Infrastructure to Vehicle Communication. Basic service in this category is the provision of simple road and lane topology information to vehicles by the infrastructure. This information could be enriched with drivers receiving a live stream captured by a traffic camera on the intersection, which allows them to see around the corner. Technical issues include providing low latency, avoiding information overload by providing only the most relevant information to the driver and graceful degradation. A better solution would be for the smart intersection to compute a live map of the intersection and the current road users, like an enhanced radar display. This map is created by fusing streams from cameras and radars installed at the intersection. The main challenge is again the latency, because now additional latency is introduced. One first example of this approach can be found in Vienna, Austria [13] with an autonomous public transport bus system and camera system with artificial intelligence to detect the traffic situation.

Vehicle to Vehicle Communication. Especially in a cooperative environment, the coordination between vehicles becomes a key factor. Basic information shared between vehicles are position, heading, or velocity. For example, drivers in a queue receive data from the first vehicle in the queue. This allows them to make a safe decision to overtake the vehicles in front or follow behind. Technical challenges are mainly scalability and latency - especially in situations involving a large number of road users, wireless communication channels can be a limiting factor.

Vehicle to Infrastructure Communication. A smart intersection can only observe what is near to the intersection. For instance, it can detect that outgoing traffic is slowing down, but not why (e.g. a car parking and creating temporary localized congestion versus a long-distance traffic jam). Smart vehicles could transmit information to the local intersection:

1. Data available right now (GPS, velocity);
2. Live streams (to be interpreted by the intersection or to be shown to traffic entering the intersection);
3. The results of scene interpretation computed in the smart car (e.g. pedestrian vs. traffic jam vs. obstacle detection).

Technical challenges include scalability and latency (hence local processing rather than relying on the cloud), network management (e.g., coordinating transmissions, requesting information on demand), prioritization in the case of information overload and security and safety (handling connection losses, malevolent interference with the network, errors in data analysis, black box logging for analysing malfunctions).

2.2 Emergency Case Management

In the case of an emergency, every moment counts to save human life or prevent permanent injuries. Thus, an emergency vehicle should receive preferential treatment by the traffic management system and an emergency vehicle should also have the entitlement to overrule (based on certain constraints) the objectives of nearby vehicles and infrastructure.

Vehicle to Infrastructure Communication. In the case of an emergency, the vehicle with the emergency must inform the area traffic management station about its current position, its destination, the emergency severity, and blue light driving operation must then be authorized.

Infrastructure to Vehicle Communication. After receiving information from the emergency vehicle, the area traffic management station starts to calculate the fastest route to the locality and notifies the emergency vehicle about it. In parallel, the area traffic management station notifies the centralized traffic management system and simultaneously takes over the control of intersections, traffic signs and sends out instructions to nearby vehicles. In the scenario given in Fig. 1, the area traffic management station initiates a green wave for the emergency vehicle and instructs all other vehicles to stop. Only the golden car is instructed to keep moving in order to let the emergency vehicle pass unhindered. In the meantime, the centralized traffic management system can further optimize the route of the emergency vehicle and re-route other traffic participants by notifying the affected stations and vehicles. The technical challenges include traffic optimization strategies, scalability, latency, network management and message prioritization in the case of information overload.

Vehicle to Vehicle Communication. If the emergency vehicle loses the connection to the traffic management system, the emergency vehicle must still be able to overrule/influence the objectives of nearby infrastructure and vehicles so that the emergency vehicle can quickly and safely arrive at the crash site. Technically this could be implemented using DSRC channels to set up a mesh network. The emergency vehicle uses the mesh network to propagate forward information about its planned route, current position and velocity. The vehicles that receive this information propagate backward information about their traffic scene interpretation, so that the emergency vehicle can re-plan its route in the case of unexpected delays due to traffic jams or obstacles. The technical challenges again include traffic optimization strategies, latency and message prioritization in the event of information overload, plus efficient mesh network routing strategies.

2.3 Dependability Concerns

In the considered scenarios dependability and privacy are of major concern. In the case of an emergency, the traffic management system and the emergency vehicle are allowed to overrule/influence the objectives of infrastructure and vehicles. Thus, the CPS road network must be designed to prevent, detect and recover from the intentional and unintentional misuse of such mechanisms. In addition, the question of how such special service permissions are integrated and managed and the impact of active influence on the overall traffic flow are of major concern. Beside the already mentioned technical challenges, this may also include the security life cycle:

- secure mechanisms to authorize and distribute the information about blue light driving operations;
- mechanisms to enable unhindered operation of the emergency vehicle even if the traffic management system is disconnected;
- mechanisms that prevent unintentional (e.g. Hardware/Software faults) or intentional (e.g. jamming attacks) disconnection of vehicles and infrastructure;
- mechanisms that detect intentional misuse;
- and mechanisms that can recover from misuse.

So, establishing trust between all parties is essential.

3 Challenges and the Proposed Solution

The paragraphs in this section summarize the elaborated challenges of the preceding section. The list is non-exhaustive and only reflects the authors' estimation of the discussed scenario. The listed items are related to one or multiple engineering disciplines including Hardware/Software (co-)design, architectural design, cloud/edge computing, embedded systems, testing, safety, security, manufacturing/product lifecycle management, legislation, and others.

System Complexity. The high number and heterogeneity of components, subsystems and the interaction with the system environment greatly increase the system complexity of CPS road networks. This includes the integration and understanding of the road user; the integration of embedded systems, edge computing, and cloud-based services; the interoperability between these components; the interface design and system scalability; the development of system deployment, integration, maintenance, and resilience mechanisms; and the management and development of new interdisciplinary products, applications, and lifecycle management including legislative issues.

Network Management. The interconnection of heterogeneous (embedded) systems is a key factor when building CPS road networks. The challenges in this engineering discipline include the trade-off between interoperability and security (especially trust and certificate management); the trade-off between network scalability offering low latency or high throughput; the message prioritization in the case of information overload; and logging mechanisms for analysing malfunctions and attack-detection.

System Development. The industry and development teams are challenged with the training of inter-domain experts (technical and social skills); with the establishment of effective communication channels between multiple domains; the development and selection of suitable methods and tools that support the whole system/product life-cycle; the development of best practices and standards; and with the development of management strategies and load balancing trade-offs between edge and cloud computing.

System Operation. The major challenges during system operation will be the technology shift (old vs. new vehicles); the system maintenance (especially Software/Hardware updates); the system resilience and availability; the system security (especially trusts, Software updates and certificate management); and the efficient and fair traffic management.

As the listing shows the design, development and operation of CPS road networks is complex, interlaced, and interdisciplinary. The fragmented landscape of standards and methods (discussed in Sect. 4) mainly deals with the concept and design phase of the specific products and elements. The common approaches for dependable development now need to be adjusted to consider additional constraints coming from highly automated and connected vehicle functionalities. Understanding the design, setup, and integration of the necessary infrastructure and other road users must become an integral part of developing modern vehicles. Applying established approaches from the automotive domain in the concept phase of CPS road networks, like Hazard And Risk Analysis (HARA) [14] and Security-Aware Hazard And Risk Analysis (SAHARA) [20] are not ideal, since they are not geared to the complex, multi-domain nature of road networks. Therefore, we suggest the use of the System-Theoretic Accident Models and Processes (STAMP) method for the initial planning and concept phase for CPS road networks.

The STAMP method was developed by Leveson and published in the year 2012 [18]. STAMP pursues the system thinking or system engineering approach combined with elements from control theory. Basically, STAMP is constructed from three concepts: constraints, hierarchical levels of control, and process models. The systems in this approach are viewed as interrelated components that are kept in a state of dynamic equilibrium by feedback loops of information and control. The development of dependability concepts with STAMP is an iterative process starting at a very high abstraction level of the system under development, followed by several refinement steps as design decisions are made. Hence, this method is better suited to develop a high-level socio-technical model of systems like CPS road networks than the automotive domain approaches mentioned. Figure 2 shows a model of the CPS road network scenario discussed in Sect. 2.

For the sake of simplicity, the model relinquishes the modelling of controllers and their detailed information flow, so Fig. 3 does not show a classical STAMP model. Each box in the model can be seen as a controller described by STAMP. Controllers influence each other vertically and horizontally. The controllers on the left-hand side impose constraints on the design and development process and influence the operational constraints, and vice versa.

Development Constraints. The development constraints shown in this model represent non-functional requirements that should be considered and integrated into the system concept development phase at an early stage. All too often, this early stage of system

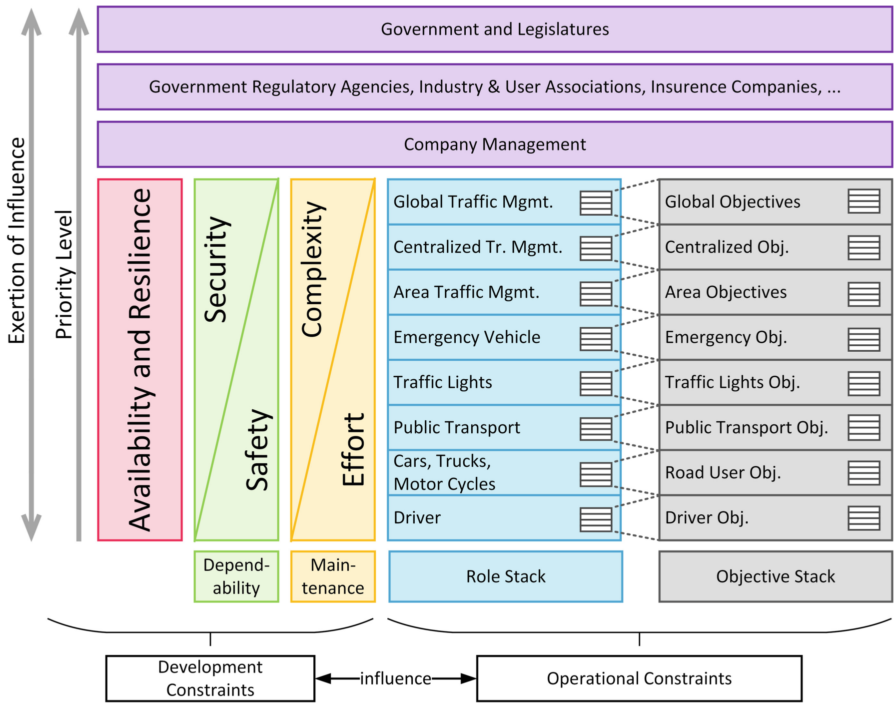

Fig. 2. High-level model of the CPS road network scenario (see Fig. 1) based on the STAMP method. This model is suggested to be used for the initial concept and planning phase

engineering is not given the attention and effort it deserves and development proceeds immediately with system architecture specification and high-level design. Inadequate concept development, however, may lead to systems that are not usable by the customer, only partially satisfy stakeholder needs, or are difficult to assure and maintain. While changes may be made later in development to make up for omissions in the early concept development stage, these later changes are increasingly expensive and disruptive as development proceeds [19].

Operational Constraints. In this model the operational constraints define roles and for each role, objectives are defined. A role reflects a traffic participant or infrastructure that is part of the traffic management system. Each role has one or more objectives e.g. traffic lights control intersections or that vehicles should drive safely and optimize their pollutant emissions. The objectives within roles and between the roles must be prioritized (e.g. emergency case management), which is reflected by stacking of the controllers. Controllers at the top of the stack are prioritized higher and can thus overrule the objectives of controllers below them. To give an example:

1. The legislature regulates the pollutant emission of vehicles.
2. The adherence of the regulation is checked by regulatory agencies. Industry and user associations work out and define standards for the industry.

3. Companies set up management structures and processes to satisfy the regulations. These processes impose constraints on system development.
4. The development constraints also influence the operation of the vehicles and infrastructure. In the given scenario, for example, a car implements predictive energy management [3]. Hence, the car must communicate with other vehicles and the infrastructure (e.g. smart traffic lights) to reduce its pollutant emission and satisfy the regulatory limits.
5. In the case of an emergency, the traffic management systems overrule the car's objectives by instructing it to quickly accelerate, resulting in the violation of the regulatory limits.

In summary, models developed with STAMP are suitable for an early stage dependability analysis and the identification of requirements, as already shown in [19]. The developed models can be further refined as design decisions are made. However, we think that applying STAMP throughout the entire development process is too elaborative and the use of domain-specific methods is required in later phases. Thus, we suggest the use of already established methods later in the development process, which is discussed in the following section.

4 Applicable Standards and Methodologies

CPS road networks are a complex domain and relevant for multiple stakeholders. This resulted in a fragmented landscape of different standards and methods, which only partially overlap. Methods are mostly defined for the domain or scenario for which a standard was developed. It exists no holistic approach to the overall system. For the infrastructure side, the European Telecommunications Standards Institute (ETSI) has defined a set of standards describing trust infrastructure, as well as V2X message structures and interfaces. However, the engineering of the vehicle itself is mainly defined by ISO standards. Figure 3 gives an overview of the standards and methods for the engineering of smart traffic systems.

ISO 26262 Road Vehicles - Functional Safety: Amajor step in this direction was ISO 26262 [14], which was published in 2011. This standard defined not only the engineering of functional safety in the automotive domain but was also taken as a template of how the lifecycle for automotive systems can be structured. ISO 26262 focus on functional safety for road vehicles. The scope of this extends to a system which implements a function on the vehicle level, referred to as item. For this function item hazards are identified, and a safety concept is developed and identified. For the identification of hazards, the Hazard Analysis and Risk Assessment (HARA) is presented in part 3, other often used methods are Failure Mode and Effect Analysis (FMEA) [1] and Fault Tree Analysis (FTA) [17].

ISO/SAE AWI 21434 Road Vehicles Cybersecurity Engineering: Currently the working draft of ISO/SAE AWI 21434 road vehicles cybersecurity engineering is in its finalization phase. It is a partial evolution of SAE J3061 [23]. The main focus is on cybersecurity for road vehicles, but other attributes are also considered. Safety is on the

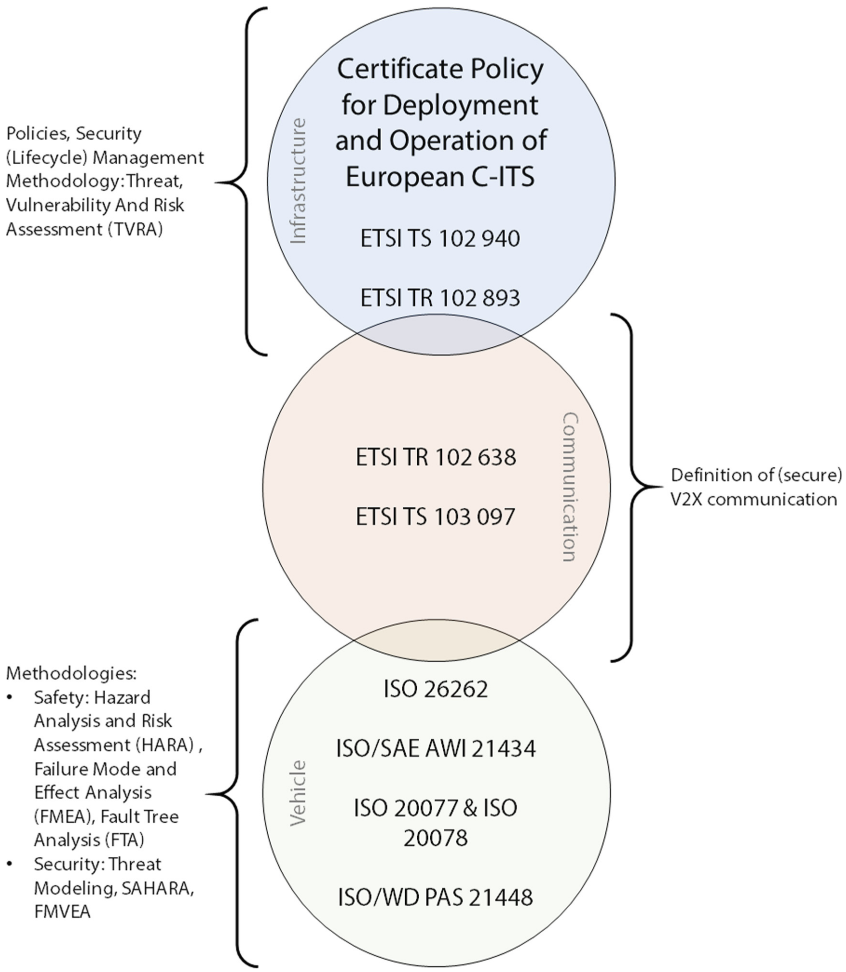

Fig. 3. Overview about standards and methods, classified in-vehicle, communication and infrastructure domain

one hand considered as one of the assets which need to be protected by cybersecurity. Others are confidentiality of sensitive data, financial impact or availability. On the other hand, safety engineering is considered as a related discipline. The generic approach is similar to ISO 26262, the scope is on a cybersecurity critical system in the vehicle and the next hop outside of the vehicle. The draft presents currently threat modelling, SAHARA [20] and FMVEA [24].

ISO 20077 and ISO 20078 - Extended Vehicle: ISO 20077 and ISO 20078, commonly summarized as "Extended Vehicle" [15, 16], describe techniques, processes and methods of how to access data in a (road) vehicle and how to access external services from a vehicle. The standard assumes that the resource and access system has already been defined during development. Based on this the process assumes there is already an existing interface (extended vehicle) and the standard is mainly concerned with evaluating new requests for interacting with extended vehicles resources and whether this would trigger any new safety, security or privacy risks. Consequently, there is no defined methodology for the design phase.

ISO/WD PAS 21448 Road Vehicles - Safety of the Intended Functionality: Defines safety engineering with a focus on safety engineering for autonomous functions, which are beyond the scope of ISO 26262. It covers both hazards resulting from functional shortcomings and from reasonably foreseeable misuse by humans and gives guidance on applicable design, verification and validation measures. The goal here is to establish the Safety of the Intended Functionality (SOTIF).

The intelligent transportation system itself is mainly defined by ETSI. ETSI works traditionally on communication and the standards thus include protocol definitions. Overall there are 63 active standards from ETSI concerning intelligent transportation systems. The focus is mostly on the communication level, while safety concerns and effects inside the vehicle are not considered in detail.

ETSI TR 102 638 Intelligent Transport Systems (ITS): Vehicular Communications; Basic Set of Applications; Definitions. [2] defines the reference architecture for on-board units (OBU) and road-side units (RSU) in addition to other ITS elements. The main focus is on defining a basic set of potential use cases and less on defining a lifecycle with methods. Some of these use cases are also relevant for the emergency use case, for example, the “emergency vehicle warning”. The standard also defines a Basic Set of Applications (BSA), a set of applications that reflect the main user needs and requirements. These applications are then specified in further documents and are implemented in services Most relevant for our use case are the three services: The **Cooperative Awareness Basic Service** [11] describes a service in which road users and roadside infrastructure can be informed about each other’s position, dynamics and other attributes. This service could be used by a vehicle indicate its type (i.e. emergency vehicle) to other road users and request for the right of way. The **Decentralized Environmental Notification Basic Service** [6] describes a service to inform road users about road hazards or abnormal traffic conditions. Here, road users could be informed about an approaching emergency vehicle or closed lanes on a motorway after an accident. Regarding infrastructure elements, [7] provides a set of services, including the **Traffic Light Control Service** which enables the prioritization of public transport and public safety vehicles at traffic lights.

ETSI TR 102 893 Intelligent Transport Systems (ITS); Security; Threat, Vulnerability and Risk Analysis (TVRA). [8] defines the methodology for the security engineering of ITS elements. The focus is more on the overall process and less on presentation of concrete methods. The methodology starts with an identification of assets, enumerates potential threats and identifies vulnerabilities which could lead to exploitation of such threats.

ETSI TS 102 940 Intelligent Transport Systems (ITS); Security; ITS Communications Security Architecture and Security Management. [10] describes the security architecture for ITS. It also defines a set of security requirements and a security management system (including life-cycle management), which is needed to establish the C-ITS Trust Model for the more general communications architecture [5]. This trust model is based on a public key infrastructure (PKI). With TS 103 097, ETSI also gives guidance on how to secure communication between road users and infrastructure elements [9].

Furthermore, from a European standpoint, the **Certificate Policy for Deployment and Operation of European Cooperative Intelligent Transport Systems (C-ITS)** [22] gives a framework for a C-ITS Trust model. It is based on Public Key Infrastructure. It includes legal and technical requirements for the management of public key certificates for C-ITS applications. The policy is binding to all entities participating in the C-ITS system in Europe. The policy is further part of the European strategy on Cooperative Intelligent Transport Systems [4], issued by the European Commission.

5 Conclusion

In this work, we discussed a realistic CPS road network scenario from the perspective of every-day situations and emergency cases. Based on this scenario we derived subjective challenges and a concept that could serve as a starting point for a future systems engineering method focused on dependability. Additionally, we gathered a brief overview of state-of-the-art standards and methods that have the potential of becoming part of an approach in this context. In future work, the presented emergency scenario will be further evaluated with selected methodologies presented in this work. Especially the cyber-security implications to safety and dependability will be assessed, with the goal of developing appropriate mitigation processes for operators and officials of authorities and organisations with public safety responsibilities.

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Design and Evaluation of Cooperative Automated Bus Lines

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Abstract. This study researched pros and cons of cooperative automated busses by means of a simulation model that renders the influence of bus concepts on key parameters, like: travel time, frequency, capacity, energy consumption and costs. Two existing bus routes are taken as base context. The bus concepts consisted of a completely autonomous bus (assumed SAE level 5), a partially automated bus (level 4) and a conventional bus. The results showed that an autonomous bus causes increased travel time for travelers. However, concepts that combine partially automated driving on dedicated lanes with cooperative driving show potential benefits from more frequent operation. Furthermore, the possibility to remain in the bus when waiting for a connection may be experienced as a comfort enhancement.

Keywords: Automated driving · Cooperative platoons · Public bus transport · Human-machine cooperation

1 Introduction

Public bus transport is a means to offer basic transport facilities to travelers. The main goal is to connect between residential areas, offices, places of interest and other means of transport (like trains). In the Netherlands, bus lines are commissioned by municipalities. Regions with smaller cities and more distant suburbs face growing economic difficulties to offer these facilities. This is due to low efficiency: The buses' (full) capacity is only used for ca. 2 h during morning rush hours. During the rest of the day many lines are almost empty. As a result, bus lines are increasingly unprofitable [1]. Nonetheless, United Nations urges for the availability of public transportation to keep cities clean (i.e. SDG Goal 11 [2]). Furthermore, municipalities in the Netherlands are required by a Dutch Social Support Act (WMO) to offer tailored transport means to people with impaired health conditions. This user group show large differences in social background, age, mental capabilities, etc. To serve their needs is an additional challenge for the availability of bus lines. Above challenges explain a huge attention in the Netherlands for new solutions of public transport, like Mobility as a Service or automated shuttles. Especially automated driving seem promising as it aims to reduce accidents, energy consumption, pollution and congestion while increasing transport accessibility [3].

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1.1 Trials with Automated Buses

In an ideal world, public transport is flexible, demand-responsive, tailor-made, sustainable, and costs effective [4]. The most significant costs in offering public bus transport is the bus driver. This is approximately half of the operational costs [5]. The implementation of automated driving in public bus transport may therefore be a means to save costs. Several pilots on automated public transport are attempted to research the possibilities of the technology and the response of the public. So far, trials with automated buses in existing infrastructure have however not been successful [6–8]. Due to required levels of reliability to take part in traffic safely, the buses have been driving very slowly, lacked advantages in comfort and travel duration – and hindered other road users. As a result, many trials faced low acceptance [8, 9].

1.2 Cooperative Buses Concept

In contrast to completely automated buses, this study explores the application of cooperative driving buses. In this concept, the 'cooperative' quality entails the capability to closely follow another bus. The bus is also capable of driving autonomously for a reduced range. During following mode, it connects to another bus that may be manually driven (See Fig. 1). Such combination allows the automated bus to travel with a human driver through more complex traffic conditions, like city centres or school regions. In fully automated mode the bus is assumed to have its own dedicated lane. The concept is intended for bus maps with divided branches and when branches merge the closer they come to a city centre. The main connections into the centre would be human driven. Cooperative buses would join from the outer branches (that have dedicated automated lanes).

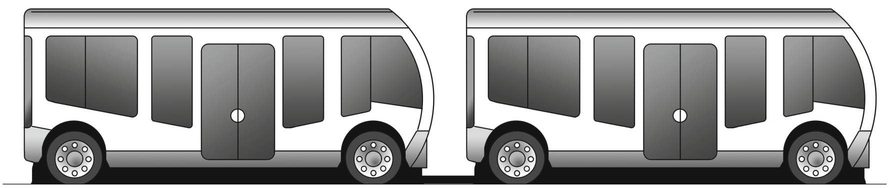

Fig. 1. Illustration of cooperative buses concept

1.3 Simulation and Assessment

Possible advantages and disadvantages of cooperative automated busses are investigated by means of a simulation model that renders the influence of Concept on performance parameters, like: travel time, service frequency, available capacity, energy consumption and costs. The routes of two existing bus lines are taken as base context. In addition to the cooperative bus concept two other concepts have been evaluated: a fully automated bus and existing manually operated buses. The latter act as base reference. The fully automated and cooperative buses include an electric drive train. The simulation is based on two existing bus routes from the municipality of Assen and Hengelo and includes real world data for operation-times, frequency of the service and occupation rate. With the results of the simulation (i.e. data from above mentioned performance parameters) a qualitative assessment will be conducted with respect to advantages and disadvantages for travelers. Other aspects that contribute to successful implementation are briefly discussed, like trust, comfort and acceptance.

2 Automated Driving in Public Bus Transport

Due to the technical challenges, automated driving is currently mostly applied at closed environments, and in restricted and predefined areas. Developments to overcome the technical challenges (for instance cooperative driving) determine the possibility to drive automatically at other places than in restricted and predefined areas. At a generic level, Fig. 2 shows the three aspects that influence the implementation of automated driving in public bus transport and they are briefly explained below:

- *Technology Readiness Level (TRL):* the state of the automated driving technology determines the maturity of the technology and reliability. Timely recognition of objects is a main driver for TRL, which in turn is influenced by vehicle speed. For reasons of reliability and safety, automated vehicles in highly complex environments operate therefore at lower average vehicle speed compared to vehicles in less complex environments.
- *Integration into the driving schedule:* The integration into the driving schedule determines the type of implementation. Integrating automated driving partially in the current public transport system support short-term implementation. In partial integration, the bus can be driven manually in the complex parts of the route, such as the city centre. In the outer areas, the bus drives automatically.
- *Infrastructure and legislation:* The infrastructure influences the possibilities of implementing automated driving with a specific state of technology. Adjustments to the infrastructure, such as the construction of a dedicated lane or traffic lights, support the safe implementation of vehicles with lower TRL. In addition, adaption of legislation is required to allow for the implementation of automated driving.

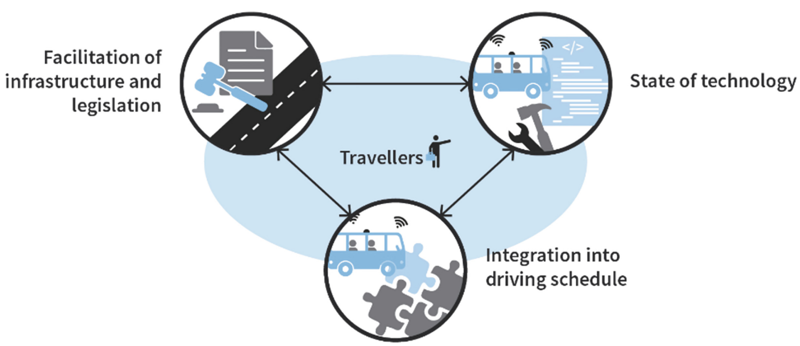

Fig. 2. Aspects that influence the implementation of automated driving in public bus transport

In addition to these aspects, the interests of the traveler should be put central, because the success of the implementation depends on whether the traveler is willing to travel by an automated bus. In addition, the interest of other stakeholders like the transport company and the governmental authorities, should be addressed.

3 Research Scope and Methodology

This study is based on two existing bus routes from the municipality of Assen and Hengelo and includes real world data for operation-times, frequency of the service and occupation rate. By means of a simulation the influence of new bus concepts on performance parameters (like; travel time, service frequency, available capacity, energy consumption and costs) are calculated. A qualitative assessment will be conducted with respect to advantages and disadvantages for travelers. This chapter will further explain the scope and approach of our research. We start with the bus concepts and case study.

3.1 State of Technology

Our study considers automation Level 4 and Level 5 [10]. According to the SAE definition [10], buses in Level 5 would be able to drive in all situations and circumstances autonomously. In Level 4 the vehicle drives fully automated only in predefined areas. For Level 4 it is assumed that the predefined situation increases reliability and therefore allows a higher vehicle velocity of the automated buses than for buses operating at Level 5. In the simulation this influence is reflected in a divide between two maximum vehicle velocities: A maximum vehicle velocity of 40 km/h is assigned to situations that exclude vulnerable road users (i.e. bicyclists and pedestrians) and 20 km/h to situations that include vulnerable road users.

3.2 Case Studies

In order to conduct the study in a realistic context, we have taken two existing bus routes as examples. The routes consist of bus line 1 in Assen and bus lines 11 and 13 in Hengelo. Bus lines 11 and 13 are analyzed together because both lines combine in one loop. Bus line 1 at Assen drives two times an hour and bus lines 11 and 13 three times an hour. The bus lines on these routes travel between the city centre and one or more districts. In current practice, the buses drive at relatively low speeds along these routes (average speed 28,6 km/h). The existing routes include dedicated bus lanes and roads with separate bicycle paths. Therefore, scenarios with automated buses driving at Level 4 are assumed possible and would than allow 40 km/h maximum speed.

3.3 Automated System-Concepts

In addition to automation level, concepts are composed that also consider two types of vehicle, i.e. a Large and Midi sized vehicle. The concepts are developed in order to research how level of automation and vehicle type influence possible application of the concepts in the existing driving schedules. Especially concepts that consider automation level 5 with a limited maximum vehicle velocity may have an effect on the bus line's time schedule, due to longer travel time compared to the conventional bus. The basic system-concepts are briefly explained below (see also Fig. 3):

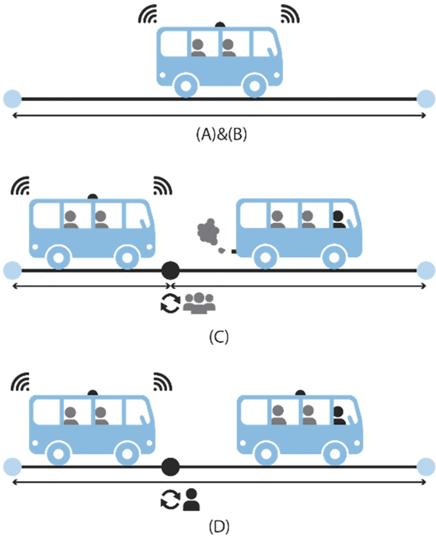

Fig. 3. System concepts that show different types for implementation of driving automation. Concepts A and B are fully automated (Concept B is limited to a maximum vehicle velocity of 20 km/h). Concept C considers partial automation while passengers need to change to a conventional bus. Concept D considers a partially automated bus capable of servicing the complete route of the bus line.

A. Concept for which the whole route is replaced by an automated bus with automation level 5 without a reduced vehicle velocity.
B. Concept for which the whole route is replaced by an automated bus with automation level 5 including a limited maximum feasible vehicle velocity of 20 km/h.
C. Concept that considers partially replacement of the bus line by an automated bus with automation level 4 which involves vehicle speed limitations. The other part of the route is driven by a bus driver in a conventional bus. This concept may require passenger to change bus.
D. Concept in which the whole route is replaced by a dual-mode bus that can be operated both manually and automatically. This dual-mode bus drives the whole route but is partially driven by a bus driver and partially automatically with automation level 4 which involve vehicle speed limitations.

In addition to automation level, the simulation also considers variations in the size of the bus, the number of buses, and the driving frequency. The size of the bus is either defined as a Midi bus (capacity up to 40 including 12 seats) and a Large bus (capacity up to 100 passengers including 31 seats). The driving frequency is either the current

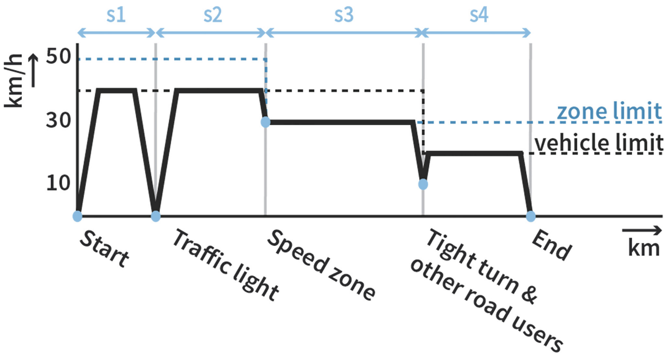

Fig. 4. Example with simulated speed profile in Matlab. The blue dots indicate observed speeds in practice. The blue dashed line indicate the maximum allowed speed in the specific road sections (zones) and the black dashed line is the maximum vehicle velocity defined for the particular concept. Based on this information, the speed profile (black line) was calculated.

frequency (2 per hour in Assen, 3 per hour in Hengelo) or an increased frequency (4 per hour). Combinations of these aspects were modelled to calculate their effects on travel time and costs and consequently to draw conclusions about preferences for any of the basic system-concepts.

3.4 Methodology

The simulation model is programmed in MATLAB and simulates the system-concepts in one hour of exploitation (See for example Fig. 4). The results of the simulation consists of data on: travel time, charge time, energy consumption and costs. With these data, the basic system-concepts will be assessed on system level by means a qualitative appraisal: To assess whether the basic system-concepts are practically applicable and attractive for the stakeholders (including travelers) additional assessment criteria are defined. The assessment criteria are total travel time, short waiting times, ability to travel spontaneously, the number of changes between vehicles, employability of buses, capacity to transport all travelers and costs.

4 Results

The aim of the simulation was to find appropriate and practically applicable implementations of automated driving for the selected bus routes in Assen (bus line 1) and in Hengelo (bus lines 11 and 13). A system-concept is practically applicable when it can be integrated into the current schedule regarding travel time, charge time, passenger capacity and costs. The selected system-concepts are considered to be an alternative to existing bus lines. In subsequent qualitative appraisal, the interests of the involved stakeholders are central: the transport company, the governmental authorities, and, in particular, the travelers.

In general, the results showed that the Midi bus is insufficient to transport the current number of travelers in Assen. This applies to all different system-concepts regardless its level of automation. In Hengelo, the Midi bus is sufficient only if the system-concepts include an increased driving frequency. In all other cases, Large buses have to be deployed.

The assessment of the four basic-system-concepts is as follows:

A. Concept A considers fully automated buses without a reduced maximum vehicle speed velocity – with regard to TRL it therefore depicts a somewhat unrealistic concept. In this concept the travellers do not have to compromise on travel time because the travel time is equal to the conventional system-concept. If exploited at bus line 1 in Assen, required costs for charging facilities outbalance the reduced labour costs. Therefore, only the low-frequency Large bus Level 5 (fully automated system-concept) is feasible in Assen – offering no direct advantages for travellers compared to the current situation. At Hengelo, savings of labour costs allow the driving frequency to go up from three to four times per hour – offering some advantages for travellers compared to the current situation.
B. Concept B considers fully automated buses with a reduced maximum vehicle velocity of 20 km/h (Henceforth, this concept represent a more realistic TRL). Since this system-concept does involve maximum feasible vehicle velocities the travel time increases. This is 24% at bus line 1 in Assen and 30% at bus lines 11 and 13 in Hengelo. This is disadvantageous for the traveller. Therefore, with an equal driving frequency as the conventional system-concept this concept is unattractive. However, in Hengelo, an increase in driving frequency is possible from the perspective of costs, passenger capacity and time. Driving with a higher frequency offers the advantage to travel more spontaneously. This results in concept B being advantageous if exploited with the higher frequency time schedule.
C. Concept C considers partially automation and the obligation for passenger to change between automated bus and manually operated bus. This system-concept includes an additional change between vehicles which is perceived as disadvantageous by the traveller due to uncertainty about catching the bus and waiting time is perceived as very long. Furthermore, the travel times increase by 15% in both bus lines at Assen and Hengelo. From the passenger perspective, this is disadvantageous compared to the conventional system concept. Consequently, this system-concept is unattractive in both the Hengelo and Assen case studies.
D. Concept D considers partially automation, similar as with concept C, but without the required change between buses. In this concept the partially automated bus waits until it is able to connect to a human-operated bus. Then, both buses will drive through mixed traffic. Similar to concept C, the travel time increases since the buses need to wait for one another. However, the traveller can wait inside the bus which makes the waiting time more comfortable and it includes less uncertainty about the connection.

Overall, the results show that automated buses with a realistic TRL (i.e. reduced vehicle velocity when operated in mixed traffic) are not able to offer benefits with regard to reduced travel time. On the contrary, these concepts require increased travel time, a trade-off also observed in field studies [8]. Nonetheless, concepts that combine partially automated driving on dedicated lanes with cooperative driving may offer a benefit of more frequent operation (due to some cost optimisation compared to conventional bus lines). Furthermore, the possibility to remain in the bus when waiting for a connection may be experienced as a comfort benefit.

5 Potential Implementation

The success of the implementation of automated driving in public bus transport not only depends on its feasibility in terms of costs, travel time and frequencies, but other aspects may also contribute at large:

People need to be willing to travel with automated buses. Trust can be increased through positive experiences of the people themselves and what they hear from their social environment. Daily users in public transport will probably become accustomed to automated driving earlier than inexperienced travelers or elderly people.

The social safety inside the vehicle should be guaranteed. Due to the absence of the bus driver, nobody is present to ensure this safety. Especially in late evenings, this could cause problems. The social safety could possibly be increased by for example equipping the bus with security cameras or employing supervisors. This includes new investments which are not taken into account in the assessment on system level.

By disengaging the bus driver nobody is present to sell tickets inside the bus itself and to check the tickets of travelers. Therefore, a new payment system is needed that takes into account travelers' conduct and avoids misuse.

The most important limitation of automated driving is its reliability for safe driving and obstacle detection within the unstable road environment bus-traffic typically consist of. For the implementation of automated driving, a risk analysis should therefore be performed and acceptable risks should be determined.

The number of involved risks in automated driving can be decreased by adjusting the infrastructure. Examples are the construction of a dedicated lane, traffic lights or reducing the number of complex road-traffic situation. This may improve reliable implementation.

6 Discussion and Recommendations

This study researched the potential implementation of partial or full automation of public buses as a replacement for conventional bus lines. This research included assumptions about the future state of technology. These assumptions can be compared to the current state of technology in the pilots of automated driving at public roads. The automated buses in the pilots drive on average approximately 15 km/h [8]. This speed is imposed due to the safety the bus has to guarantee in all occasions. The step towards approval of 40 km/h or more is very big. The question is when and whether this will be actually achieved. The assumed reliability of complete autonomous vehicles at automation Level 5 seem not realistic [11]. The results of this study show that partially automation with buses that drive automatically at restricted parts of the bus's route is a reasonable and feasible approach.

This research applies the basic system-concepts to two case studies to simulate the influence of automated driving on the current public bus transport system. Of course, more case studies should be investigated in order to validate the general influence of automated driving on public bus transport. Special attention should be given to tranches of bus lines to more remote areas since such application is most challenging for conventional bus lines to offer an economically feasible service.

Lastly, in the assessment is assumed that a higher frequency offers some compensation for increased travel times. Further research on travelers' behavior should be performed to validate this assumption.

While our study is based on a model simulation, acceptance remains underexposed. More research is urgently needed on acceptance and overall implementation. An important aspect is for example the experience of travelers with automated public bus transport and the appreciation. Furthermore, this study shows that adjustments to the infrastructure can accommodate the implementation of automated driving. However, more research is needed to scope out benefits of these adjustments in more detail as well as required costs and any adverse effects. Furthermore, this research includes many assumptions, such as the actual future state of technology and purchase costs of automated buses. Within the simulation model these parameters are flexible, so when there is more certainty about these parameters new simulations with updated parameter values need to be performed.

7 Conclusions

This study researched possible advantages and disadvantages of cooperative automated busses by means of a simulation model that renders the influence of Concept on performance parameters, like: travel time, service frequency, available capacity, energy consumption and costs. The routes of two existing bus lines are taken as base context. The concepts consisted of a bus driving completely automated (assumed automation level 5), a bus driving partially automated (automation level 4) and a conventional bus.

Overall, the results show that automated buses with a realistic TRL (i.e. reduced vehicle velocity when operated in mixed traffic) are not able to offer benefits with regard to reduced travel time. On the contrary, these concepts require increased travel time, a trade-off also observed in field studies [8]. However, concepts that combine partially automated driving on dedicated lanes with cooperative driving show potential benefits of offering more frequent operation. Furthermore, the possibility to remain in the bus when waiting for a connection may be experienced as a comfort benefit.

To conclude, for the case studies of our study, it is possible to offer Level 4 automated buses that are practically applicable. The results of our simulation show that such concept comes with travel times, charging duration, and passenger capacity that is compatible with the current situation. In addition, the concept either reduces costs or allows for an increased travel frequency while remaining within the same costs budget as the conventional system-concept. A remaining question is however whether a more frequent bus connection will increase the attractiveness compared to a somewhat longer travel duration.

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Sustainable Shared Mobility Interconnected with Public Transport in European Rural Areas

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Abstract. Just over one quarter of the EU-28 population lives in rural areas, possibly reflecting a trend towards leaving inner city areas in search of more (affordable, qualitative, open, peaceful) space, in suburbia, towns, or the countryside. Despite the positive connotations associated with rural dwelling, rural areas present conditions that require further support towards the adoption of smart integrated mobility solutions. The lower population density makes running public transport at high frequency inefficient, expensive, limited and not meeting the local demand. This, in turn, provokes an increase in the share of private cars ownership among rural inhabitants, which has negative environmental and socioeconomic impacts. Addressing these challenges, the EU-funded project "SMARTA 2-Sustainable Shared Mobility Interconnected with Public Transport in European Rural Areas" sets to deploy, implement and evaluate four demonstration sites in East Tyrol (AT), Trikala (GR), Águeda (PT) and Brasov (RO) involving sustainable, shared and integrated rural mobility solutions interconnected with public transport and supported by multimodal travel information services.

Keywords: Rural mobility · Sustainable shared mobility · Public transport · e-Car sharing · Carpooling · e-Bikes · Multimodal travel information services · Demonstrators · Evaluation framework · Behavioural incentives · Nudging

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1 Introduction

Cities all over Europe have been working on creating the right framework conditions for the implementation of smart mobility (in particular with respect to standardisation, interoperability and data exchange) and/or on developing Sustainable Urban Mobility Plans (SUMPs) to raise awareness about and promote the use of alternative means of transportation (e.g. carsharing, park and ride, bicycles). Although cities suffer from congestion and air and noise pollution, the switch to sustainable transport alternatives is facilitated by lower requirements for vehicle range and greater availability of transportation options (public transport, walking and cycling infrastructure and shared vehicles).

On the contrary, rural areas present conditions that require further support towards the achievement of the objectives set by the 2011 White Paper on Transport (European Commission 2011) and the adoption of smart solutions. For instance, the lower population density makes running public transport at high frequency inefficient, expensive, limited and not meeting the local demand. Rural residents frequently have fewer public transportation options and depend on family members to drive them to appointments (Jentsch 2017). This, in turn, provokes an increase in the share of private car ownership among rural inhabitants, which has a negative impact on the environment. Furthermore, the lack of access to transport options often translates into the lack of accessibility of important services that are usually concentrated in towns and cities, such as health and education, and even supermarkets and shops (Eurostat 2017; Syed et al. 2013). The relative isolation of rural communities and longer travel distances to urban areas act as barriers to seeking and accessing services by rural residents. Most importantly, rural communities are confronted with higher risks of poverty or social exclusion as depicted in Fig. 1. The risk of poverty or social exclusion in 2015 was higher in Greece's and Romania's rural populations than in the cities or towns and suburbs (Eurostat 2017).

Overall, poor transport contributes to social exclusion in two ways. It can prevent people from participating in work, learning, health care, food, shopping and even taking part in community building activities such as volunteering and participation in collective actions. Second, people in remote areas also suffer the worst effects of road traffic through pollution and pedestrian accidents. Thus, "*poor transport has costs for individuals, businesses, communities and the state*" (Social Exclusion Unit 2003).

Addressing these challenges, the EU-funded project "SMARTA 2- Sustainable Shared Mobility Interconnected with Public Transport in European Rural Areas" sets to select, deploy, implement and evaluate four demonstration sites that implement sustainable shared rural mobility solutions interconnected with public transport supported by multimodal travel information services. The four demonstration sites are in the following rural areas: East Tyrol (AT), Trikala (GR), Águeda (PT) and Brasov (RO).

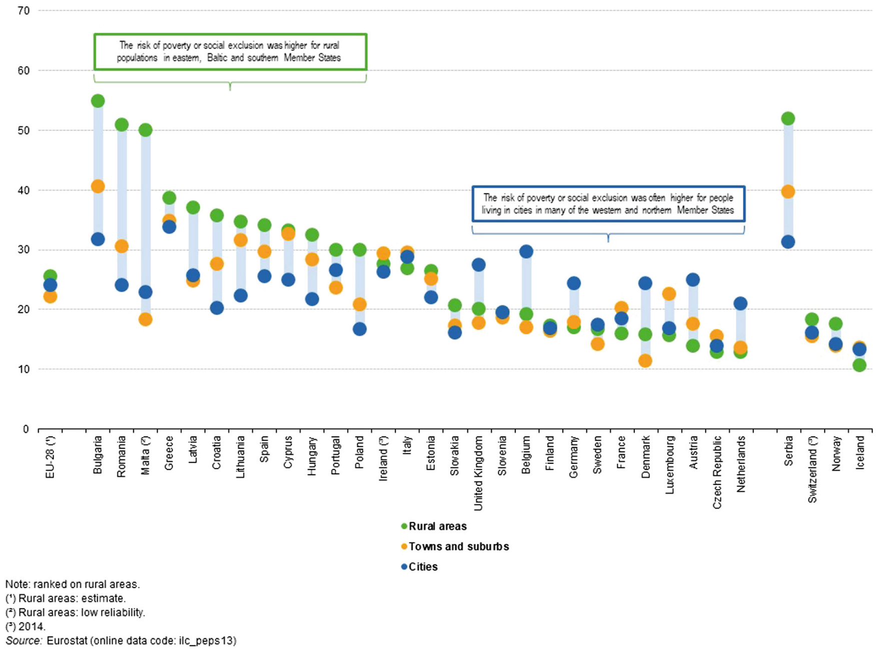


Fig. 1. Share of people at risk of poverty or social exclusion, by degree of urbanisation, 2015 (Eurostat 2017)

The outcomes of the implementation of sustainable shared services in the demonstration sites will be monitored, recorded, analysed, and assessed using the "SMARTA" Evaluation Framework[1]. All activities of the SMARTA 2 project will be complemented by customised communication, dissemination and exploitation actions and behavioural nudging incentives (Thaler and Sunstein 2009) to incentivise local citizens to use the new services provided.

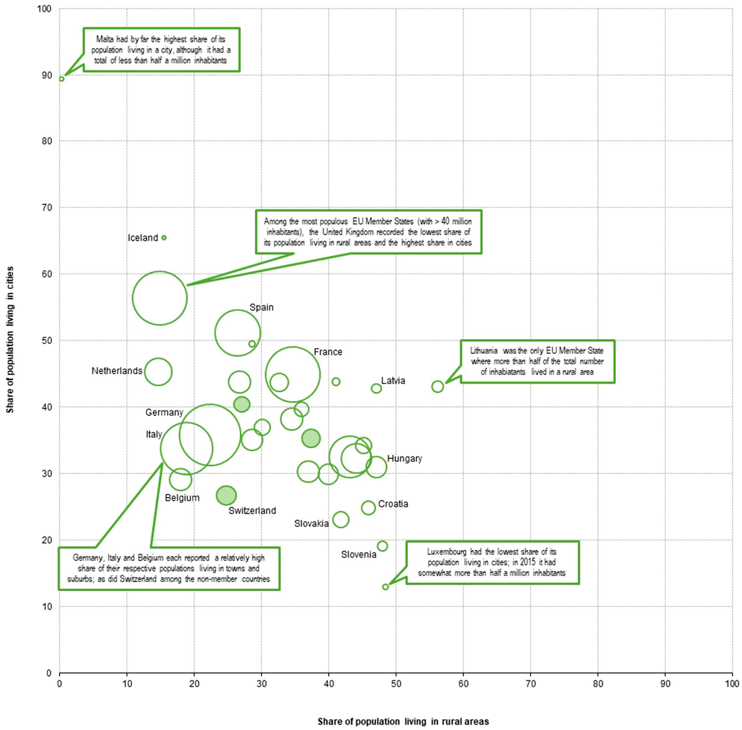
The synthesis of all quantitative and qualitative information collected, will highlight the lessons learnt and the transferability elements of the demonstrators, explaining how on-demand services, vehicle automation and digital solutions can help address mobility needs in rural areas and which measures are needed to improve transport options for rural areas in line with the goals set in the 2011 White Paper on Transport.

1.1 Transport Challenges in the Rural Areas

According to the latest Eurostat data on rural areas (2015), just over one quarter (28.0%) of the EU-28 population lives in a rural area, with a somewhat higher share living in towns

[1] SMARTA 2 complements the project "SMARTA: Pilot project — Sustainable shared mobility interconnected with public transport in European rural areas (developing the concept of "smart rural transport areas" (SMARTAs))" by offering a testbed for exploring the efficiency of the evaluation framework developed under the SMARTA project. For further information on the SMARTA project, please visit: https://ruralsharedmobility.eu/.

and suburbs (31.6%). Between 2010 and 2015 a gradual increase in the number of people living in rural areas across the EU-28 was observed, while the share of people living in cities declined at a relatively rapid pace. These patterns possibly reflect Europeans leaving inner city areas in search of more (affordable) space, in suburbia, towns, or the countryside (Fig. 2, Source: Eurostat).



Note: the area of each circle is proportional to its average population in 2015; the shaded circles denote non-member countries (Iceland, Norway, Switzerland and Serbia).
Source: Eurostat (online data codes: ilc_lvho01 and demo_gind)

Fig. 2. Overview of the distribution of population by degree of urbanisation, 2015 (Eurostat 2017)

There are a number of real or anticipated advantages that attract people to live in rural areas: lower housing and living costs, more space, a better social fabric, less pollution, closer proximity to nature, a less stressful lifestyle. These advantages are juxtaposed against a range of (potential) drawbacks, such as fewer local education or job opportunities/choices; difficulties in accessing public services or transport services; or a lack of cultural/social venues for leisure activities requiring infrastructure (Eurostat 2017). People may also choose to move to live in rural areas because they wish to access more affordable dwellings and benefit from lower costs of living. These may be people who cannot afford a private car and may not be able to sustain the higher costs of rural public transport. The lack of access to transport options often translates into the lack of accessibility of important services that are usually concentrated in towns and cities, such as health and education, and even supermarkets and shops.

According to Eurostat (2017), rural populations are more likely to have unmet needs for health care due to expenses and distance to travel; and they tend to leave education early and have lower educational attainments. More generally, poor connections with city centres usually imply negative consequences on the provision of courier services, such as post and package delivery and, possibly, also on tourism and agriculture. Poor connections with city centres and service hubs may also translate in a higher unemployment rate. Although regional differences exist, the share of people aged 18 to 24 who are neither in employment nor in further education or training (NEETs) is higher for rural areas than for towns or cities. When distinguishing between men and women, rates tend to grow for women, signalling the existence of a gender gap.

These issues pose consequent challenges on transport: for instance, the lower population density makes running public transport at high frequency inefficient. Therefore, public transport options tend either to be very expensive or very limited and not (always) meeting the local demand. This, in turn, provokes an increase in the share of private car ownerships among inhabitants of rural areas, which has a negative impact on the environment. Moreover, specific morphological conditions may make the adoption of electric vehicles a poorly appealing option and require, instead, the use of larger and more polluting vehicles.

Insufficient transportation in rural areas has various side effects: rural areas become less attractive, making people prefer to move (back) to the city, thus further reducing the population density and causing the closure of services (schools, hospitals, shops) that are no longer considered sustainable. This has repercussions in terms of increased rural poverty and social exclusion for those who stay. According to Eurostat's findings, "*most of the Member States that joined the EU in 2004 or more recently recorded a higher risk of poverty or social exclusion among their rural populations than in cities or in towns or suburbs*" (Eurostat 2017). This is particularly the case in Bulgaria, Romania and Malta, but the share of rural population at risk of poverty or social exclusion was situated within the range of 30–40% also in Latvia, Croatia, Lithuania, Cyprus, Hungary, Poland, Greece, Spain and Portugal. The categories that are mostly affected by the challenges of rural mobility are vulnerable ones, notably the elderly, children, women and people with mobility impairments.

Thus, rural areas present conditions and challenges that require further support towards the achievement of sustainable and viable transportation adapted to the needs of (current and future) end users.

The European Union has been implementing initiatives to try to tackle some of the challenges mentioned above under the European Commission's CiViTAS and other transport-related programmes (including the Intelligent Energy Europe programme and the Transport Research and Innovation funding via Horizon 2020). These initiatives complement other relevant European actions, such as the Connecting Europe Facility, the European Fund for Strategic Investments and the European Strategy for low-emission mobility.

1.2 On-Demand and Shared Mobility Services Interconnected with Public Transport

Traditional transport systems are inefficient to address the needs of the entire range of the population, and especially of those residing in rural areas. Demand Responsive Transport is one of the most well studied and proposed transport solution addressing this problem in an economic and efficient way (Papanikolaou et al. 2017). Demand Responsive Transport (DRT) is "*a user-oriented form of passenger transport characterised by flexible routes and smaller vehicles operating in shared-ride mode*"(Interreg 2018), where day-to-day operation is determined by the needs of its users.

The last decade several European cities have benefited from establishing and using flexible and demand responsive transport services applications with the support of European funding (Ambrosino et al. 2016). DRT services are deployed complementary to the conventional, scheduled passenger transport (fixed lines and timetable), as they usually aim to address dispersed mobility needs, both during hours of low demand and in areas of low population or where target users are dispersed amongst the general population, e.g. people with mobility impairments and elderly, tourists. Given their flexibility, DRT services are suitable to serve niche market customers such as those travelling in off-peak hours, low demand zones and making airport connections; users with mobility impairments (elderly, disabled); and in areas not accessible by conventional bus services. These factors contribute to giving a social role to this kind of services.

Most often, DRT services have been (or are) operated as a single mode, by a single operator, with little or no integration with other transport schemes. However, the experience gained shows a great potential for improved operation and a large-scale take-up of DRT concepts, models and technologies. Within a service-sharing economy where the concept of Mobility as a Service (MaaS) is becoming a concrete market option, new technologies and business models are leading to the introduction of new solutions and DRT could be integrated with public transport, vehicle sharing and taxi systems. In addition, the driverless revolution in which autonomous driving technology is anticipated to become viable, safe, convenient and cost-efficient (Bartolo et al. 2016) could improve the efficiency of DRT or other alternative transit systems.

On the other hand, concerns have been raised regarding the implementation of DRT services. Many examples of promising DRT schemes have failed due to various reasons, such as: the lack of a robust methodological framework capable of indicating the cases and preconditions in which a DRT system would be 'successful'; unsuitable strategic objectives; or the undefined role within the public transport system (Papanikolaou et al. 2017).

2 The SMARTA 2 Project

2.1 Approach and Methodology

The overarching objective of the SMARTA 2 project is to deploy, operate and monitor four demonstration sites across Europe that involve sustainable shared rural mobility solutions interconnected with public transport and supported by multimodal travel information services. Each of the four sites represent a different area of Europe, in terms of geography, rural landscape, types of mobility needed and used, maturity in using interconnected transport services, and local transportation needs. The outcomes of the demonstration sites will be recorded, analysed and reflected together with local citizens, stakeholders and European counterparts to identify the success factors and obstacles that impact the adoption of multimodal interconnected public transport services at local rural level. An important element of the activities will be the design of customised communication, dissemination and exploitation actions that will take place at local, regional and EU level aiming at incentivising local citizens to use the new services supplemented by behavioural incentives and nudging.

The SMARTA 2 project commenced with the selection and setup of the demonstration sites, in close consultation with local transport stakeholders so as to ensure that the services to be implemented will be in line with the needs and requirements of the areas at stake and will help address real rural transportation problems. As a first step, a mapping of the existent geographical features, population and mobility ecosystem in each rural territory was performed. This creates a baseline against which it is possible to evaluate the effects of the demonstrators and what the areas have done to ensure their success. The operation of the demonstrators will be closely monitored via the SMARTA Evaluation framework, which aims to help practitioners, local and regional authorities and national and EU authorities comprehend what are the important elements that are necessary for an effective, feasible and (widely) accepted implementation of a rural mobility service[2]. The recorded outcomes will be discussed with regional stakeholders from all traffic management levels as well as quadruple helix representatives[3] to validate them and further explore possible actions that could be taken on regional and supra-regional level to leverage sustainable shared rural mobility solutions in the future. Overall, the discussions will concentrate on how on-demand services, vehicle automation and digital solutions can help address rural mobility needs, as well as identify those (policy) measures that are necessary to improve rural transport options in line with the goals set in the 2011 White Paper on Transport.

Overall, the implementation of the demonstrators will give an insight into and provide evidence on:

a) the evolution of the four rural areas' mobility needs,
b) how shared-use mobility schemes can contribute to addressing such needs,
c) the relevance and added value of on-demand services in improving sustainable shared mobility interconnected with public transport in European rural areas,
d) whether and how mature digital solutions contribute to meeting mobility demand,
e) which methods can be employed for engaging with stakeholders in rural areas and involving them in the design of customised transport services and products, and
f) whether nudging can affect rural residents' transportation choices, supporting the adoption of sustainable shared solutions.

[2] For further information, please visit: https://ruralsharedmobility.eu/wp-content/uploads/2019/08/SMARTA-Evaluation-Framework-1.pdf.

[3] Such as: policymakers, academia representatives, researchers, industry and business representatives, representatives of the community, including civil society organisations, citizens associations, etc. For further information on the notion, one may consult (Yawson 2009), (Edquist et al. 2009), and others.

In parallel with the selection, deployment, operation and evaluation of the demonstrators, communication and dissemination activities will be performed to facilitate the uptake of the services from locals. To this end, customised communication and dissemination activities will be carried out on two parallel levels, the local and the European one. While communication and incentivisation at local level will be more intense at the beginning of the project to increase stakeholder engagement and create buy-in for the demonstration sites, communication at European level will be intensified during the second half of the project, when the first results from the evaluation are expected to be known, in order to support transferability and scale-up.

All results of the project will be compiled into the SMARTA 2 Toolkit that will reflect the key lessons learnt and the actionable knowledge produced from all four demonstrators. The aim of the Toolkit will be to enhance the uptake of sustainable solutions for interconnected rural mobility at the regional and national level in the four countries where the demonstrators took place and also across the EU after the completion of the project.

2.2 The SMARTA 2 Demonstrators

The demonstrators selected to participate in the SMARTA 2 project (Fig. 3) are: East Tyrol (AT), Trikala, (GR), Águeda (PT), and Brasov (RO). These sites have been selected as they:

- provide geographical coverage, representing areas with different rural mobility needs,
- present complementarity in terms of their target audiences, from people travelling to the urban areas for work, to elderly people who cannot drive for themselves, to students and younger adults without a driving license and/or without car ownership,
- offer insight and viable solutions to current political transport related discussions,
- build on previous experiences of (past/ongoing) shared mobility projects and services, including e-carsharing, e-bikes and in one case vehicle automation (driverless buses). All these experiences will be taken into account to see the pros and cons of (automated) shared mobility solutions in addressing mobility needs in rural areas.

2.2.1 East Tyrol, Austria

The East Tyrol region is a political district of the Austrian province of Tyrol that borders the federal states of Salzburg and Carinthia as well as the Italian regions of South Tyrol and Veneto. With 2,020 km^2, East Tyrol covers almost one sixth of the Tyrolean territory and thus is the largest district in the country. The permanent settlement area occupies only 8.2% of the total area of the district, whereas the proportion of forest (39.6%) and alpine pastures (32.0%) is above the national average. The city of Lienz is the administrative, economic and cultural centre and traffic hub. The district counts 48,879 inhabitants (as of January 2015). Lienz (11,844 inhabitants), Matrei (4,667) and Nußdorf-Debant (3,325) are the most populous communities in the district, followed by Dölsach (2,338), Virgen (2,199) and Sillian (2,051). The remaining 27 municipalities have less than 2,000 inhabitants each.

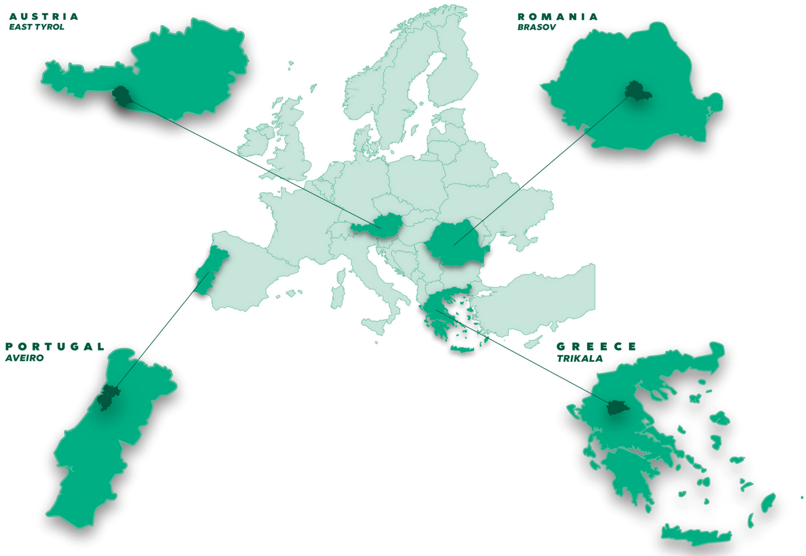


Fig. 3. SMARTA 2 Demonstration sites

Given the low population density and the spread of the population on the territory, mobility remains very much dependent on the use of private cars. Families often own two or three vehicles. The ecological and economic costs are high.

Environmental sustainability and economic viability of public transport are two open issues that the province of East Tyrol has been addressing by committing to the expansion and improvement of public transport services. The frequency has been increased, the infrastructure improved and tariffs adjusted. Through SMARTA 2, an economically attractive and environmentally friendly mobility service will be created by combining the basic public transport service with a supplementary e-carsharing system.

The objective of the East Tyrol demonstrator is to build on previous last mile initiatives implemented in the area, including a shared taxi service, an e-carsharing system and community taxis with voluntary drivers, so as to provide an open, connected, multimodal and rural environment. As a result, smart and sustainable options can be promoted among target users as an alternative to the use of private cars. It should also be noted that the e-carsharing will be operated via energy produced from local renewable energy sources. Thus, SMARTA 2 will also aim to explore the contribution and potential usage of renewable energy sources (e.g. wind, hydro, solar, tidal and thermal) to produce electricity in rural areas that can sustainably power mobility solutions.

2.2.2 Trikala, Greece

The Municipality of Trikala is situated in the Region of Thessaly, covering an area of 608.48 km^2 and counting 81,355 inhabitants (2011 census). The municipality is divided into 8 Municipal Sections: the city of Trikala (67,000 inhabitants), the Paleokastron

Municipality (2,732), the Estiaiotida Municipality (2,729), the Kallidendrou Municipality (2,193), the Megala Kalyvia Municipality (2,798), the Faloreia Municipality (3,966), the Paralithaion Municipality (2,660), and the Koziaka Municipality (2,123).

The municipality is faced with several rural transport challenges:

- The periphery is poorly served by the public transport (no regular routes).
- The use of private cars in order to drive to the city centre is extensive.
- Increased traffic, congestion and limited parking at the city centre.
- Lack of sustainable mobility solutions for people with low income that dwell outside the city centre.
- No last-mile public transport services exist (most users walk, bike or drive their cars to move within the city).

Trikala's demonstrator will focus on developing a carpooling system in the villages of Megala Kalyvia and Megarchi. Carpooling will be connected to the existing public transport system in the city of Trikala. An online application along with a call centre will provide real-time information about the expected arrival time of the buses at the stops and inform on available carpooling options, while an on-demand service will allow users to send a request for a bus or a taxi as well as book other services offered at the Info Point on Trikala's main square, i.e. storage lockers, rent a bicycle or a wheelchair scooter.

Trikala's SMARTA 2 demonstrator will leverage Trikala's past experiences in vehicle automation (CityMobil2[4]) as well as potential linkage with the ongoing vehicle automation project "*Avint: Autonomous vehicles integrated within the urban context*"[5], funded under the Greek Partnership Agreement for the Development Framework 2014–2020.

2.2.3 Águeda, Portugal

Located in the Aveiro Region, the Municipality of Águeda is characterised by a lack of connectivity between the city of Águeda and the rural areas. With a population of about 48,000 inhabitants and a total area of 335.27 km^2, the Municipality of Águeda has overall a low population density, aggravated by the fact that about one third of the population (14,571 inhabitants) live in the city of Águeda, the main urban centre of the Municipality.

In 2008, Águeda joined the Covenant of Mayors, signed the Aalborg Commitments and developed its Local Agenda 21. Following these commitments, Águeda implemented several initiatives in the area, such as the design of ICT solutions to promote the digitalisation of administrative procedures towards becoming a "Paperless Municipality"; the provision of free Wi-Fi access in all the city areas; and the implementation of beÁgueda[6], a public service of shared electric bicycles that allows registered users to move around the city.

[4] For further information please visit: http://www.e-trikala.gr/portfolio/citymobil2-2/.

[5] For further information please visit: https://www.avint-project.eu/index.php/en/home-en/about-en.

[6] For further information, please visit: https://www.cm-agueda.pt/pages/1086.

However, several transport challenges remain to be addressed, especially in the abovementioned rural areas, such as:

- Low public transport offer.
- Lack of connectivity between the city of Águeda and the rural areas.
- High use of private cars to move to and from the city.
- Low bike usage for daily transport although Aveiro is characterized as a two-wheel territory.
- Low usage of regional trains.
- Low usage of the e-bike public sharing system.

Águeda's demonstrator overarching objective is to leverage the existent electric bike sharing system – beÁgueda – and extend it to the rural areas to complement the existing regional train routes, especially for young people/students who need to reach school on a daily basis. In this way, the demonstrator will contribute to addressing the abovementioned challenges.

The e-bike services will be supplemented by a DRT minibus that will be used by the elderly or people with reduced mobility, funded by the "Águeda Smart City Lab", a nationally funded initiative for the decarbonisation of Portuguese cities.

2.2.4 Brasov, Romania

The Brasov Metropolitan Area consists of 18 local communities, a mix of urban and rural, small and large ones, which overall count 472,777 inhabitants. More than half of them, almost 270,000 inhabitants, live in Brasov. The city of Brasov provides education, health, culture and job opportunities for a large part of the metropolitan area population. Rural communities gravitating around the city are dwelled largely by young people who grew up in the city and moved out of it to set up a family.

The area is largely defined by natural barriers (mountains) and adverse conditions in winter, which significantly affect the modality and inter-connection of available public and private transport services. Private car usage in rural communities in the area is not only required due to the geographical and climatic features but is also closely linked to a traditional perspective that associates car ownership with independency and a higher socioeconomic status.

The objective of the Brasov demonstrator is to test shared and integrated mobility solutions in the rural communities that are part of the Brasov Metropolitan Area. The focus is on using public transport regular services – instead of private cars – combined with alternatives such as Bus Rapid Transit (BRT), DRT, carpooling, and cycling. The demonstrator will also include community-building activities that will support the rural community members in acknowledging their role and responsibility in the problem (traffic congestion, air pollution) and in defining the solution that best answers to mobility needs and territorial challenges. Moreover, on a long-term perspective, the demonstrator aims to contribute in improving the "transport solidarity" among those that own a car and those who do not own one, facilitating the access of the latter to the city centre via ride sharing. From an operational perspective, the demonstrator will operate via an online platform that will enable users to offer and book shared trips to the public transport terminals at the periphery of Brasov or other locations in the city connected to public transport hubs.

2.3 The SMARTA 2 Contribution in Improving Rural Shared Mobility

With the above in mind, SMARTA 2 sets to gather valuable information and raise awareness about a domain that often goes unspoken when it comes to smart and connected mobility. The project is:

(i) setting up four demonstrators of sustainable shared mobility interconnected with public transport in four Member States (Austria, Greece, Portugal and Romania);
(ii) exploring how multimodal travel information services, (e-)carsharing, healthy and active travel options (bikes) and interoperability with existing public transport services (can) respond to existing, urgent needs at local level; and
(iii) recording how smart rural mobility solutions can contribute to creating an understanding of the relevance and added value of shared use mobility schemes and on-demand services.

The demonstrators are in line with the goals set in the 2011 White Paper on Transport and the Commission's environmental objectives, as they aim to reduce private car use and increase the amount of resource efficient options. Thanks to the application of telecommunications, electronics and information technologies to transport, the demonstrators contribute to gathering useful information which can help implement the EU Directive on intelligent transport systems (Parliament 07 July 2010) and the corresponding work programme to rural areas. Moreover, through the Austrian demonstrator, we will explore the contribution of locally produced renewable energy to the implementation of interconnected mobility services.

The effects of the implementation of the demonstrators will be analysed using SMARTA's Evaluation Framework. Yet, so far – via the conduct of public consultations and open discussions in all demonstrator areas as well as interviews with relevant stakeholders – the project has highlighted the gaps in measurements and understanding of baseline conditions, which are key to assess the effects of any smart transport interventions.

Overall, the two projects will help identify what it takes to establish 'smart rural transport areas', by conceptualizing, identifying and piloting smart transport services. This experience is anticipated, in the long-term, to support the European Union to decide which sustainable, on-demand smart mobility solutions can help enhance the travel experience of its diverse rural populations and what market and legal framework conditions are needed thereof.

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Autonomous Vehicle Shuttle in Smart City Testbed

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Abstract. The rapid development of intelligent control techniques has brought changes to the automotive industry and led to the development of autonomous or self-driving vehicles. This paper presents self-driving autonomous vehicle (AV) shuttles in the smart city context and discusses different aspects necessary to consider when deploying AV shuttles. The smart city testbed is described where one of the key units is a self-driving last-mile shuttle bus named ISEAUTO. The objective of the ISEAUTO project is to establish a smart city testbed on the university campus where different types of experiments about future urban mobility can be studied. Vehicle and pedestrian safety is experienced as a key safety issue in the paper.

Keywords: Autonomous vehicles · Self-driving minibus · Safety · Smart city

1 Introduction

Transportation service today is not limited to the movement of humans, animals and goods from one location to another, but is deeply integrated into Industry 4.0 and Smart City by implementation of Internet of Things (IoT) to collect data and use these data to manage assets and resources efficiently. Autonomous vehicles are valuable units for the smart city concept, the number of sensors to observe the environment in order to determine the path and detect other traffic participants like vehicles on the road, pedestrians on the crossroads and any other unexpected circumstances they may encounter. As autonomous vehicles are not science fiction anymore, they become constantly closer to reality. Today, a great number of startups, universities, car manufacturers and private companies are already investing in the development of autonomous vehicles infrastructure.

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The first 5G pilot network in Estonia has been launched in the end of year 2018 on the TalTech campus, where companies and start-ups are expected to participate in developing future services or test new business models. The campus of TalTech is going to be developed as a smart city testbed. It is equipped with necessary infrastructure as well as being home to many scientific researches that are already exploring in vital 5G areas such as autonomous transportation, Internet of Things, smart buildings & city infrastructure, industry automation, and remote virtual reality (VR). ISEAUTO last-mile bus will be one of the first collaborative projects that will be developed through 5G test network (Sell et al. 2018). The next step is to present how ISEAUTO empowered by 5G technology can operate in complicated traffic and communicate with the surrounding infrastructure.

The current paper describes the main challenges in the testbed integration into smart city using ISEAUTO self-driving last-mile shuttle bus developed at TalTech as an example and discusses an overview of similar projects and their approaches for the integration into smart city. Special attention focused on vehicle safety, possible risks and safety hazards is experienced.

2 Literature Review

A few years ago, first papers predicted that automobiles will drive autonomously under limited conditions between 2020–2025, under most conditions by 2025–2035 and fully automated driving will reach a 50% market share by 2050 (e.g. Kyriakidis et al. 2015; Wadud et al. 2016). Clements and Kockelman (2017) studied economic effects of fully automated vehicles via analyzing the potential effect in the following industries: automotive, electronics and software technology, trucking–freight movement, personal transport, auto repair, medical, insurance, legal profession, construction and infrastructure, land development, digital media, police and traffic violations and oil and gas. They conclude that the potential combined economic impact of connected and fully automated vehicles is $1.2 trillion in the US or $3,800 per American per year (Clements and Kockelman 2017). In this perspective, the potential effect is enormous and calls for future research on driverless vehicles and connected platforms.

Although most studies still focus on traffic simulations, more authors are linking automated transport with human behavior and environmental factors similarly to the ISEAUTO project. For example, (Harb et al. 2018) are using naturalistic experiments for analyzing the travel behavior of people by mimicking fully automated traffic by providing 60 h of free chauffeur-service driving per household for one week. This is tested in the sample of 13 US-based subjects and track each subject for 3 weeks. Harb et al. (2018) found that people tend to significantly increase their mileage during the chauffeur week. In terms of environmental factors, there is no linearity on the effect of automation. For example, Wadud et al. (2016) test potential net emissions through various scenarios and find that automation can both reduce road transport GHG emissions and energy use by half or then nearby double them - depending on scenarios. They also conclude that many energy-reduction benefits can be realized through partial automation.

In general, there tends to be limited or no research on public opinion on actual automated driving experience (even based on those low-speed, low intensity and transit employee coupled real-life tests like the ISEAUTO project). Therefore, we still need to consider more theoretical technology adoption-based survey results. For example, Becker and Axhausen (2017) have performed meta-analysis on different surveys interested in traveler's behavior changes towards driverless vehicles and pointed out the most important factors to be researched in future are safety, ownership, willingness to pay and passion for manual driving.

When considering the public opinion which is based on survey data (and not linked to any actual urban tests), results are heterogeneous. For example, Kyriakidis et al. (2015) performed an Internet-based survey with approximately 5000 responses from 100 countries and found that manual driving is the most preferred mode, although the majority agreed that fully automated driving will substitute manual driving latest in 3-4 decades. Regarding potential risks, respondents were most concerned about software hacking, legislative changes and safety. Haboucha et al. (2017) research the ownership preference based on 700 respondents living in Israel or North America. They develop a model for autonomous vehicles (AV) long-term choices and conclude that 44% would keep regular vehicles, while early potential adaptors are young, more educated and spend more time in vehicles. Interestingly, Haboucha et al. (2017) also found that Israelis are more willing to switch to automated vehicles compared to individuals of North America.

Zmud et al. (2016) applied a car-technology acceptance model and run online survey based on 500 residents of Austin (Texas) and concluded that most people would prefer self-driving vehicle to Car2Go or Uber solutions. Regarding the travel innovation, the majority of people were conservative: they would not change their place of residence, would not predict increase in annual miles nor the number of vehicles owned. Interestingly, Bansal and Kockelman (2018) performed more specific surveys across Texas based on 1000 respondents connecting willingness to pay with automation levels 2–4. Although the survey is a couple of years old (and absolute numbers could be inflated by now), they pointed out that people are willing to pay around $ 3000 extra for level 2 of automation, $ 4500 for level 3 automation and $ 7500 for level 4 automation.

In the case of public transport, results are more promising: Dong et al. (2017) performed a survey in Philadelphia (US) on close to 900 university students and staff and the willingness to switch to driverless buses is more automation-likely: over two-third is willing to use driverless buses over traditional ones with a condition that a transit employee is on board. In contrast: only 13% are willing to take the bus without transit employees onboard.

In any case, there is a need for more empirical evidence on actual interaction of automated vehicles with users, pedestrians, (non-automated) vehicles, devices and network -the core aim of the smart city integration of this paper.

3 Smart City Integration

Being mindful of possible global scaling, Estonia together with its partner countries are proceeding development, innovation and demonstration project activities culminate with pre-deployment results and guidelines. Looking into a larger scope, not only traditional manufacturers are investing in AV and smart city, but also many IT giants are racing in this field. Outside the EU, the global trend of AV development and some examples of its integration into smart city concept are shown in the table below (Table 1).

Table 1. Global companies and their AV/smart city performance

Company	AV and smart city	Time	Location
Alphabet (Google)	Launching self-driving taxi service in Arizona for paid passengers	Dec, 2018	US
Nvidia	Building AV platform for city mapping and parking	Jul, 2017	US, China
Apple	Project Titan, autonomous driving carOS	Jan, 2018	US
SB Drive	Shuttle bus on public city roads for citizen commuting	Early 2019	Japan
Nissan	Seamless Autonomous Mobility (SAM) for city connected vehicles	Jan, 2017	Japan
nuTonomy	AV fleet as free taxi service pilot	Aug, 2016	Singapore
Baidu	Open roads test drive in a smart city pilot zone	Nov, 2016	China
Tencent	AI Lab, TAD Sim for AV simulation and testing	Nov, 2018	China
Alibaba (Amap)	Cloud computing & Big Data for AV real-time mapping	Oct, 2017	China
Nio/NavInfo	Connected vehicles and AV navigation, traffic data	Aug, 2016	China
FAW	Enabling Smartphone Controlling AV fleet and autonomous parking	2018	China

The smart city is not only about autonomous vehicles - it is a full ecosystem of interconnected smart units, AI based decisions and big data analytics. When building a smart city test site, it is important to design it in a modular way where new functions and units can be added and interconnected. Key indicators of the mobility in smart city concept are sustainable and green mobility, connected and autonomous vehicles, energy efficiency and zero emission. Nowadays, most studies on the charging of electric vehicles and their interaction with renewable energy have focused on private vehicles, mostly assuming that vehicles are used once or twice a day and charged at night. However, some early works (Iacobucci et al. 2018) on the integration of shared autonomous electric vehicles with renewable energy sources predict at least 20% savings for households with rooftop solar power shifting from utility power and hybrid private vehicles to the micro grid with autonomous electrical vehicles.

The idea of TalTech Smart City campus concept is to merge technologies and services through 5G network. For the time being, technologies available at TalTech campus are an autonomous vehicle shuttle ISEAUTO, delivery robots Starship and a zero-energy dormitory building. Additionally, smart streetlights and crossings were introduced and TalTech students are using/developing smart light vehicles like bikes, scooter, skateboards, etc. ISEAUTO will be one of the first collaborative projects that will be developed together by 5G test network. The main goal is to show how the AV shuttle ISEAUTO operates in traffic and communicates with the surrounding infrastructure by 5G technology. Services that would be available through 5G cloud platform will improve traffic by prevent collision avoidance (V2X (Vehicle to Everything), V2V (Vehicle to Vehicle) and mmWave Radars), make it more secure by testing new communication technologies, data validity and integrity. Open car platform will provide a test platform for new services such as vehicle ordering processes and payments. The TalTech smart city testbed is designed under these key components and open for new functions and units in the future. The general architecture and initial elements of the TalTech Smart City testbed is shown in Fig. 1.

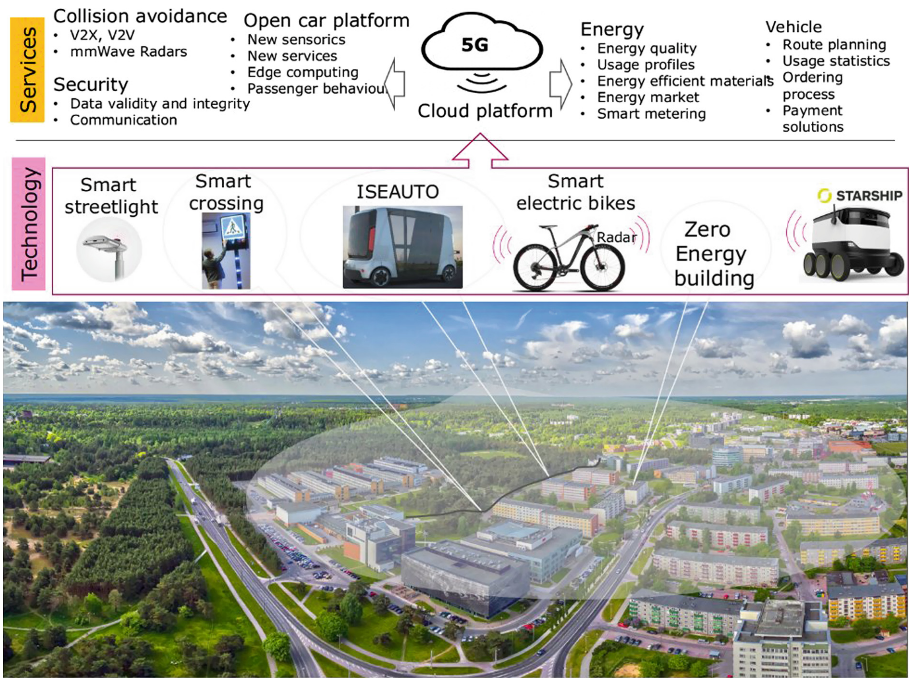

Fig. 1. Services and technologies in TalTech Smart City campus testbed

3.1 AV Shuttle in Smart City Environment

TalTech in cooperation with Silberauto and ABB Estonia has developed and deployed an AV shuttle minibus called ISEAUTO (Sell et al. 2018; Rassolkin et al. 2018) shown in Fig. 2. The first version of the vehicle is an experimental platform for research and experiments in automated and connected vehicles while the second version is already a street-legal prototype ready to be tested on real streets of Tallinn. Two connected and automated vehicles perform experiments of V2V and V2X in the smart city testbed.

An objective of ISEAUTO project is to establish a smart city testbed in the university campus where different types of projects about future urban mobility can be studied. The smart city testbed is a real-life environment where self-driving cars, delivery robots

Fig. 2. Version 1 and Version 1.1 of AV shuttle ISEAUTO

and smart infrastructure objects are placed. ISEAUTO last-mile shuttle bus provides a base for vehicle-to-everything (V2X) platform, a vehicular communication system that incorporates more specific types of communication as V2I (Vehicle-to-Infrastructure), V2V, V2P (Vehicle-to-Pedestrian), V2D (Vehicle-to-Device), V2G (Vehicle-to-Grid), or any entity that can be connected with the vehicle.

The whole project includes all kinds of different test-driving scenarios via manual and autonomous modes so to find potential issues or security threats. Testing and combining new sensors for improved localization and navigation as well as developing an architecture that would enable data usages via different sensors simultaneously. Performing tests under different weather conditions like snow, rain, fog etc. for each sensor can help develop an optimal algorithm for autonomous driving. This will also help to define an optimal set of sensors functioning for localization, object detection and classification as well as safety and situation awareness. Evaluating the scenario where some of the most computing-intensive tasks of robot control are performed on the server and sensor data is broadcasted over 5G network can map potential loopholes and provide initial mitigations. The use of edge computing can drive down the cost of each individual vehicle, but it must ensure no sacrifice of safety. Thus, safety mechanisms and triggers need to be designed for the liability evaluation. To develop methods and tools for safety risk analysis and to implement appropriate measurements, the self-driving system in real traffic conditions needs to be tested and the safety measurements should be evaluated under human supervision. When the vehicle is controlled remotely, analyzing potential cyber-attacks and the communication security mechanisms would evaluate scenarios where it would be necessary to (partly) control the vehicle remotely.

Researches on human-machine languages to communicate between self-driving vehicles and pedestrians at crossroads and bus stops will answer the question of how to build a trustworthy bridge between autonomous vehicles and human. This includes finding the best communication visual language, involving disabled people and defining communication methods suitable for all groups of audiences.

Electrical system optimization and battery management can save energy through V2I communication for example the charging systems in the city. Combining different control techniques for electric motors can realize efficiency improvement of the whole propulsion motor-drive system (incl. batteries). Based on the existing control methods, detailed work will be carried out to identify the changes in electric propulsion motor-drive components properties over its lifetime, which can be fed back into the lifetime models for each part of the system.

To further elaborate our smart city integration scenario on ISEAUTO, a data flow within the ecosystem is described in Fig. 3. Through the Mobility-as-a-Service (MaaS) interface, an end-user can send his requirement digitally and the control room can distribute and reallocate current resources via its fleet management and will send a vehicle to reach the designated position through an optimal route planning. On top of the vehicle operating process, big data and cloud computing can be achieved more efficiently by 5G technology thus all the V2X communication will benefit better precision and less latency. For the priority of safety, an HAVI (Human-AV-Interface) adoption has been experimented on ISEAUTO and the collaboration with Starship Technology will foresee the roadmap of building up a mutual network protocol with their delivery robots.

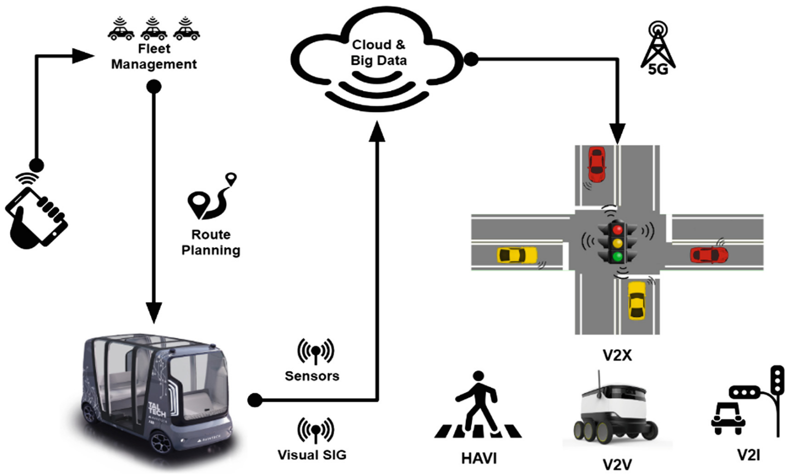

Fig. 3. Data flow illustration of ISEAUTO integration into smart city

TalTech Smart City campus concept will help to evaluate passenger and pedestrian behavior and interaction with autonomous vehicles. Sharing information about people transportation may improve route planning of the vehicle itself and could be valuable for energy consumption balancing, e.g. for climate control devices. Autonomous electric vehicles usage statistics could be used for user profile optimization of zero-energy building. An electrical vehicle itself could be a part of smart grid that can be used not only as an external energy storage, but also for power quality correction (Anton et al. 2014). Test platform such as ISEAUTO could be a valuable tool for testing various scenarios using weather data and transport patterns.

However, one of the key elements in the smart city testbed are AV/V2X use case scenarios. To bring autonomous last-mile shuttle busses into a real-life test, several support and integration features must be considered, and appropriate facilities and systems should be provided. Some of the practical functional units supporting a successful integration of last-mile AV shuttles into a smart city environment are described in detail.

3.2 Fleet Management

The Fleet Management system (FMS) is responsible to integrate single vehicles to the general system. The FMS has the following requirements:

- Route planning and rerouting;
- Data gathering;
- Live fleet monitoring;
- Robustness;
- Accident mitigation.

The vehicles could meet different obstacles on predefined routes, which requires dynamic rerouting in local or global path. Local rerouting can be done automatically, e.g. car is stopped on the road ahead, but global re-routing e.g. road is blocked by construction work, must be confirmed by human operator. Vehicles have predefined route specified by the points. In case of need (e.g. traffic jams or blocked road) a new route can be calculated. In case of a global re-routing requirement, the vehicle is requesting the decision from the operator who either confirms a new automatically generated route or keeps the predefined default route. For the safety analysis the data gathering and logging is essential. Automatic data should be also gathered about the route condition (congestion, accidents, roadblocks) and the real-time traffic data i.e. accidents, traffic jams, roadblock. Open data source services like Google Maps, Waze and local authority can be considered when planning a journey.

Live fleet monitoring is based on real-time information of the fleet units. The dedicated software enables to monitor different aspects of the fleet units in real-time: precise location, moving/ standing, speed, battery level, temperature in the vehicle etc. The information is available to the operator, but also integrated to other systems. The monitored aspects are adjustable to specific vehicles, time, day and other characteristics. In this case, deviances from the predetermined status immediate intervention can be triggered. For example, if the battery level drops under the defined limit the vehicle stops automatically in nearest defined stop point. The passengers are notified, but also the nearest maintenance team will be alerted automatically to move to the site for inspection. In case of vandalism or if the emergency button is pressed, the system automatically alerts the nearest security service team. Furthermore, another fleet unit will be alerted to aim for the location to pick up the passengers.

Robustness, low-latency and cybersecurity are essential for fleet management and control. 5G will offer several solutions to implement security encryptions, low-latency information exchange and robust communication. ISO/SAE 21434 Road Vehicles Cybersecurity engineering standard guideline defines the system design requirements.

Even with well-established fleet management and secure communication there is always a chance for an accident. Therefore, proper accident mitigation concepts must be implemented to the vehicle core level. For example, in event of a communication failure the communication system between the vehicle and the operator will be backupped. In case of a failure in the main system, the backup system will start to operate. The safety solution is capable to detect and manage different issues that have caused the communication failure. e.g., in case of vandalism the backup system automatically alerts the nearest security service team. All accidents will be stored into on-board black-box type safety controller, which enables later analysis of the situation.

3.3 Control Room Functions And Remote Operation

The control room functionality is a part of fleet management system providing real-time information of the full fleets on the map, by connecting all vehicles with run-time parametric. Remote operators and management can also focus on the selected vehicle for example for a full historical record to access the performance, track and run-time parametric. However, the most important functionality of the control room is to provide safety and smooth service for full fleet as well as single vehicles. In case an intervention is needed due to safety or other reasons, the control room must have the functionality to execute at least emergency stop commands. In more advanced situations, full control of the vehicle can be taken over. The function is like teleoperation of multi-robot remote control system (Sell and Otto 2008). In case the remote control over the vehicle is necessary to acquire, the operator has full visual feedback from the vehicle. Even in manual regime, the operator can see the AI algorithm object detection and classification results, or boxes drawn on the video stream. All critical system sensor information is displayed on the screen (e.g. battery level, speed, warnings, etc.)

In the planning stage, the control room is a physical place for mission and route planning. Route planning is a mission definition view and is usually done in advance. However, the actual mission and planned mission can be compared, and gaps determined. For example, planned trajectory and actual trajectory enables to detect static obstacles on the road, changing traffic situations and other anomalies, which can be considered when planning a new mission in the same area. Furthermore, interaction with passengers and capacity evaluation can be measured and analyzed within the system.

4 Testbed Set-up and Experiments

Under the smart city framework, transport & mobility powered by Information and Communications Technology (ICT) still values safety as traditional vehicles normally do. A legal and cyber-risk management framework is requested for using fully AV under normal traffic conditions on regular roads. When considering how to provide more efficient, convenient and sustainable public services, self-driving vehicles are more than just cars without human intervention, but rather a disruptive force for tens if not hundreds of services, both in private and public sectors. Thus, both in-vehicle and on-road safety has been incorporated into the testbed set-up scheme.

4.1 Vehicle Safety

AV shuttles are mostly electrical, that represent a completely different technology compared to traditional internal combustion engine vehicles. That means different safety hazards, related to the characteristics of high-power electric equipment should be presented. Several standards e.g. ISO 26262 already exist for the construction of such vehicles in terms of reducing potential risk towards the passengers and the rescue team who could be exposed to hazards. The introduction of AV shuttles require compliance with security rules that are inherent for the electrical vehicle (EV), people who are professionally working in this area must be trained on how to react in case of an accident. For that reason, during the ISEAUTO operation a specially trained operator, also for the purpose of vehicle safety, is accompanying the bus. However, ISO 26262 does not address unique electrical and/or electronic systems in special purpose vehicles such as vehicles designed for drivers with disabilities. Therefore, different risks associated with EV technology must be carefully assessed and taken into account (Van den Bossche 1994):

- electric system safety;
- functional system safety;
- battery charging safety;
- vehicle maintenance, operation and training.

Electric system safety includes protection against electric shocks, direct or indirect contacts. That means all parts and frame of EV should be protected against contact by persons in or outside the vehicle. Functional system safety is mainly concerned by hardware failures and software bugs. (Mariani 2018) That means that EV control unit must ensure a reliable and safe operation of the vehicle in case of system warnings, avoid possible damage through excessive torque, overcurrent or fierce accelerations, provide emergency disconnection of devices, provide fail-safe operations (incl. cases of power surge prevention, frame faults, electromagnetic compatibility, etc.). The battery is the most critical item on board of EV. There have been numerous real-world examples of EV catching on fire after a crash and in the garage where they were being stored; in some cases, this may have been while the vehicle was being charged (O'Malley et al. 2015). To rank a risk factors and determinate the risk level a risk analysis report for ISEAUTO last mile bus has been provided.

AV shuttles not only have several technical challenges but also there are moral ones. Namely, there are no exact assessment parameters or standard to put driverless vehicle on the road. Today, driving with human-controlled vehicles is a considerable safe activity, but it is expected that AVs would have to do better as most of the fatal accidents are caused by human driver. However, to reach this goal many challenges needs to be properly addressed and eventually solved. There are several safety issues needs to be taking into consideration when developing AVs:

- Complex social interactions
- Bad weather conditions
- Incompatible regulations & legislations
- Increasing cyber security & data privacy threatens
- Inadequate examinations and incorrect base maps
- Challenging ethical acceptance.

4.2 On-road Pedestrian Safety

The integration of AV into smart city frame is closely related to human consciousness and behavior. Especially the acceptance of the self-driving technology should be broadly discussed. Above all the criteria, safety is generally treated as a priority by many stakeholders like General Motors, NVIDIA, Waymo, who have released their self-driving safety report, respectively. It is always better to think ahead and validate the related hypothesis through field tests. ISEAUTO is expected to perform as a low-speed shuttle bus, which ensures that people have a fully understanding of its intention. To this, a HAVI (Human-Autonomous Vehicle-Interaction) experiment (as Fig. 4) has been carried out since February 2019 on TalTech university campus to investigate how pedestrians would react and communicate with AV. A novel design for the front LED panel on ISEAUTO platform presents three movable patterns (Table 2) to deliver messages, which can help people make decisions when encountering an AV at crossroads.

Table 2. Illustration of light design for the experiment

Definition	**Moving Arrows (Pass)**	**Red Cross (Stop)**
Visualization		

Additionally, a face-to-face survey after the experiment helped to identify the attitude of pedestrians. Participants in the experiment and at the same time as respondents to the questionnaire were randomly chosen on the campus as they approached to AV shuttle in the crossroad. They come from 10 different nationalities as Bengali, Chinese, Estonian, Iranian, Georgian, Japanese, Nigerian, Romanian, Russian and Ukrainian. Besides asking for some basic information, this questionnaire features six subjective choice questions. From the experiment results, we can get an idea of how people react to

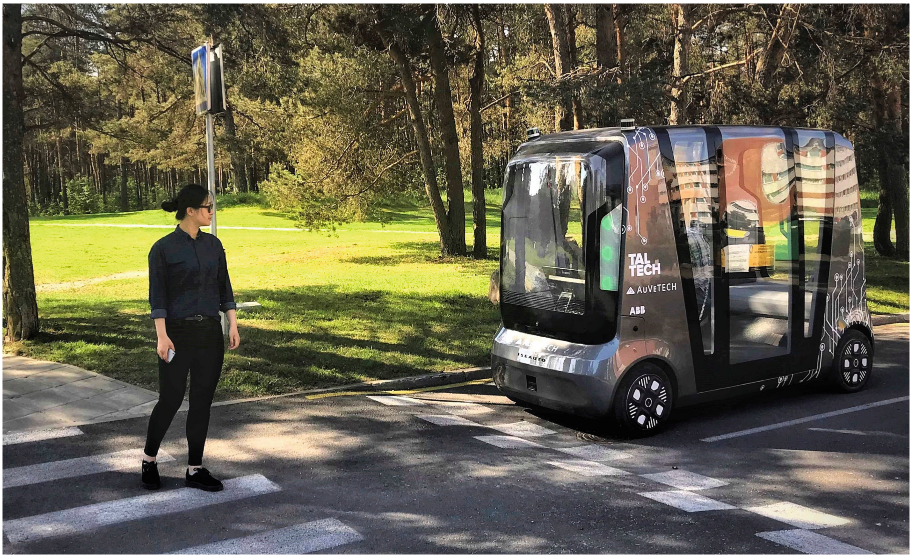

Fig. 4. Experiment when a pedestrian crossed the road with green arrow lights on the car

the autonomous vehicle when they're not informed of the situation beforehand and the HAVI at the crossroad happens naturally without and interference or external influence. There was no drill for the experiment, and they didn't know about the light designing concept until this road testing. Respondents divided equally between male and female, giving a good example for non-bias analysis and to avoid the gender influence. Two thirds of the represented are people of the youngest age group as 18-24. Also, the educational level was distributed almost proportionately from high-school students to PhD researchers but with a small margin of bachelor level students. Almost everybody confirmed that it is necessary to make HAVI experiments in public areas while also willing to share the roads with AV. However, when comes to the feeling towards the interaction with AV, the results surprisingly almost present a tie between being "absolutely fine" and "cautious". Color signals are preferred as the message delivered during HAVI by most of the participants. However, due to its new trial on HAVI, the lights design of the ISEAUTO platform was only clearly understood by half of the respondents while the rest were confused or had no idea of the meaning. As a generalized conclusion, it is widely accepted that there should be a special pattern on the vehicle to assist pedestrians' decision making to help improve the AV safety performance. Detail results of the experiment are discussed in paper Wang et al. (2020).

4.3 Use Case of AV Shuttle in City Traffic

TalTech Smart City campus experiments are ahead of real AV deployment issues but showing the way. At the same time, pilot use cases are going on in open roads in different cities around Europe. One of them is the Sohjoa Baltic project deploying real-life automated bus pilots on open roads among Kongsberg, Helsinki and Tallinn between

2018 and 2020 as well as in smaller cities like Zemgale and Gdansk (see sohjoabaltic.eu). The pilots are integrated into the city transport networks following the last mile concept. The demonstrations in Kongsberg, Helsinki and Tallinn run for 4–8 months, 5–6 days a week on lower-intensity but open urban roads and are expected to attract thousands of passengers for free test-rides as part of a last-mile concept. Importantly, this project has been studying user experience of passengers by surveying them after the ride in various locations where the experiments take place. This will reduce the gap between theoretical attitude towards automated buses (most research is based on online surveys among general population that has no experience with automated driving) and empirical results (this is one of the first cross-countries comparative research projects to study the actual attitude towards automated buses). We are also developing a methodological approach (based on this paper) to investigate pedestrians' behavior and attitude towards on-spot automated last-mile buses in the case of the Sohjoa Baltic project. In Tallinn, the route connects tram stops with the National Art Museum inside one of the biggest park areas with a considerable number of pedestrians and various social groups (families with children, the elderly or tourists).

Although the Sohjoa Baltic project in Tallinn in still ongoing until mid 2020, some of the key results can be drawn. Firstly, passengers taking the ride (over 150 respondents, approximately 5% of all users) gave very strong feedback to the general safety and security on-board. The question "*How do you feel about general traffic safety on-board? Please mark on a scale of 1 to 7*." received an average score of 6.0 and "*How do you feel about your personal security on-board? Please mark on a scale of 1 to 7*." reached even 6.4. On the other hand, we asked the same questions from the control group (55 respondents) in more theoretical way without linked to the actual driving experience ("*How would you feel about general traffic safety on-board? Please mark on a scale of 1 to 7" and "How would you feel about your personal security on-board?"*) and this gave significantly lower average scores (4.8 and 5.0 respectively).

Although the pilot is ongoing and these are just some first results, one can draw first conclusions that in order to increase the adaption of AVs, open public pilots are increasing the trust in new technologies if designed properly. After the pilots are finalized, we could also do cross-country comparisons as the same survey has been (or will be) conducted in other pilot sites in Finland, Norway, Poland and Latvia. On the other hand, it also came out that these pilots could be designed with better operational capacity. When asking feedback from four operators recruited to this project by Tallinn University of Technology via the mid-evaluation panel interview it was clear that the Navya autonomous bus operated by Danish company Holo had too many issues leading to downtime. The most common issues were related to *technology* (weak support), *weather* (seasonal changes) and *traffic* (there was one small traffic accident caused by a passing vehicle on open roads).

5 Conclusion

With the thriving evolution of digital technologies, such as robotics, IoT, AI and powerful computing machines, vehicles in general, and cars in particular, are swiftly changing. European Commission has created a full-scale scope for better integrating Connected and Automated Mobility (CAM) into future society developments. Meanwhile, implementing a Mobility Value Chain (MVC) for Connected, Clean & Autonomous Vehicles (CCAV) within EU is also under discussion. This global leader vision regarding AV is to finally establish a sustainable, efficient, interoperable and safe road transport sector, which all citizens can benefit from. When considering the actual implementation of the smart city testbed, the digital connectivity among V2V, transport infrastructure and other road users is expected to significantly improve the safety of future automated vehicles and its full integration in the overall smart city transport system. However, several unsettled impact factors to integrate AVs to existing transportation system in a safe and secure way still exist and needs to be addressed (Razdan et al. 2019; Taiber et al. 2019).

The paper gives an overview of the smart city concepts and in particular, the AV shuttle operations and deployment issues based on an AV shuttle ISEAUTO. As the connected autonomous driving is getting into the focus in EU and innovation hubs, the paper describes more detail the 5G and V2X communication opportunities and benefits. The main practical conclusion of the experiments with 5G in context of the AV shuttle and smart city is remote control functionality and V2V collaboration. Even 4G is reliable in most cases in terms of latency and data bitrate, it is still not guaranteed by the technology. Therefore, 5G is crucial to implement safe remote driving option. However, early 5G networks suffer the stability and lack of finalized firmware for terminals and base stations. There is also competition between 5G manufactures as well as political issues, which slows down the implementation of 5G networks. V2X communication relying on the dedicated short-range communications (DSRC) uses slightly different variations in Europe, US and Japan but is well established and provide solid solution for the communication between vehicles and smart traffic signs experimented in TalTech smart city testbed.

As a practical example, a pilot project Sohjoa Baltic is described which gives valuable practical results of deploying AV shuttle vehicles in real traffic in city of Tallinn. All introduced activities of a new TalTech Smart City concept are driven by the purpose to be an innovation hub and real CCAD testbed in Europe.

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Human Factors

How Are Eye Tracking Patterns in Takeover Situations Related to Complexity, Takeover Quality and Cognitive Model Predictions?

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Abstract. In the development of highly automated driving, strong focus is laid on the takeover and the improvement of takeover quality. Some research has shown that the complexity of a traffic situation has an influence on the takeover. However, different approaches towards complexity in driving exist and the topic has so far not been addressed sufficiently. In this study, a differentiation between subjective- and objective complexity is drawn. Their impact on eye movement patterns is evaluated and compared to the resulting takeover quality. Results of a driving simulator study show that objective and subjective complexity have an influence on several eye movement patterns. These eye movement patterns serve as an indicator of the resulting takeover quality. Furthermore, traces of the eye movement patterns are compared to predicted traces of the cognitive model for the takeover task. It can be shown that the cognitive model predicts visual traces in different traffic situations well. In order to support individual drivers during a takeover, it is thus important to consider complexity measurements in the development of cognitive assistance systems. Based on information about the environment and the cognitive model for the takeover task, a cognitive assistance system can be developed. In addition to that, eye tracking information further improves cognitive assistance systems.

Keywords: Highly Automated Driving (HAD) · Takeover · Objective complexity · Subjective complexity · Cognitive assistance · Takeover quality · Cognitive modelling · ACT-R · Eye tracking

1 Introduction

In current transportation research, the development of highly automated driving is a central topic (Sheridan 2016). Approaching SAE level three (SAE-International 2018) of highly automated driving, the driver will remain as fallback when the automation reaches a limit (Louw et al. 2015; SAE-International 2018). In those cases, a takeover request is triggered. In level three highly automated driving (SAE-International 2018), most of the takeover situations will be non-critical (Eriksson and Stanton 2017). Hence, the focus in this study lies on different non-critical takeover scenarios, the corresponding eye movement patterns and the resulting takeover quality. However, as the driver is

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allowed to engage into non-driving related tasks (NDRT) and becomes passive during the automated mode, it is fallacious to assume that the driver is able to takeover control within seconds (Sheridan 2016). This passiveness is (together with a poor design of system interfaces and lowered vigilance) identified as one of the main factors that create a loss of situation awareness (Endsley 2017). Additionally, the takeover is a complex task in which the driver has to shift the attention back to the driving environment, perceive the surrounding traffic and take over the driving task. Hands and feet have to be relocated, situation awareness (SA) regained and the driving task executed (Kerschbaum et al. 2015; Zeeb et al. 2015). Several cognitive and motoric processes have to happen within a small amount of time. The behaviour of a driver is thereby determined by complex interactions with other traffic participants (Klimke et al. 2014) and the system itself. When working with adaptive systems in dynamic situations, people are faster, more concurrent, feel safer and more comfortable (Lasota and Shah 2015). The development of adaptive cognitive assistance systems is thus highly important to increase safety, comfort and takeover quality during a takeover. Such assistance systems need to incorporate mental calculations, communication, assessment of rel¬evant information and scanning for traffic (Estes et al. 2016). By cooperating with the driver and assuring the mutual understanding between human-agents and machine-agents, conflicts can be reduced or avoided (Ampore et al. 2014).

1.1 Complexity in Takeover Situations

To define situation complexity, several approaches that differ in their concept of complexity exist (e.g. Baumann and Krems 2007; Damböck and Bengler 2012; Haerem and Rau 2007; Paxion et al. 2015; Radlmayr et al. 2014; Schlindwein and Ison 2004). The complexity of a situation can be distinguished based on objective characteristics such as the traffic situation, the type of traffic environment or the weather condition (Scharfe and Russwinkel 2019a). Furthermore, the objective complexity of a situation can vary with road geometry (rectilinear vs. curvilinear), roadside environments (quantity and variability of traffic signs, variability of scenery) and traffic density (low vs. high; Paxion et al. 2015). Damböck and Bengler (2012) show that less complex scenarios result in a higher takeover quality. The complexity of a situation in their study is varied based on the necessary reaction (e.g. obstacle avoidance). However, other aspects that are relevant for the objective complexity are not included. Especially concerning the update of SA during a takeover, objects that add up to objective complexity are highly important. Additionally, similar driving situations (with the same objective complexity) can lead to different perceptions of complexity, depending on the driver. The same task for example is perceived as less variable and more analysable by experts than by novices and experts perform better (Haerem and Rau 2007). Hence, objective characteristics of the driving environment can be experienced more or less complex depending on the individual driver. The subjective perception of complexity of each individual driver can be described as subjective complexity. Schlindwein and Ison (2004) understand subjective complexity as a result of a particular perception of a situation or as the result of a distinction between expectation and situation development. Furthermore, the subjective complexity of the current traffic situation has an impact on the regaining of SA and the mean takeover time (Radlmayr et al. 2014). However, this finding lacks in defining aspects that add up to subjective complexity. In this study, a clear differentiation between subjective and objective complexity in the context of non-critical takeover situations is drawn and defined.

As the traffic environment is the most critical and dynamic part of driving, this study focuses on the traffic environment to define objective complexity. The objective complexity of a decision situation is defined in terms of the amount of relevant objects in the surrounding environment of a certain situation. The relevant objects are located within a predefined area in relation to the position of the ego-object. In driving, these objects are mostly vehicles in the traffic environment that are relevant in the current situation for the ego vehicle. Additionally, the vehicle interior (car multimedia, human-machine interface, non-driving related tasks and passengers) adds up to the objective complexity. As the latter are held constant in this study and do not change throughout the whole experiment, these aspects are not further regarded for the evaluation of objective complexity. Furthermore, all relevant objects that influence objective complexity can vary in their attributes (e.g. relevance, attention stimulation, and amount). These aspects are also held constant in the present study.

The subjective complexity of a decision situation is in this study understood as the individual perception of complexity in a certain traffic situation. Depending on driving experience and the situation complexity (Haerem and Rau 2007; Paxion et al. 2015), different individuals perceive the same situation in different ways. Additionally, the current cognitive state of the driver (e.g. vigilance, state of situation awareness) has an impact on the perception of complexity. Altogether, subjective complexity describes an individuals' subjective perception of complexity in a certain traffic situation and is task and resource dependent.

Both, objective and subjective complexity are assumed to influence eye movements of drivers. Different eye movement patterns can be examined to evaluate attention strategies. During a fixation, the eyes are nearly stationary, whereas in saccades very fast movements of the eyes occur, shifting the attention from one location to another. When a moving object is tracked, the eyes move in smooth pursuits (Hayhoe 2004). Saccadic eye movements reflect cognitive processes and "seeing" is inextricably linked to the observer's cognitive goals (Hayhoe and Ballard 2004). Moore and Gugerty (2010) showed, that as task demand or visual (objective) complexity increases, the fixation rate also increases. Further, the more frequent fixations are on an important object, the better the SA for these events (Moore and Gugerty 2010). Short and frequent fixations are associated with effective tracking of a dynamic scenario (Crundall et al. 1998) and an improvement of SA due to distributed attention across all relevant objects. Thus, mean fixations can work as a measure of performance (Moore and Gugerty 2010) and SA in complex environments. Furthermore, key environmental parameters to allocate attention in dynamic scenarios are the frequency of information change and the task value. When tasks have a high value, areas of interest (AOI) relevant to the task are examined more frequently (Horrey et al. 2006).

1.2 Cognitive Modelling in Highly Automated Driving

Cognitive modelling is a suitable solution in highly automated driving to simulate involved hu¬man agents. Such a simulation is necessary for an individual adaption in highly automated driving (Markkula et al. 2018) and the development of adaptive cognitive assistance systems. Within advanced driver assistance systems (ADAS), cognitive driver models allow the anticipation of the driving behaviour of the driver and traffic participants in the close vicinity. Such a prediction of the surrounding traffic can be used to adapt and improve the reaction of ADAS to be more comfortable and reasonable for passengers (Klimke et al. 2014). This becomes especially important in takeover situations. Besides the enhancement of comfort, safety and takeover quality can be increased using a cognitive driver model for the takeover. Based on cognitive takeover modelling, time dynamics of human perception, scene interpretation and decision-making (Markkula et al. 2018) can be considered for the development of cognitive assistance systems in driving. To keep the driver in-the-loop and support during takeover situations, Braunagel et al. (2017) propose an ADAS that includes supplementary features (gaze guidance, increased decelerations) based on the complexity of the traffic situation, the current non-driving-related task of the driver and gazes on the road. However, this approach does not understand the underlying cognitive processes of a driver in different takeover situations. Some cognitive model approaches for driving situations already exist (Cao and Wang 2010; Salvucci 2006). Nevertheless, they do not include the takeover in highly automated driving. Scharfe et al. (2020) developed a cognitive model for the takeover in highly automated driving. This model is able to represent cognitive processes during a takeover in different traffic situations and to predict individual differences and errors that match empirical data. To support a safe takeover, such complex driver models need to be integrated into embedded systems (Klimke et al. 2014). The integration of such a cognitive model into highly automated driving systems enables a higher-level assessment of the traffic situation to adapt cognitive assistance systems and increase safety, comfort and takeover quality. In a highly complex situation and a driver who perceives the situation as such, the automation would decelerate to give the driver more time for the takeover and support by projecting the best manoeuvre trajectory for example. Contrary, in a complex situation that the driver is used to and does not perceive it as complex, additional information (e.g. weather at destination, next appointment) could be presented to prevent vigilance. As Scharfe and Russwinkel (2019b) have already shown that the objective complexity has an impact on the subjective complexity, the current study focuses on the relation between the two complexity variables, eye tracking patterns and the resulting takeover quality. The following hypotheses are investigated in this study:

H1: The objective complexity is related to eye movement patterns in a takeover situation (Fig. 1).

Fig. 1. Examined relationships between complexity, eye movement patterns and the takeover quality (H 1-3; source: own figure)

H2: The subjective complexity is related to eye movement patterns in a takeover situation (Fig. 1).

H3: Eye movement patterns are related to the takeover quality in a takeover situation (Fig. 1).

H4: The cognitive model for the takeover task (Scharfe et al. 2020) is able to predict empirical eye movement traces validly.

2 Methods

In order to produce comparable data under exactly the same traffic conditions, a driving simulator is used for the study. The driving simulator consists of a moveable driving unit to create a more realistic driving simulation and six monitors that create a 360° surround view. The simulator works with the driving simulation SILAB (WIVW-GmbH 2014). Prior to the study, a ten-minute learning session is included. In this learning session, participants are acquainted with the simulator dynamics, notifications and the takeover itself. For eye-tracking measurements, TOBII glasses (TobiiAB 2015) are used. These glasses provide a remote solution to track eye movements. TOBII glasses use pupil centre corneal reflection. Using a light source to illuminate the eye, reflexions of the eye can be captured and the light source on the cornea and in the pupil detected. Based on this a vector can be formed to calculate the gaze direction (TobiiAB 2015). Together with the eye-tracking information, the TOBII glasses produce a video that represents the visual scene of participants. These videos are additionally evaluated to rate the takeover quality. The implementation of the study has been approved by the ethics committee of the TU Berlin in April 2019 and by the Robert Bosch GmbH.

2.1 Participants

All of the participants provide pre-knowledge of highway situations, as they are all regular drivers. Most of the participants drive on a daily basis averaging 30 min per ride of which most of the time is spend on highways. The majority of participants state a moderate driving style (Fig. 2).

2.2 Study Design

Six different scenarios are used to create situations with a different amount of relevant vehicles in the surrounding traffic environment (Sect. 2.3.1). Every participant took over the driving task three times per scenario, resulting in overall 18 takeover situations. In three blocks, each scenario is represented once per block in randomized order. After the introduction phase, participants started their first drive at a parking lot. Participants are instructed to drive onto the highway and move to the centre lane, where they turn on the automation as soon as it is available. After activating the automation, they take a quiz on a mounted tablet next to the centre console. As soon as the automation triggers a takeover request, the quiz stops immediately (no switch off needed) and the driving task has to be resumed. Each takeover is triggered on the centre lane at a speed of 120 km/h. Participants are instructed to try to keep the speed around 120 km/h, take an action decision based on

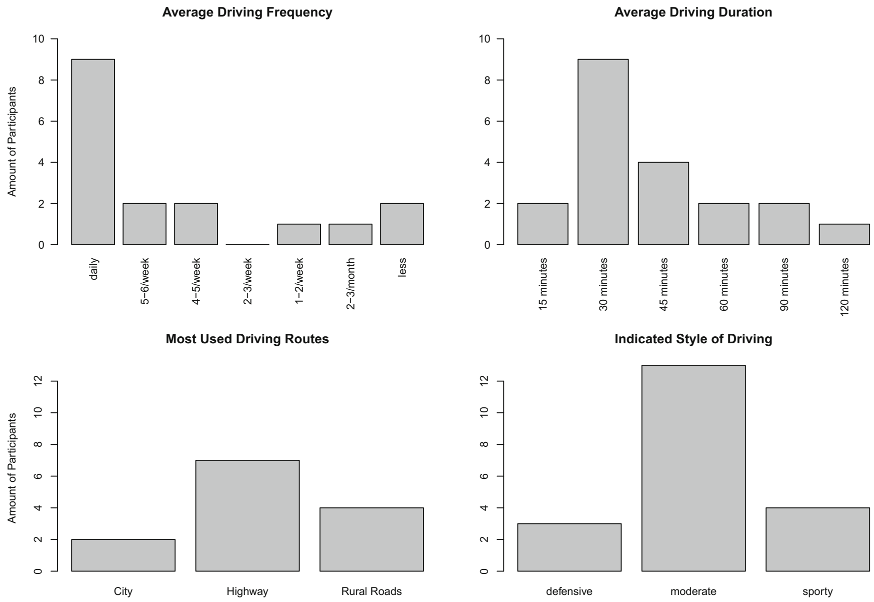

Fig. 2. Distributions of driving statistics of the participants (N = 20; source: Scharfe et al. 2020).

the surrounding traffic environment, verbalize their action decision aloud and perform the corresponding manoeuvre. Each scenario triggers a certain manoeuvre that is the best solution in the traffic situation. This is dependent on the speed and position of relevant vehicles in the traffic environment, the instruction is to stick to the obligation to drive on the right and try to avoid hard breaking or acceleration (speed around 120 km/h). Hence, when the right lane is free, the best solution is to change to the right lane. If the right lane is occupied and the leading vehicle is faster or driving at the same speed, car following is the best solution. In cases where the right lane is occupied and the leading vehicle is clearly slower than the ego vehicle, a lane change to the left is the optimal solution. After each manoeuvre execution, participants drive to the next parking lot where a rating sheet measuring subjective complexity (NASA-TLX; Sect. 2.3.2) is filled out. Afterwards, participants continue with the next scenario.

2.3 Variables and Measurements

In this paper, the two manipulated variables objective and subjective complexity are measured. Subjective complexity is not an independent variable, as it is influenced by the objective complexity (Scharfe and Russwinkel 2019b). In this study, it is used as pseudo-dependent variable as together with the impact of objective complexity, the impact of subjective complexity on eye movement patterns is first examined. Second, the influence of these eye movement patterns on the takeover quality is investigated. The traces of the eye movement measurements are third compared to visual predictions of a cognitive model (Scharfe et al. 2020). Variables and the used measurement methods are described in detail in the following section.

2.3.1 Objective Complexity

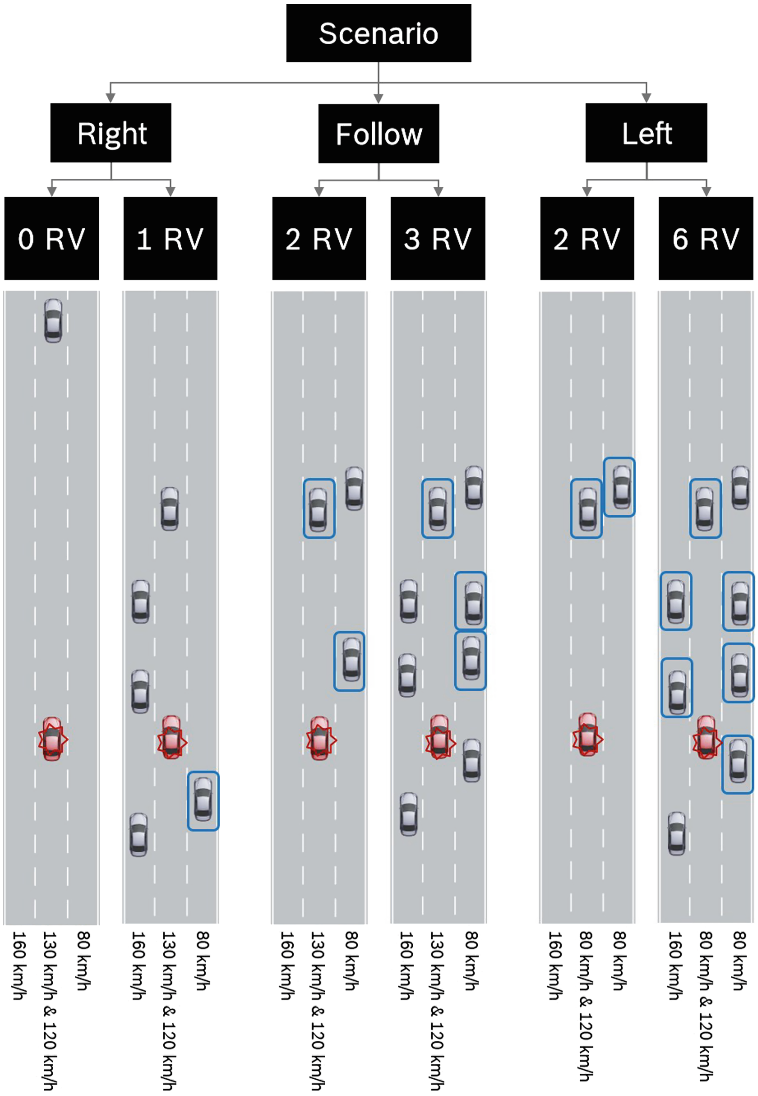

Fig. 3. Traffic scenarios during the takeover request. Blue squares mark relevant vehicles in the given scenario situation, the red star marks the ego vehicle (source: Scharfe et al. 2020).

The independent variable objective complexity is manipulated in this study and based on the amount of relevant vehicles in the traffic environment. Vehicles in the surrounding traffic environment that have a direct impact on the ego vehicle are defined as relevant. Hence, these relevant vehicles triggering the necessity to react are the reason for a certain manoeuvre or have to be considered during a manoeuvre. A takeover request is always activated when the vehicle is driving on the centre lane in the automated mode. The six scenarios that are represented in the study trigger either a lane change to the right, a lane change to the left or car following on the centre lane based on the obligation to drive on the right. Each manoeuvre has to be resolved in two traffic scenarios of different complexity. This results in overall six different scenarios that vary in their amount of relevant vehicles in the surrounding traffic environment (0, 1, 2, 3, 6; Fig. 3).

2.3.2 Subjective Complexity

To measure subjective complexity after each scenario, the multidimensional rating sheet NASA-Task Load IndeX (NASA-TLX; Hart 1986) is used. As subjective complexity is not manipulated throughout the experiment, it is not a direct independent variable, but a pseudo-dependent variable. It is influenced by the independent variable objective complexity (Scharfe and Russwinkel 2019b) as well as assumed to have an impact on eye movement patterns in takeover situations (Fig. 1). Subjective complexity indicates how complex different drivers perceive a traffic situation. Due to the sub-scales of the NASA-TLX, it is the most suitable rating sheet to measure subjective complexity. On a 20-point Likert-scale, the six sub-scales mental demand, physical demand, temporal demand, performance, effort and frustration are measured. The item weighting as in (Hart 1986) is not used in this study as it is not beneficial for the current purpose and has been criticized in the past (Gross 2004). During the whole study, participants rate their subjective complexity after each scenario, resulting in 18 measurements of subjective complexity.

2.3.3 Eye Tracking Patterns

Eye-tracking patterns are measured using the TOBII glasses (TobiiAB 2015). Based on these measurements, the amount of transitions between different AOIs is measured. Furthermore, information about the amount that drivers look at the human-machine interface (HMI), the left lane, the centre lane and the right lane are extracted. In addition, the number of gazes into the left and into the right mirror are evaluated. To compare the empirical eye movement patterns with visual predictions of the cognitive model by Scharfe et al. (2020), traces of the AOI transitions are captured.

2.3.4 Takeover Quality

The dependent variable takeover quality is measured using the take-over controllability rating (TOC; Naujoks et al. 2018). It is a standardized rating scheme, capturing control transitions from automated to manual driving. On a scale from one to ten, the takeover quality is rated, integrating different aspects of driving performance into a global measure when evaluating video material of a takeover situation. The aspects braking response, longitudinal vehicle control, lateral vehicle control, securing/communication, vehicle/system operation and the facial expression of the driver are rated on different sub-scales. A faultless and high takeover quality is rated with low values (=1). Higher values indicate a bad quality of the takeover (10 = uncontrolled; Naujoks et al. 2018). Based on the video material of the TOBII glasses that show the perspective of the driver, the last variable (facial expression) is not included.

3 Results

In a simulator of Robert Bosch GmbH in Renningen, the study was conducted in April and May 2019 after a successful pre-testing. Evaluation results base on N = 20 (13 male, 7 female) participants who took part in the study with a mean age of M = 26.2 years and a standard deviation of 2.69 years (SD = 2.69).

3.1 Statistical Evaluation

Regression analysis is used to examine the influence of subjective and objective complexity on eye-tracking patterns and the relation between eye-tracking patterns and the takeover quality. To test on normal distribution, homoscedasticity and outliers, residual vs. fitted, normal Q-Q, scale-location and residual vs. leverage plots are used. Results show that significant relation-ships between the two complexity variables, eye tracking patterns and the takeover quality exist. Figure 4 shows the evaluated relationships that are significant in black. Arrows that are light grey are tested but do not show significant results. The specific regressions are described in detail below. Further, mean eye movement traces are compared to mean traces of the cognitive model for the takeover task (Scharfe et al. 2020).

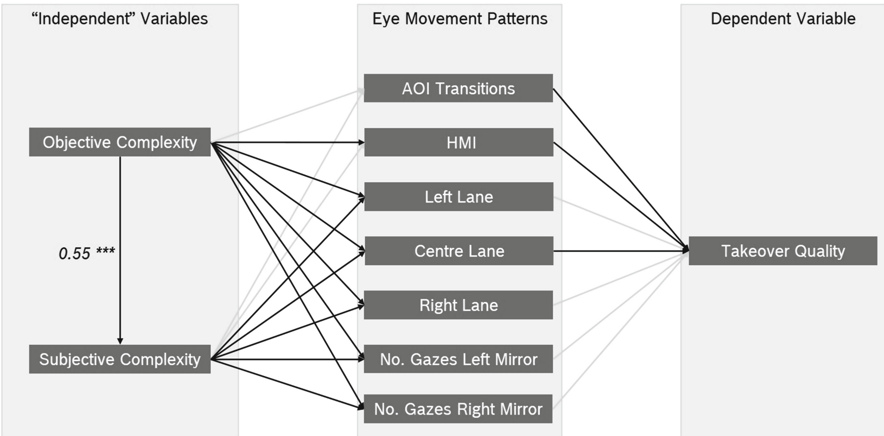

Fig. 4. Results of evaluated regression analysis that are significant (black) and insignificant (light gray; source: own figure).

3.2 The Influence of Objective Complexity (H1) and Subjective Complexity (H2) on Eye Tracking Patterns

As depicted in Fig. 4 the objective complexity has a significant impact on all eye tracking patterns except for the AOI transitions. Table 1 shows the slope of the regression, t values, the explained variance and the significance level. Drivers looked less onto the

HMI with a rise in objective complexity. Furthermore, the right lane and the right mirror are attended less in higher objective and subjective complex situations. However, this is due to the fact that scenarios in which a lane change to the right is necessary, objective complexities are rather low. Similarly, left lane and left mirror are attended more with a rise in objective and subjective complexity as left manoeuvre scenarios naturally come with a higher objective complexity as more vehicles are relevant for the action decision and the manoeuvre. In addition, more glances go to the centre lane in highly subjective and objective complex situations (Table 1).

Table 1 Regression results of the relationship between objective complexity/subjective complexity and eye tracking patterns (significance codes: 0 ***' 0.001 **' 0.01 *' 0.05.' 0.1 ' 1; source: own table).

Eye Tracking	Objective Complexity			Subjective Complexity		
	β	t(311)	R^2	β	t(311)	R^2
AOI Transitions	0.21	1.82	0.01 .	no significance		
HMI	-1.72	-4.75	0.06 ***	-0.43	-1.81	0.01 .
Left Lane	1.37	3.84	0.04 ***	no normal distribution		
Centre Lane	2.08	3.14	0.03 **	0.9	2.13	0.01 *
Right Lane	-2.29	-3.35	0.03 ***	-1.54	-3.59	0.04 ***
Gazes Left Mirror	0.3	10.01	0.24 ***	0.1	4.81	0.07 ***
Gazes Right Mirror	-0.15	-5.77	0.09 ***	-0.05	-3.24	0.03 **

3.3 The Relationship Between Eye Tracking Patterns and Takeover Quality (H3)

Only three of the seven eye tracking patterns that have been evaluated are significant (Fig. 4). This is due to the fact that in four cases, the data is not normally distributed. Table 2 shows the results of the evaluated regression analysis. It shows that the amount of AOI transitions can serve as an indicator of takeover quality. Fewer AOI transitions are related to a better takeover performance. The amount that drivers look onto the HMI can additionally be used as an indicator for takeover quality. Similarly, a lower frequency of the drivers glance onto the HMI indicates a better takeover quality. This comes along with an increased amount of time that drivers look onto the centre lane in situations with high takeover quality.

3.4 The Comparison Between Predicted Eye Tracking Patterns of the Cognitive Takeover Model and Empirical Patterns (H4)

The cognitive model of the takeover task predicts visual traces that represent the AOI that have been attended. Those predictions are compared to the traces of the AOI transitions that are found in the empirical data. All traces start when the takeover request is triggered

Table 2. Regression results of the relationship between eye tracking patterns and takeover quality (significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' 1; source: own table).

Eye Tracking	Takeover Quality		
	β	t(311)	R^2
AOI Transitions	-0.06	-2.52	0.02 *
HMI	-0.03	-3.51	0.04 ***
Left Lane	no normal distribution		
Centre Lane	0.01	3.02	0.03 **
Right Lane	no normal distribution		
Gazes Left Mirror	no normal distribution		
Gazes Right Mirror	no normal distribution		

and end ten seconds after the takeover request. The ten seconds are chosen, as most of the literature recommends a takeover time of ten seconds (e.g. Damböck et al. 2012; Melcher et al. 2015). The mean traces are illustrated in Fig. 5, Fig. 6, Fig. 7, depending on the manoeuvre that is triggered in the situation. Mean model traces are shown on top, mean empirical traces on the bottom. On the right hand-side, the scenario with a lower complexity is illustrated; on the left hand-side, the more complex scenario is depicted. The x-axis shows the amount of AOI transitions within the ten seconds. The dotted lines represent the time in steps of two seconds. On the y-axis, the AOIs are shown with the following coding: right shoulder (RS), right mirror (RM), non-driving-related task (NDRT), right lane (RL), front lane (FL), human-machine interface (HMI), left lane (LL), left mirror (LM) and left shoulder (LS).

Figure 5 shows the mean traces for scenarios in which a lane change to the right is the best manoeuvre. In the scenario without relevant vehicles in the traffic environment, model and empirical traces are quite close to each other. Participants tend to focus longer on the centre lane and check the right lane more often than the model does. In addition, participants recheck the HMI and move their attention to the left lane in the end. In contrast, the model directly looks into the right mirror without checking the HMI and the left lane again. Participants additionally show seven AOI transitions more, than the model does. In the situation with one relevant vehicle in the surrounding environment, mean traces differ more between the model and empirical data. The model shows eleven AOI transitions more, than participants do. Furthermore, participants focus on the centre lane first before checking the right lane and double-check the HMI. Contrary, the model focuses on the front lane less than two seconds and then starts to look at the right lane. As in the lower complex scenario, the model does not recheck the HMI. This shows that the model is already able to represent the most common AOI transitions but lacks in rechecking the HMI. Furthermore, in both cases it only looks at the right lane twice, whereas participants check the right lane three times.

In Fig. 6, the follow manoeuvres are shown. In the condition with two relevant vehicles, model and empirical traces are quite close to each other. In contrast to the participants however, the model focuses constantly on the right lane after five seconds.

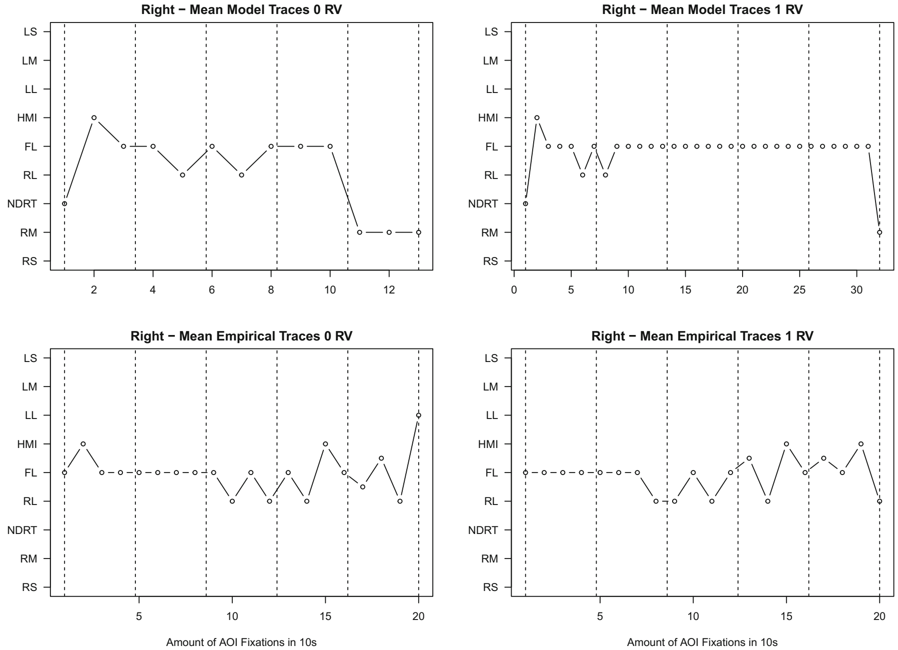

Fig. 5. Mean traces of right maneuver scenarios (right shoulder (RS), right mirror (RM), non-driving-related task (NDRT), right lane (RL), front lane (FL), human-machine interface (HMI), left lane (LL), left mirror (LM) and left shoulder (LS); source: own figure).

Additionally, participants also start looking at the right lane after five seconds but always bring their attention back to the front lane and the HMI. In the scenario with three relevant vehicles, participants check the right lane earlier, than the model does. As in the less complex follow manoeuvre, participants move their attention between the right and the front lane, while the model keeps the attention on the right lane. Similarly, to the right scenarios, the model lacks in rechecking the HMI in both follow manoeuvre scenarios. Additionally, marginally (three) less AOI transitions are performed by the model.

Mean traces of left manoeuvre scenarios are shown in Fig. 7. Interestingly, in both scenarios (two and six relevant vehicles), neither participants nor the model look at the left lane during the first eight seconds. Furthermore, in both scenarios participants check the HMI more often, than the model does and look far more onto the HMI than the front lane during the first four seconds. While the model starts checking the right lane after four seconds, participants then start to shift their attention to the front lane. After eight seconds, the model already looks into the left mirror, while participants then start to check the right lane. However, while the model seems to be slightly faster in the less complex scenario, participants show an earlier AOI transition to the left lane in the more complex scenario. Overall, the model is much faster in building up situation awareness in the left manoeuvre scenarios than participants and the participants perform nine AOI transitions more than the model. All mean traces show similarities in their patterns. However, the model can still be enhanced based on the above-described differences.

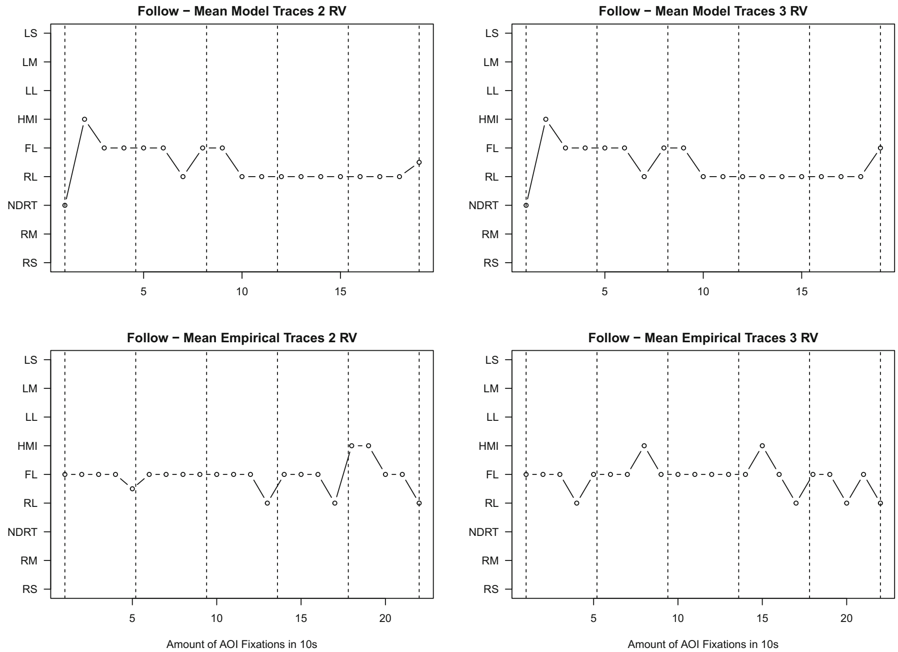

Fig. 6. Mean traces of follow maneuver scenarios (right shoulder (RS), right mirror (RM), non-driving-related task (NDRT), right lane (RL), front lane (FL), human-machine interface (HMI), left lane (LL), left mirror (LM) and left shoulder (LS); source: own figure).

4 Discussion

Results show that objective as well as subjective complexity have an influence on eye movement patterns during a takeover in highly automated driving. Furthermore, several eye movement patterns can serve as an indicator of the resulting takeover quality. This is a highly important finding as it shows that the usage of eye tracking in highly automated driving is highly beneficial and can be used to adapt cognitive assistance systems to the individual driver. Such a system could combine information about the traffic environment with eye movement patterns. In a highly complex scenario, for example eye tracking could be used to track the subjective complexity of the individual driver and predict the resulting takeover quality. If the takeover quality has to be enhanced, vehicle parameters and the HMI could be adapted to support the driver. In a case, where the subjective complexity is high and the takeover quality could be enhanced, gaze guidance, projection of the best trajectory and the longitudinal control could be adapted to give the driver more time and support him during the manoeuvre. In cases where the driver does not perceive the situation as complex, but vigilance is high for example, measures can be taken to energize the driver (e.g. presentation of interesting information). In order to develop cognitive assistance systems that support the driver during a takeover, it is important to understand the drivers' cognitive processes. Scharfe et al. (2020) developed such a cognitive model that is able to represent cognitive processes during the takeover process validly. However, in this paper visual traces of the cognitive model for the takeover task

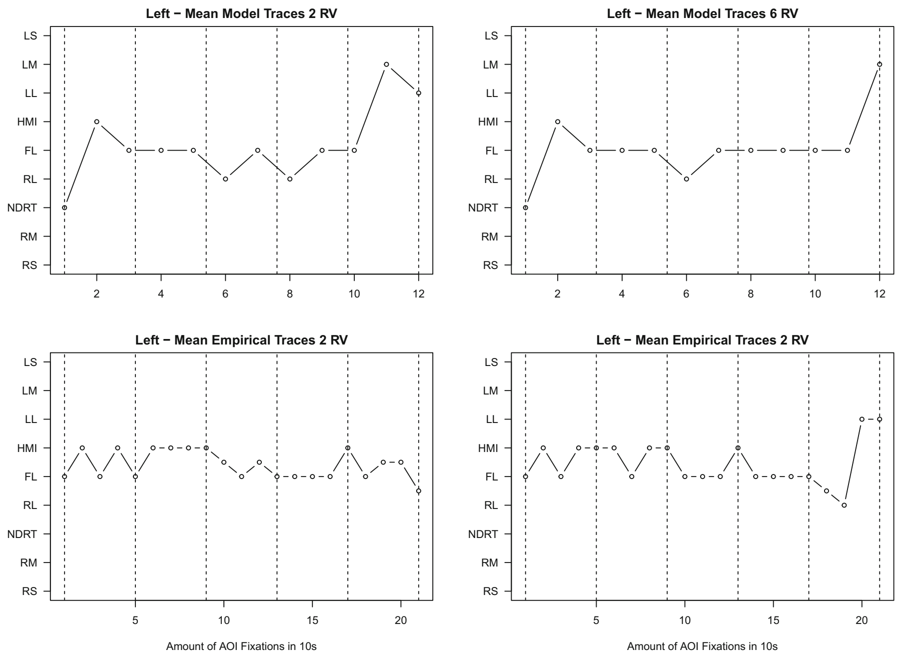

Fig. 7. Mean traces of left manoeuvre scenarios (right shoulder (RS), right mirror (RM), non-driving-related task (NDRT), right lane (RL), front lane (FL), human-machine interface (HMI), left lane (LL), left mirror (LM) and left shoulder (LS); source: own figure).

are compared to eye tracking data of an empirical study. Results show that the visual traces of the cognitive model match empirical data very well. Still, variations between model predictions and empirical traces exist. Future research should focus on comparing the cognitive model to different empirical data of the takeover task. Furthermore, other factors that might have an impact on the takeover should be investigated. If more factors that are relevant are identified, better cognitive assistance systems can be developed.

5 Conclusion

In highly automated driving, cognitive assistance systems are highly beneficial to improve safety, comfort and takeover quality. This study displays important factors that have to be considered in the development of cognitive assistance systems. Furthermore, the cognitive model for the takeover task is shown to be a valid basis to understand and predict human cognition and visual traces. These findings provide a solid basis for future research on cognitive assistance systems.

6 Acknowledgements

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Automatic Detection and Prediction of the Transition Between the Behavioural States of a Subject Through a Wearable CPS

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Abstract. The PRESLEEP project is aimed at the fine assessment and validation of the proposed proprietary methodology/technology, for the automatic detection and prediction of the transition between the behavioural states of a subject (e.g. wakefulness, drowsiness and sleeping) through a wearable Cyber Physical System (CPS). The Intellectual Property (IP) is based on a combined multi-factor and multi-domain analysis thus being able to extract a robust set of parameters despite of the, generally, low quality of the physiological signals measured through a wearable system applied to the wrist of the subject. An application experiment has been carried out at AVL, based on reduced wakefulness maintenance test procedure, to validate the algorithm's detection and prediction capability once the subject is driving in the dynamic vehicle simulator.

Keywords: Cyber physical system · Embedded SW · Biomedical engineering

1 Introduction

Drowsy driving is a very risky factor that usually evolves into fatal road accidents. The development of technologies capable of predicting sleep onset at the wheel represents one of the greatest challenges in the field of accident prevention systems. A non-intrusive device is needed that can not only classify but also predict sleep onset, in order to alert in advance the driver.

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2 FED4SAE Project: A Wearable CPS for the Automatic Detection and Prediction of the Awake, Drowsiness and Sleeping Stages (PRESLEEP)

PRESLEEP is a R&D project funded through the FED4SAE (Federated CPS Digital Innovation Hubs for the Smart Anything Everywhere Initiative) framework. The project is aimed at the fine assessment and validation of the proposed proprietary methodology/technology, for the automatic detection and prediction of the transition between the behavioural states of a subject (e.g. wakefulness, drowsiness and sleeping) through a wearable CPS.

The background know-how relies on accurate medical and engineering analysis, previously performed by the SAT core team, which resulted in several patents filing.

The methodology relies on the deep analysis of physiological features primarily extracted through the photoplethysmography (PPG) technology.

PPG is a non-invasive optical technique for detecting microvascular blood volume changes in tissue bed beneath the skin, which are due to the pulsatile nature of the circulatory system.

PPG has important implications for a wide range of applications in cardiovascular system assessment, vital sign monitoring, blood oxygen detection, and became a mandated international standard for monitoring during anaesthesia. It is worthy to note, however, that the single spot monitoring and the need to apply a PPG sensor directly to the skin limit the pulse oximetry applicability in situations such as perfusion mapping and healing assessments or when free movement is required.

Moreover, the conventional PPG sensors need to be firmly attached to the skin in order to get a good a high-quality signal. The introduction of fast digital cameras into clinical imaging monitoring and diagnosis systems as well as very advanced solutions based on ultra-short-range RADAR technology, the desire to reduce the physical restrictions, and the possible new insights that might come from perfusion imaging and mapping inspired the evolution of the conventional PPG technology to imaging PPG (IPPG). IPPG is a noncontact method that can detect heart-generated pulse waves by means of peripheral blood perfusion measurements.

The PRESLEEP project is focused on the following objectives:

- complete development of the methodology for the automatic detection and prediction of the transition between behavioral stages based on physiological parameters extracted through contact reflective PPG technology;
- complete development of the wearable CPS prototype with particular respect to the embedded SW coding of the proprietary algorithm for the automatic detection and prediction of the transition between behavioral stages;
- verification and validation tests on the wearable CPS operating in realistic environmental conditions at AVL;
- detailed definition of the wearable CPS (Hardware/Software) specifications for the further industrialization process with a selected supplier.

It is very important to note that the original aspect of the proposed methodology is the additional contribution provided by the real time assessment of the emotional stages.

Moreover, the IP will initially run on a wearable CPS but a parallel activity based on IPPG technology has started.

Consequently, a wide range of applications, where the drowsiness of the subjects is a relevant factor, can be successfully addressed.

3 A Multi-factor and Multi-domain Analysis: An Innovative Approach for the Assessment of the Behavioural States

The proposed methodology has been developed extrapolating from the PPG signal all the information that carries on. This has been done collecting data from the time and the frequency domain.

From the frequency domain; from the latter, is possible to import the fundamental frequencies that compose the signal, instead, for the former, the time domain analysis has been performed acquiring and analyzing the signal in its amplitude and its frequency.

3.1 Related Works

In literature, there are plenty of scientific works aimed at develop methodologies able to classify the awake and the sleep phases. Some of them use the information coming from the driving experience, more precisely the steering angle, the acceleration and deceleration of the vehicle (Pomerleau 1995; Sayed and Eskandarian 2001; Thiffault and Bergeron 2003; Sałapatek 2017) [1–4]; others, instead, extract information from the camera, analyzing the facial behavior.

There are also works aimed at analysing the acquired biological signals such as the ECG (Electrocardiogram), the EEG (Electroencephalogram) or the PPG.

Jabbar et al. (2018) shows a method based on a deep learning algorithm implemented on an Android application. This approach has been developed towards real-time drowsiness detection analysing the facial landmark key point, with an accuracy of more than 80%; the network has been trained using the data coming from 18 subjects [5].

Even focalizing its method on the analysis of the facial landmarks, (Mehta et al. 2019)'s work computes two parameters: Eye Aspect Ratio (EAR) and Eye Closure Ratio (ECR), in order to detect driver's drowsiness based on an adaptive thresholding algorithm. This system has been tested using a random forest classifier on 50 volunteers, demonstrating an accuracy of 84% [6].

de Naurois et al. (2017) presents a novel and a multifactorial study that includes three types of measurements, elaborated by an artificial neural network, in order to detect drowsiness. There are three types of measurement: physiological, behavioural and mechanical. The physiological ones are acquired using the ECG and the PPG; consequently, the heart rate, the action of the autonomic nervous system and the respiratory rate are extracted. Behavioural measures include the blinking frequency and its duration, the PERCLOS (percentage of time eye closed) and the position of the head. The car measurements contain all the information coming from the driving manoeuvre, from the steering angle to the acceleration pedal angle. The methodology was tested on 21 participants (average age $\pm$ SD: 24.09 $\pm$ 3.41 years; 11 men and 10 women) in a realistic simulator, demonstrating an accuracy of 96% with a prediction on micro-sleep between 15 s and 5 min in advance [7].

Awais et al. (2017) proposes a method capable of detecting the sleepiness state using a multi-factor and multi-domain system. It acquires data from ECG and EEG, then they are classified using a support vector machine (SVM). Heart rate, heart rate variability, including LF/HF ratio, are extracted from the ECG, while a series of features have been extracted from the EEG, including time-domain complexity and statistical measures, that are the absolute and relative powers in the domain frequency. By combining the information coming from the two signals, it is possible to achieve an accuracy level of about 80%, testing the system on 22 subjects in a simulator-based driving environment [8].

The works of Boudreau et al. (2013) and Chouchou et al. (2014) are focused on the demonstration that there is a close correlation between the heart rate variability (HRV) and the action of the autonomic nervous system (ANS), therefore with the sleep stages [9, 10]. The methodology proposed by Li et al. (2013) has the purpose of detecting drowsiness by monitoring HRV.

This has been done in three different ways:

- the first one is FFT-based and takes into account 1-min time-window;
- the second one is still FFT-based, but considers a 3-min observation window;
- the third one is wavelet-based, from which entropy and kurtosis are extracted. Then, a support vector machine (SVM) performs a classification.

Considering an experimental activity with 4 subjects (3 males and 1 female), the FFT-based approach produces an accuracy of 68.8%, a sensitivity of 62.5% and a specificity of 75%. Instead, the wavelet-based approach provides a 95% of accuracy, sensitivity and specificity [11].

The methodologies mentioned above offer less effective solutions, neither in terms of robustness nor in prediction.

3.2 Proposed Method

The proposed methodology has been developed considering an observation window where several physiological parameters are extracted and analysed concurrently in the frequency domain and in the time domain.

3.2.1 Frequency Domain Analysis

The proposed algorithm monitors cardiocirculatory activity through some parameters derived from the analysis in the frequency domain. The prediction of falling asleep is carried out by detecting the microsleep, which in sleep medicine is seen as “K” phases on the EEG signal. Usually, the microsleep anticipates the falling asleep step of some minutes.

Two parameters DOD (Drowsiness Onset Detection) and SOP (Sleep Onset Prediction) have been defined and extracted from the PPG power spectrum.

DOD and SOP change over time as a function of the action of the Autonomic Nervous System (ANS). Then the action of the sympathetic nervous system and the parasympathetic nervous system are correlated to behavioural state of the subject.

When DOD exceeds a predefined value, the microsleep is detected thus identifying the drowsiness onset. As a consequence, sleep onset is predicted when SOP is below a predefined value able to subdivide the data related to the awake state from the data related to the sleep state (Fig. 1).

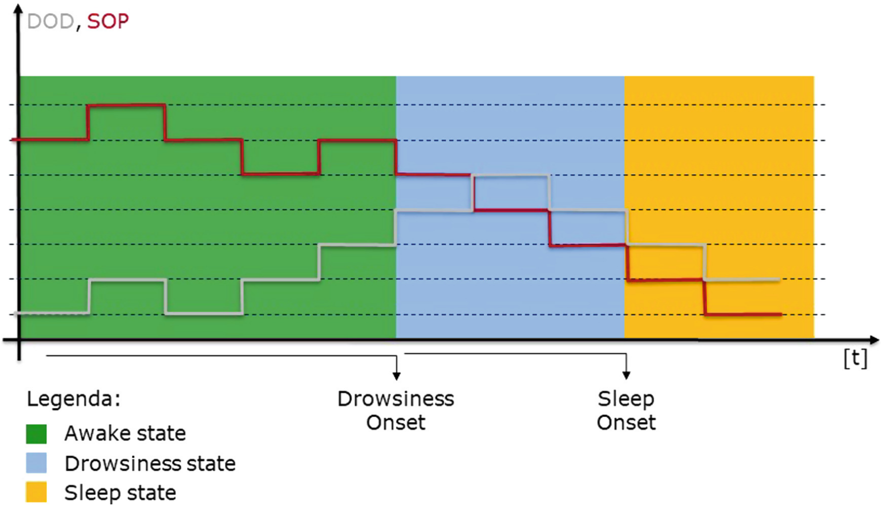

Fig. 1. The behaviour of DOD and SOP over the time, indicating the phases according to their values.

The monitored phenomena have a dynamic nature, therefore learning and adaptive control for individual self-calibration of the physiological parameters of the subject are included.

3.2.2 Time Domain Analysis

The analysis in the time domain is closer to the daily sleep medicine activity, where the quality of sleep phase is analysed. In particular, it is relevant to observe the variation of the PPG signal changes in terms of amplitude and frequency during the different behavioural phases. The automation of this medical procedure requires some mathematical operators such as the standard deviation, the mean value, the percentile, etc.

This time domain analysis is also used for the automatic recognition of emotional stages parameters:

- Average NN, is the average time between normal heartbeats. Low values denote an elevated heart rate that could indicate excitement, physical activity and coffee assumption. Higher NN values typically denote resting.

- SDNN, is the standard deviation of the time between heartbeats and can be used to estimate physiological stress.
- RMSSD, is the root mean square of successive differences of heartbeats and it has been used to predict the perceived mental stress.
- SDSD, is the standard deviation of successive differences between adjacent NNs.
- NN50, is the number of adjacent NN intervals that differ from each other by more than 50 ms (NN50) and requires a 2 min epoch. The proportion term pNN50 is NN50 divided by the total number of NNs. A high percentage indicates complexity in heart rate variability, correlated with good psychological and physiological state.

4 Application Experiments and Validation of the Results

The application and the validation activity have been subdivided into 3 different steps:

- algorithm development and validation using MATLAB, Inc, analysing the complete polysomnographic analysis recorded during the night;
- implementation of the algorithm in a wearable device;
- algorithm validation in a realistic environment.

These validation tests have been performed with respect to the falling asleep step, so, the microsleep that does not necessarily lead to a sleep phase are classified as false positive.

4.1 Algorithm Development and Validation

This validation phase has been focused on the behavioural analysis of a number of healthy adult subjects (21 acquisitions, 20 complete registrations, 9 males and 11 females, average age 44.3 years, interval 18–81 years). The data have been continuously acquired, for about 12 h (8.00 pm, 8.a.m day + 1) and including the night sleep. Then the data have been analysed by medical doctor expert in sleep medicine in order to classify the different behavioural stages along the timeline.

This first validation step has shown very good result reaching almost 95% in terms of sensitivity, specificity and accuracy.

The algorithm, in these cases, can predict the phase of falling asleep with an average of almost 5 min.

4.2 Algorithm Implementation in a Wearable Device

For a real-time acquisition and detection, the algorithm has been implemented on a wearable device. The system is composed of a powerful wearable development platform, named Hexiwear, and a Raspberry PI. The first one acquires the signal, elaborate it and send the results in to the Raspberry PI through Bluetooth, where they are displayed and then saved in a log file (Fig. 2).

Fig. 2. Wearable CPS and data logger

4.3 Algorithm Validation in a Realistic Environment

Another validation step has been done with an application experiment, once the subject is driving/driven in the dynamic vehicle simulator at AVL (Graz, AT).

A relevant activity has been performed in order to integrate the WCPS into the SW environment of the dynamic vehicle simulator, as shown in the figure below (Fig. 3):

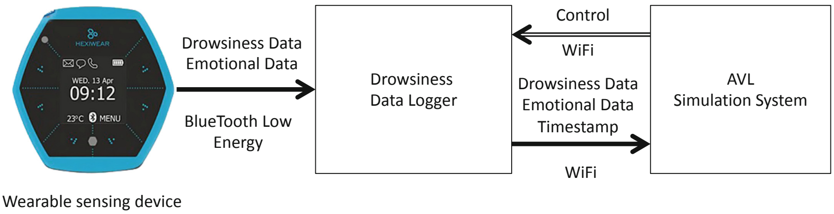

Fig. 3. WCPS integration into the AVL IODP environment

The objective of the AE is to validate the algorithm's prediction capability once the subject is driving/driven in the Dynamic Vehicle Simulator (DVS).

This is considered the most reliable and realistic test which can be carried out to detect the transition between behavioural states until drowsy/sleeping conditions.

Maintenance of Wakefulness Test (MWT) is considered a useful clinical test for the evaluation of excessive sleepiness by the Task Force of the American Academy of Sleep Medicine (AASM). It requires the patient to fight against sleepiness in a soporific condition and it is considered as a validated, objective measure of the ability to stay awake.

According to the medical literature and taking into account the main object of such a study, it is reasonable to execute a Reduced Maintenance of Wakefulness Test (R-MWT).

The R-MWT uses a limited set of sensors, which are essential to assess the transition from drowsiness to sleep state.

The objective of such a test is to compare physiological parameters recorded by a standard polysomnography and the WCPS during a R-MWT performed in a simulated driving context. In particular, in the case of a transition from wakefulness to sleep state, during the driving simulation, the WCPS's ability to predict and identify falling asleep will be verified.

The study has been approved by the technical and scientific committee of J Medical Center (Torino, Italy). All participants will receive details about the study and then will sign written informed consent before undergoing the test.

This activity focused on acquiring data for validating the algorithm in a realistic environment. Although the noisy room, the validation has given good results. The analysis has been conducted on a number of healthy adult subjects (21 acquisitions, 9 males and 11 females, average age 44.3 years, range 18–81 years). Then the data analysis has been performed by medical doctor expert in sleep medicine, thus basically confirming the high sensitivity and specificity values obtained in the previous experimental activities.

The algorithm, in these cases, can predict the falling asleep phase with an average of almost 3–4 min (Fig. 4).

Fig. 4. The final application experiment on the dynamic vehicle simulator at AVL

5 Further Steps and Conclusions

The PRESLEEP project has supported the development of an innovative methodology to analyse the behavioural transition of a subject through a multi-factor and multi-domain IP running in real-time on a wearable CPS.

A realistic Application experiment has been carried out on the Dynamic Vehicle Simulator at AVL.

It has been proven that the algorithm predicts the time horizon when the subject will fall asleep (at least 5 min before the sleep onset) and detects the drowsiness onset (1 min resolution).

Further analysis based on a new set of experiments, in different operating conditions, are planned and will be performed in Q1-2020.

A preliminary discussion regarding the exploitation of the result with a selected industrial partner is on-going.

A feasibility study concerning the application of the IP on contactless PPG technology (e.g. short-range RADAR) is currently under development.

Shortly, the purpose of the application is a wearable CPS worn during the driving experience, then the short-range RADAR installed in the car will provide at the data acquisition.

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Human Driver's Acceptance of Automated Driving Systems Based on a Driving Simulator Study

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Abstract. One research area within the development of automated vehicles deals with the impact analysis on traffic flow by numerical simulation. This study investigates human drivers' acceptance while interacting with different levels of automated vehicles on highways including on- and off-ramps. Reactions between conventional, human driven vehicles (CV) and automated vehicles (AV) were tested using a driving simulator. Gaps and headways between vehicles were recorded and analyzed. The analysis indicates similar behavior between CVs and aggressive AVs (short headways) while prudent AVs were perceived less favorable by the test drivers. Additionally, long headways showed more disturbance in traffic flow than shorter headway setups of the automatic distance control (ACC).

Keywords: Driving simulator · Automated vehicles · Driver's acceptance

1 Introduction

Since decades, the development of driving assistant systems provides an important topic in automotive engineering. Especially the evolution in technology in the last ten years showed that the former dream of autonomous vehicle is within grasp. Cars and trucks get equipped with sensors and systems to be automated-vehicle-ready and researchers incorporate the behavior of automated vehicles (AV) in new models as shown in [1] or [2]. In general, the effects of AVs on the driving behavior of drivers from conventional vehicles (CV) is not considered in these models. As described in [3], lead vehicles often influence the driving behavior of following vehicles. Since the stability of traffic flow in dense traffic depends heavily on the driving maneuvers of individuals, it is essential to know about changes of human driving behavior in mixed traffic conditions. The perception and acceptance of human drivers while interacting with AVs have to be investigated more closely.

Traditionally, tests and validations of automated driving systems are carried out by on-road testing of vehicle prototypes on public roads and test tracks as well as

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by driving simulator studies. Human-in-the-loop testing in driving simulators have the advantage that full vehicle prototypes are not necessary. Moreover, the driving scenarios are repeatable, numerous traffic situations can be tested at lower costs and ceteris paribus, traffic- and weather conditions can be guaranteed. These circumstances make a driving simulator study perfectly suitable to estimate the confidence of human drivers' perception and interactions with AVs.

2 Methodology

In this study, 24 test drivers traveled along a motorway segment including entries and exits. All test drivers were human but the surrounding vehicles of the driving simulator scenes were simulated. In the base scenario, the neighboring vehicles were modelled like human driven vehicles (CV). This chapter on methodology includes a description of the driving simulator as well as the approach to evaluate the driver experience and its impact on the traffic flow.

2.1 Driving Simulator FASI

The Institute of Automotive Engineering at Graz University of Technology has developed a fixed-based driving simulator (FASI) using a full vehicle setup who already performed several studies [4–7] investigating human driver behavior. Figure 1 shows that a central co-simulation platform synchronizes individual software and hardware modules in real-time (without recognizable latencies) in order to avoid simulator sickness.

On the hardware side, the simulator has an active steering wheel, active brake pedal and passive throttle, which takes care of the haptic response. Nine LED monitors cover over 180° of the field of view, where four 55″ monitors in the front of the front windshield predict an autostereoscopic visualization. Four 23″ monitors serve the side windows and the last monitor covers the rear window. A sound system cares for the simulation of the engine, traffic, wind and wheel-rolling noises.

Additional bass shakers in the driver's seat simulate the vibrations of the engine. In order to isolate the test persons from external interference, a light-proof wooden construction with sound-absorbing elements was built around the driving simulator.

The lower part of Fig. 1 shows exchangeable software based modules, which work with self-developed modules or with commercial programs such as AVL-VSM or PTV VISSIM. The colored elements in Fig. 1 were used in this study.

2.2 Simulation Approach

In general, driving simulators contain an ego-vehicle controlled by a test driver and a simulation environment including external vehicles. In many cases, the trajectories of external vehicles are predefined, so that the driving behavior of the test driver has no impact on the external traffic. The FASI interface with the traffic flow simulator VISSIM leads to a realistic feedback between the ego vehicle and its surrounding vehicles. This means that the neighboring vehicles react to the driving behavior of the test driver. The traffic flow simulator had to be adopted in order to model AV specific driving functions

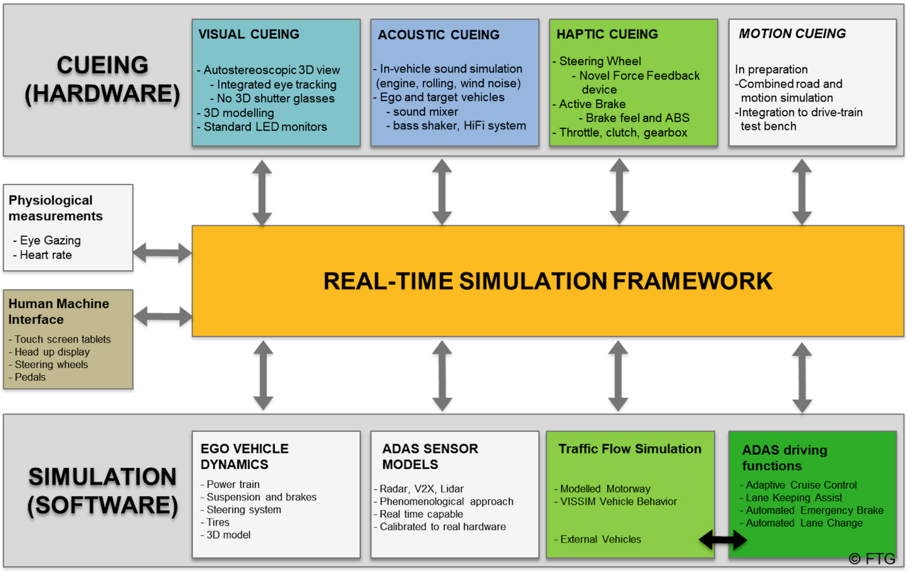

Fig. 1. Components of the driving simulator FASI as used in this study

marked as advanced driving assistance system (ADAS) in Fig. 1 and further specified in Sect. 2.2.2.

Due to the regulated conditions under uninterrupted traffic flow conditions, it is assumed that automated driving will initially start on motorways [10]. The Austrian government has released the “automated driving regulation” as a legal framework to test automated driving functions on motorways. In this study, we assumed a fictitious single three-lane motorway. In order to avoid distorted acceleration data, the highway was built as a straight road. A total length of 14 km was modelled including five on-ramps respectively off-ramps. The first three exits were situated in front of the associated entries, while the last two junctions were modelled including weaving sections (on-ramps before off-ramps) (Fig. 2).

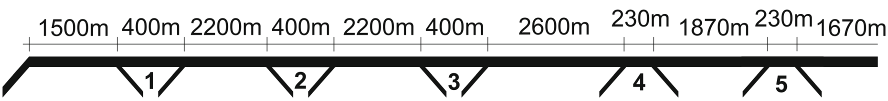

Fig. 2. Motorway layout

The designs of the on- and off-ramps follow Austrian guidelines (RVS 03.05.13) regarding the lengths, widths and lane markings of the acceleration and deceleration facilities. In order to prevent a monotonous unrealistic travel experience, the road was supplemented by various design elements, such as concrete baffles, noise barriers, bridges and a tunnel in the immediate vicinity of the road, as well as landscape features such as mountains, clouds and vegetation (Fig. 3).

Fig. 3. Inside view of the driving simulator

This motorway was modelled in the FASI and duplicated in the traffic flow simulator VISSIM. The VISSIM scenarios differed by total traffic volume and driving behavior of the driver-vehicle agents depending on the start of travel of the FASI test driver (ego vehicle). The legal speed of the different road elements (130 km/h motorway, 60–80 km/h on- and off-ramps) was superseded by individual speed choices (desired speed behavior), so that each VISSIM vehicle shows realistic human driver behavior. A 10% truck rate was assumed.

Three scenarios of levels of automation were modeled as follows.

2.2.1 Human Driving Behavior – SAE Level 0

In the first scenario, all vehicles except the ego vehicle were assigned to a driving behavior corresponding to SAE level 0. This level describes a conventional vehicle without automated driving functions (like lane keeping assists or adaptive cruise control). Depending on the vehicle class, different speed distributions were stored in the simulation for the desired speed on the main road. While cars showed an approximate normal distribution between 80 and 170 km/h, trucks were assigned a uniform distribution between 84 and 88 km/h [11]. The VISSIM default distributions of desired acceleration and deceleration were adopted according to [12]. The proposed desired headway was set to 1.05 s accordingly [13]. Furthermore, extensive calibration of the weaving process of entering vehicles on the on-ramp was undertaken by adaptions of lane-specific routing. Cars on the main lane received a cooperative lane change behavior whereas vehicles on acceleration lanes excepted also higher decelerations of following vehicles, to be able to merge in the traffic flow. In addition, a larger safety distance to the leading vehicle is maintained compared to the vehicles on the main lane.

2.2.2 Automated Driving Behavior – SAE Level 4 with 1.8 s Headway

In this scenario, the vehicles in the vicinity of the ego vehicle have highly automated driving functions according SAE level 4 as discussed in [12]. However, the AV functionality was only implemented for the vehicles on the motorway but not while merging from the on-ramp. While traveling on the acceleration lane the AVs followed a human initiated merging process, thus a VISSIM related lane change was conducted. On the motorway itself, the vehicles were controlled by fixed ADAS functions such as constant headways and desired speeds not exceeding the speed limit. In addition, short platoons of three vehicles were enabled by car-to-car communication (C2C). Vehicles within a platoon can reduce its safety headway down to 0.5 s and act like a single large vehicle when changing lanes. If an AV is not part of a platoon, the headway is set to 1.8 s. This value is based on the interpretation of the German and Austrian Road Traffic Act (StVO) asking for a sufficient safety distance. This distance is interpreted to be sufficient if the headway exceeds 1.8 s and is called “prudent safety distance”.

Since VISSIM 8.0, being used in this study, does not support platooning, the driving functions of the AV were imported as an external driver model using a dynamic link library (DLL). The DLL was called for each AV in each time step (20 Hz) in order to calculate driving parameters for the longitudinal and lateral behavior. The structure of the DLL is shown schematically in Fig. 4. A separate DLL was designed for cars and trucks, respectively.

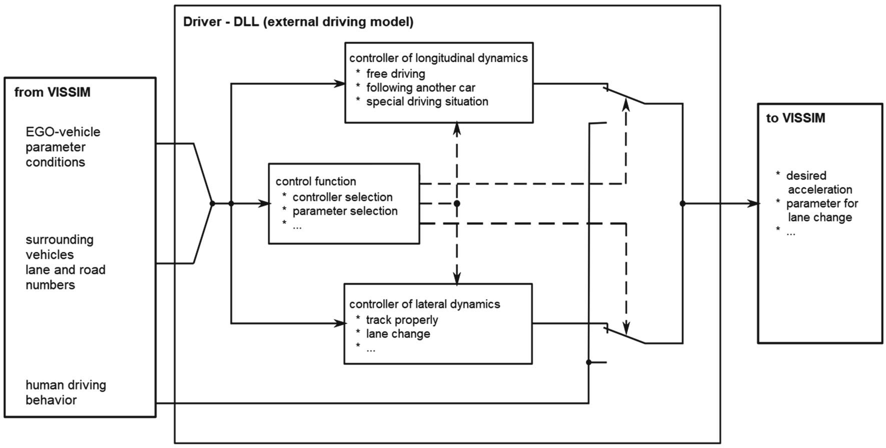

Fig. 4. Software module to replicate ADAS functions for AV

2.2.3 Automated Driving Behavior – SAE Level 4 with 0.9 s Headway

In the third scenario, all vehicles, with the exception of the ego vehicle, are modelled as automated vehicles corresponding to SAE level 4. Both, the structure and the logic of the DLLs are identical. However, the parameter settings are different form scenario 2. Vehicles not being part of a platoon travel at a headway of 0.9 s. This value is justified by the current legal practice in Germany. If the value of the gap in meter is less than one quarter of the speed in km/h, drivers risk a criminal complaint. Similar gaps can be measured under current dense commuter traffic conditions in metropolitan areas. It is related to rather aggressive safety perceptions.

2.3 Methodology of Test Driver Survey

Each test person drove the motorway segment three times in a row including scenario one, two and three. The sequential order was varied, so that it was unknown to the test driver whether all external vehicles were human driven (Scenario 1), prudent AVs (Scenario 2, SAE level 4_1.8) or aggressive AVs (Scenario 3, SAE level 4_0.9). After each test drive, the test person had to reply to a questionnaire asking about the driver experience on a six-level scale. Low numbers indicate dislike while high values show consent. The results in the next chapter show the average values of all 24 participants. No rectification of individual responses has been conducted since the consent level has not shown any individual biases. The questionnaires were conducted by an instructed interviewer who may have added personal comments of the participants during the test drive itself.

Slightly more males (14 men) than females (10 women) participated in the study. The age varied between 20 and 61 years with a slight over representation of young drivers (42% between 20 and 29 years and 25% between 30 and 39 years). However, this had little impact on the driving experience, since only 12% had their driving license less than 3 years. The annual mileage shows that the test persons are experienced drivers (30% drive more than 20.000 km/a; another 30% between 10.000 and 20.000 km/a and 20% still more than 5.000 km/a). Furthermore, the drivers often use the motorway (54% between 1.000 and 5.000 km/a and 34% more than 5.000 km/a).

2.4 Methodology of Traffic Flow Analysis

During each test drive, the trajectories of the ego vehicle and all adjacent vehicles were recorded. The analysis of the trajectories should indicate differences or similarities of the driving behavior including gaps, headways and accelerations following a lead vehicle and conducting a lane change. A following-process of a test driver was defined if all three condition were met:

- Driver had the same lead vehicle for at least 10 s, this value being determined approximately by a random analysis of the recorded video material.
- Distance between the ego and the lead vehicle is less than 250 m.
- The considered driving situation lasted longer than the time span resulting from the median of the speed differences and the median of the distances between the two vehicles.

Diagrams with distance over speed difference allow a visual evaluation of the car-following behavior. The extent of oscillation corresponds with the degree of accelerations and decelerations. In addition to the car-following, several other maneuvers (lane change, vehicles on destination lane, driving maneuvers of other vehicles) do influence driving behavior. To evaluate the whole trip of the test drivers the standard deviation of the acceleration (acceleration noise) was calculated. The acceleration noise is a good indicator of the homogeneity of a journey [13] and is described mathematically as:

$$AN = \sqrt{\frac{1}{T}\int_0^T \left[a_{(t_i)} - a_{ave.}\right]^2 dt}$$

AN ... Acceleration noise $a_{(ti)}$ acceleration at discrete time step
T ... trip time $a_{ave.}$ average acceleration

If a vehicle is forced to decelerate quickly due to a lane change of another vehicle, this causes disturbances in the overall traffic flow. Therefore, the times-to-collision (ttc) and headways of the used gaps while lane change maneuvers were examined.

3 Results and Discussion

3.1 Perception of Test Drivers

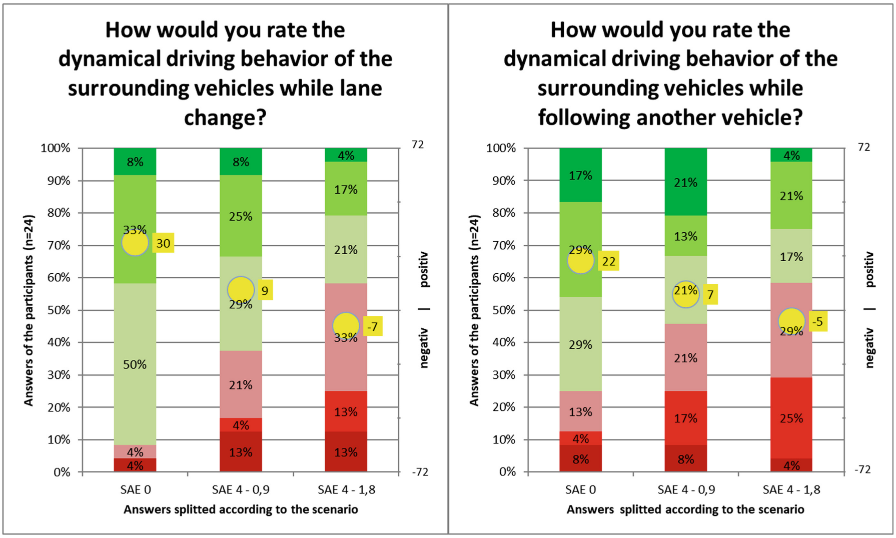

Fig. 5. Exemplary results of the interviewing

The results of the survey indicate that the test driver felt rather uncomfortable in the scenario with prudent AVs, while the scenario with aggressive AVs show a relatively positive attitude. However, the human driving behavior has been generally preferred (Fig. 5).

This could be because the driving behavior corresponds most closely to what the participants are used to in everyday life.

4 Impact on Traffic Flow and Driving Behavior

In order to detect changes in the following behavior, similar driving situations must be compared. For example, the vehicle in front should move as constantly as possible (with only slight accelerations and decelerations), since otherwise human latencies lead to large scatter in the diagrams. Likewise, similar speeds should be maintained in the compared driving situations, since these significantly influence the selected distance and the reaction path covered in the diagram. Figure 6 shows the driving behavior of random participants while following a CV (left diagram) and an AV (right diagram), respectively. Driving behind a CV often lead to smaller variations in the following distance.

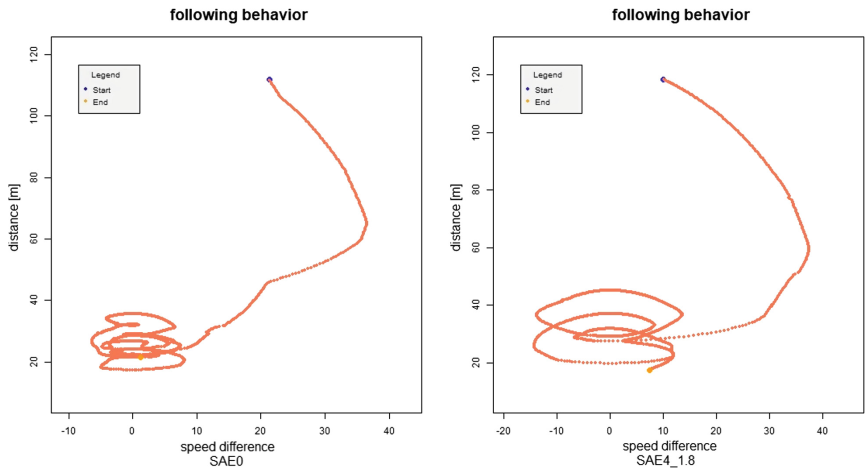

Fig. 6. Distance over speed difference while following a vehicle with human driving behavior (left) and while following a vehicle with automated driving behavior (right), respectively

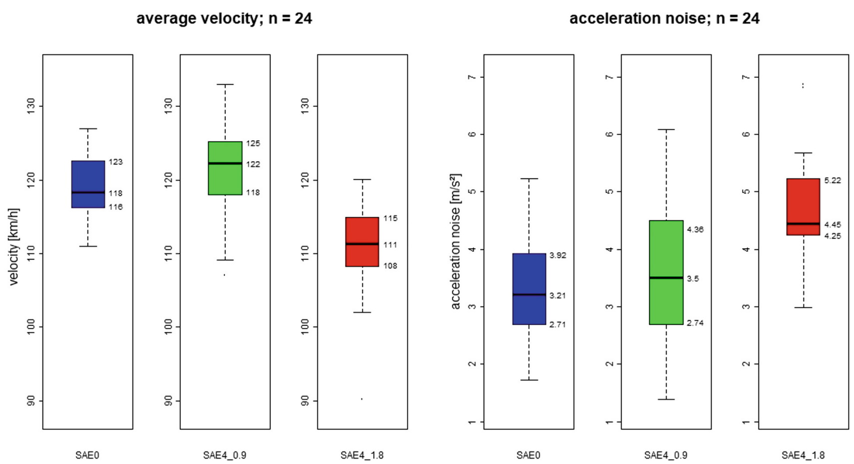

Fig. 7. Boxplot of the average velocity (left) and the acceleration noise (right)

The analysis of the driving dynamics showed that scenario SAE level 4_1.8 resulted in a lower average speed of the test drivers (Fig. 7 - left), compared with scenario SAE level 0. The highest value of the acceleration noise was also determined in this scenario (Fig. 7 - right). Since the 25% quantile value in scenario SAE level 4_1.8 is higher than the 75% quantile value in scenario SAE level 0, an indication of a change in driving behavior is assumed. Due to the overlap of the inter-quartile ranges of the scenarios SAE level 0 and SAE level 4_0.9, no clear change in driving behavior can be determined from the boxplots.

When analyzing the lane change behavior, the time to collision to the rear vehicle on the target lane is an important indicator of risk disposition in this maneuver. Because the time-to-collision is calculated as distance divided by speed difference, it gives the remaining time in which the rear vehicle needs to recognize the lane change of the participant and needs to adapt its speed to avoid a crash. Figure 8 shows the accepted time-to-collisions of the participants while initializing a lane change. Especially the lowest values of two seconds time-to-collision indicate an increased willingness to take risks or an overlooked vehicle. The same conclusion is found in the evaluations of the accepted time gaps.

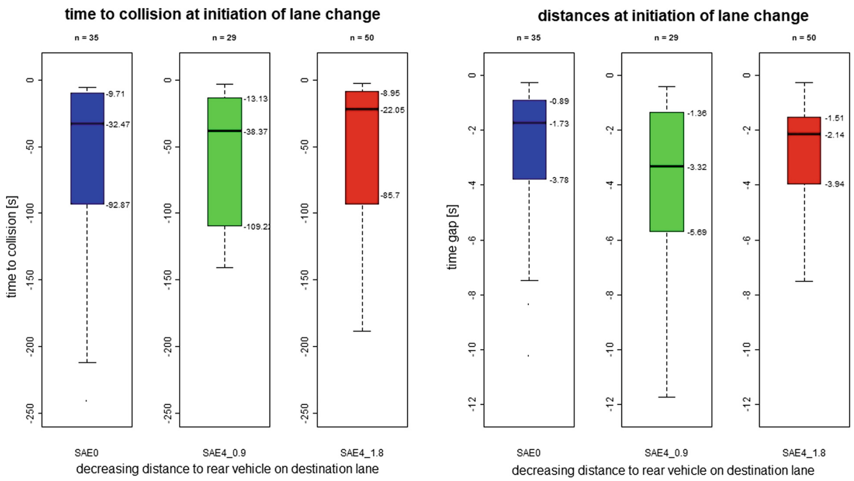

Fig. 8. Accepted time-to-collisions (left) and gap (right) while initiating a lane change

5 Conclusion

Although this study is limited regarding the number of test persons and scenarios tested, there are some interesting findings. One of the key results is an indication that long headway (1.8 s) are not evaluated as comfortable. This is in line with the general observation with current Level-1 ACCs. If the headway is set to values above 1.5 s than it is likely that human drivers may squeeze into this gap and the semi-automated vehicles falls back. If the headway is rather short (0.9 s) the drivers felt more comfortable although this situation leads to unsafe traffic conditions. Further tests will be conducted especially including automated merging and lane changing at entries and exits. The overall capacity of a motorway heavily depends on an efficient and co-operative lane change and gap acceptance process at interchanges, exits and entrances and should be investigated closely within mixed traffic conditions.

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ALFRED: Human Centred Artificial Intelligence to Humanize the Automated Vehicle Actions

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Abstract. One of the main reasons for contested innovations to fail is the negligence of societal needs and public acceptance in due time in the development phase. In the specific case of the connected automated vehicle (CAV), there is an important degree of scepticism based on the awareness of the complexity and the risks of this technology. The SUaaVE project aims to make a change in the current situation of public acceptance of CAV by enhancing synergies amongst social science, human factors research and automotive market. The main ambition in SUaaVE is the formulation of ALFRED, defined as a human centred artificial intelligence to humanize the vehicle actions by understanding the emotions of the passengers of the CAV and managing corrective actions in vehicle for enhancing trip experience.

Keywords: Autonomous driving · Emotion · HRV · ECG

1 Literature Review

As the technology development for automated functions in vehicles progresses and the market introduction of connected automated vehicles (CAVs) approaches, deployment roadmaps start emphasizing societal issues related to CAV technology [1]. A comprehensive report on Responsible Research and Innovation states that the chief reason for a contested technology to fail is that the societal needs and public acceptance is not taken into account in due time [2]. A recent international and broad survey showed that although people are fascinated by CAV, 43% of people would be afraid of travelling in an automated car [3]. Furthermore, gradual deployment of CAV also implies that CAVs will co-exist with other road users (vulnerable road users and conventional vehicles) for some time, making the harmonization and acceptance by other road users a prime subject. For all this, the latest Automated Driving Roadmap [1] published by ERTRAC (European Road Transport Research Advisory Council) ascribe paramount importance to public acceptance, user awareness, and ethical issues related to CAV.

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At present, EU Member States do not have a specific policy to enhance public acceptance of CAV or to ensure user involvement [4]. Despite the fact that before users accept it, they should have the opportunity to become aware of what it is, avoiding the feeling of deception and distrust in the main stakeholders, public or private. The approach based on the technology push threatens social viability of innovative technology like CAV, as it creates a gap between the well-thought technical reliability and public acceptance.

Acceptance is a multi-faceted construct ranging from psychological factors to the characteristics of a decision-making process. Trust in new technology is one of the key determinants of public acceptance and confidence, directly, by influencing the adoption of it, and indirectly, by inducing affect towards a new technology [5]. Trust in automated systems can be increased by making the system more human-like [6], which will make the vehicle more predictable and usable for passengers and other road users in its surroundings. In fact, trust in CAV is based on feelings of safety and acceptance, making the emotional process one of the most influential aspects of confidence [7]. Therefore, the emulation of emotions and social norms in the design of CAVs will help in building a possibly more comfortable, trustworthy and collision free CAVs. However, the exact mode of implementation is still under discussion [8].

Grey areas in CAV technology, on the other hand, may overshadow the expected benefits in the eyes of public. A recent report [9] revealed that acceptance of CAV had a decreasing trend in the US as the society got aware of the complexity of the technology and the risks in cybersecurity and data privacy. Experience to enhance acceptance of new technologies points a change in the way the stakeholders and the public interact during decision-making process. Representatives of both parties favour transparent, participatory, and fair process to enhance public acceptance. This approach helps to reduce fear and clarify grey areas while creating trust.

2 What Is SUaaVE?

The SUaaVE project (SUpporting acceptance of automated VEhicle), funded from the European Union's Horizon 2020 Research and Innovation Programme, aims to make a change in the current situation of public acceptance of CAV by leaning on a Human-Driven Design (HDD) approach, enhancing synergies social science, human factors research and automotive market by means of an iterative process of assessment, co-design and prototyping.

SUaaVE emerges from a participatory process promoting collaborative and co-design methods to empower end-users as well as other stakeholders, ensuring the acceptance of this concept from a societal and individual perspective. In this line, the process involves above 4,000 users (passengers, traditional and future drivers, vulnerable road users) as well as 100 experts and stakeholders along the project. SUaaVE focuses on the human side, working to improve more "intangible" aspects as safety perception, attitudes and, in general, emotional appraisal of passengers in CAV (Fig. 1).

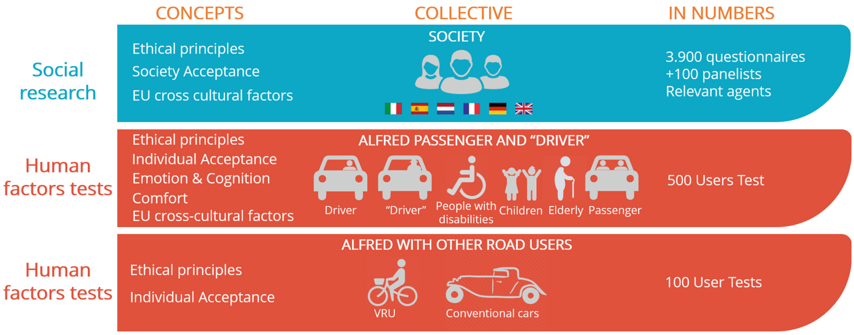

Fig. 1. HDD approach and user involvement along the project.

The application of the HDD approach in SUaaVE will be materialised through two different and complementary approaches:

- At societal level, with the formulation of frameworks to enlarge public acceptance in the deployment of CAVs for all the potentially involved society; current and new drivers (adults, senior citizens, children, and people with disabilities) as well as VRUs.
- At individual level, under the conceptualisation of ALFRED, understood as the integration of the emotional experience of the passenger and ethical principles in the artificial intelligence (AI) that manages the control of highly automated CAVs.

The result of the project will benefit society representing a breakthrough in the public acceptance of future CAVs for both the society as a whole and, in particular, for all road users. Furthermore, in the case of industry, SUaaVE will facilitate a better integration of human factor in the deployment of CAV by tackling a Human Driven Design approach, promoting a competitive advantage of European automobile manufacturers to keep and extend their leadership in transport industry all over the world.

3 Who Is ALFRED?

ALFRED is conceived as the fundamental architecture to understand the emotions and the cognitive state of the passenger(s) on-board of the CAV and to adapt the vehicle features to enhance the in-vehicle user experience, while increasing acceptance. Compared to the CAVs developed under the traditional approach, ALFRED will contribute with two artificial intelligence units in the decision-making processes of the CAV (Fig. 2):

- **"EMpathY" Unit** (**EmY**), which will be in charge of understanding the **emotional** and **cognitive state** of the passenger, while considering **ethical principles** (*Sensing and interpreting*).
- **"Adaptive, Cognitive and Emotional"** (**ACE**) **Interface**, formulated as the control strategies for the management of CAV behaviour to enhance trip user experience on-board (*Acting and communicating*). This will include the communication with the passenger via HMI and vehicular dynamic response.

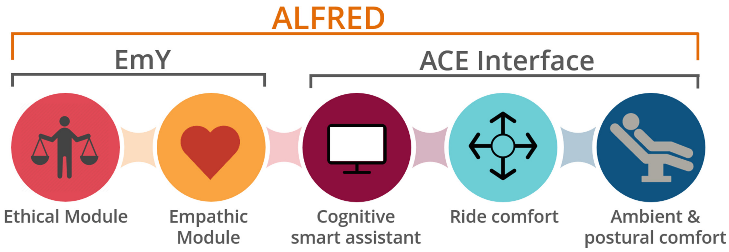

Fig. 2. ALFRED components.

3.1 EMY

The empathic module intends to understand the passenger's emotional and cognitive state during the trip. An emotional model will estimate the particular state experienced by the passengers (in Real-Time) based on body biometrics. Then, the empathic module will identify what current factors influence the emotional state, such as the vehicle dynamics (ride comfort), the environmental conditions (traffic density, behaviour other vehicles, presence of vulnerable road users, etc.), the interior ambient conditions and postural comfort.

Furthermore, the current emotional state will be compared with a passenger's projected state. The purpose is to verify if the predictions are reliable since other external factors, unable to be estimated, may also affect the passenger's state. These external factors can be contextual or unexpected road events. If a mismatch is stated, ACE interface will act accordingly to the vehicle features to achieve the target passenger's states.

3.2 ACE

ACE Interface will manage the in-vehicle experience, aiming to enhance passenger's satisfaction (Fig. 3). This will be carried out through:

- **Cognitive smart assistant**. In highly automated driving scenarios, the vehicle is required to provide suitable information to the passengers (or "drivers" in case of L4) in order to permit them to understand the current driving conditions, so that they accept the decisions made by the CAV, without feeling neglected and treated as a cargo to be delivered. If the information is not updated and adapted to the passengers' emotional and cognitive state, they may not understand the reaction of the vehicle (such as hard break, swerve, etc.) in response to road events, thus provoking the rejection of CAV. Under this issue, a cognitive smart assistant will be developed to provide the passenger with an effective communication of information about the current behavior and future intentions of the CAV in an appropriate and relevant manner. The estimation of the passenger state (contextualized through a categorical emotional map and reinforced by an emotional model) will be used by the cognitive smart assistant to (1) increase user situational awareness in anticipation of potentially critical events, warning and assisting the "drivers"; and (2) to adapt the communication in non-critical events to make the CAV experience more enjoyable.

- **Ride comfort. Development of algorithms** to adjust the vehicle dynamics in Real-Time, within the definition of acceptable thresholds of safety and comfort. This will cover real-time operational and tactical functions required to operate the vehicle in traffic (including longitudinal and lateral vehicle motion) with the objective of enhancing perceived safety throughout the trip. Ride comfort management will be guided by the passengers' emotional state, taking into account the emotions that could be inferred by dynamic adjustments to other road users, seeking both a satisfactory emotional state for the passengers and the acceptance for other road users around the vehicle. Dynamic Driving Tasks (DDT) will be adjusted by theses algorithms and will also include the ethical rules for the decision-making processes of CAV.
- **Ambient and postural comfort**. Settings to enhance comfort and a more effective/pleasurable use of the time spent travelling, aiming to guarantee the feeling of well-being. The emotional state of the passenger will be used as a reference for setting ambient condition in the vehicle (lighting, heating and air conditioning, postural preferences) as well as considering their combination, incompatibilities and threshold values.

4 The Emotional Model

4.1 The Emotional Model of the Passenger

SUaaVE will use two sources for a better understanding of the passenger emotional state, much on the way on how emotions are treated in a social environment. On the one side, EmY will be aware of the contextual factors involving the experience in the Ego Car: the purpose of the trip (work travel, day shift, holidays, etc.), the state of road (density of cars, weather conditions, etc.). On the other hand, the Ego Car will be monitoring the passenger itself: behavioural aspects such as face expression, and bodily changes such as respiratory rate or heart rate.

These two sources complement each other to have a reliable understanding of the emotions on the passenger and allow ALFRED to use different approaches of emotion management. The analysis of the contextual factors allows an anticipatory management of the user state, while monitoring the passenger allows a reactive management of emotions.

A different methodology will be used in the analysis of emotions:

- The analysis of contextual factors will use a categorical approach: The OCC model [18].
- The monitoring of the passenger will use a dimensional approach.

The OCC model presents a cognitive structure of emotions being one of the most used appraisal methods in the literature [11–13]. Through this method, the passenger is described by a set of variables defining a group of individual categorized emotions. The trigger of the emotion is related to the events, agents and objects that surrounded the individual.

On the other hand, the dimensional model is a bi-dimensional model of valence-arousal dimensions. The passenger will be instrumented for recording several physiological signals (i.e. heart rate variability) in order to obtain the individual's valence-arousal value and its trend in real time through signal processing and analysis.

The data obtained via these two methods will be combined in order to achieve a more robust map of the passenger state (Fig. 3). The consistency between the results of each model will allow a more reliable estimation of the passenger state.

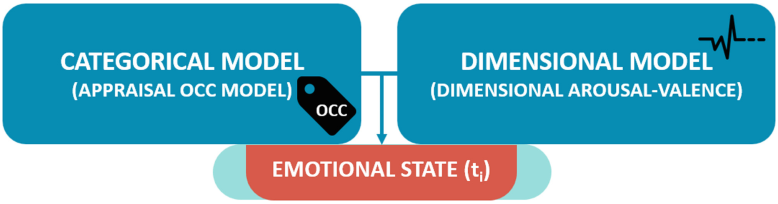

Fig. 3. Representation of the two approaches that build the emotion recognition model.

Once the emotional state of the passenger is estimated, different strategies will be developed to recover from negative emotional states (i.e. provide more information to the passenger about the trajectory to reduce the level of fear) and to reinforce the positive emotional ones (i.e. arrived in time successfully, give information of having saved time following a given route).

4.2 OCC Model

The OCC model develops a convincing cognitive structure of emotions in terms of the eliciting conditions of emotions and the variables of their intensities. The authors elaborate a systematic description of the cognitive generation of emotions and it is quite popular among researchers building systems that try to understand an individual emotion and its interaction with an artificial character. For this reason, the model served as a basis in the challenge of creating an empathic module in the autonomous car that could detect, anticipate and provide answers and recovery strategies for the emotional state of the passenger.

The present methodology pursuits to build a construct about reactions to events, agents, their beliefs and actions and objects that will draw a complete list of emotions. To each of the elements, namely events, agents and objects, there is a different kind of reaction, pleased vs displeased, approving vs disapproving and liking vs disliking, respectively. Those 6 global reactions are the ones that are differentiated in more specific reactions that will be the ones defined as "emotions" [18].

The appraisal is based on three central variables: desirability, praiseworthiness and appealingness, applying respectively to events, agents and objects. The desirability is assessed in terms of the complex goal structure, and concretely a focal goal which is the one interpreting the event. So, it depends on in which way the event is facilitating or obstructing the goal. The same way, the praiseworthiness is evaluated as the judgement of an agent's action in the framework of the individual norms and standards, and how it is judged good or wrong. In the case of the appealingness, it depends on ones' attitudes, in the sense of his or her preferences or likings. The intensity of the emotions is defined by local variables and by global variables. The global variables affect all groups of emotions and tell the degree of intensity of the experience. The local variables affect only specific groups of emotions.

From the definition of the three elements: events, agents and objects; and the three groups of variables: central, global and local. The authors of the model defined 22 emotions, from joy to distress and include 5 steps for the process: a) classifying the event, action or object encountered, b) quantifying the intensity of affected emotions, c) interaction of the newly generated emotion with existing emotions, d) mapping the emotional state to an emotional expression and e) expressing the emotional state.

4.3 Dimensional Model

The emotion monitoring is carried out through different methodologies that can be grouped as follows:

- Prediction through events: Categorization of emotions.
- Measurements through physiological signals: Valence and arousal.

Based on relevant works about emotion computing [10–19] an algorithm is developed with the purpose to predict an emotion on the basis of the information obtained from the environment of the vehicle, the context of the trip, and the passenger's personality. The approach is to train the algorithm through the experimentation in order to create a vast enough database to achieve predictions with considerably good accuracy. Figure 4 presents a scheme of the different elements of the algorithm. The algorithm includes the box of "decision making" that will also consider information from other modules such as the cognitive module.

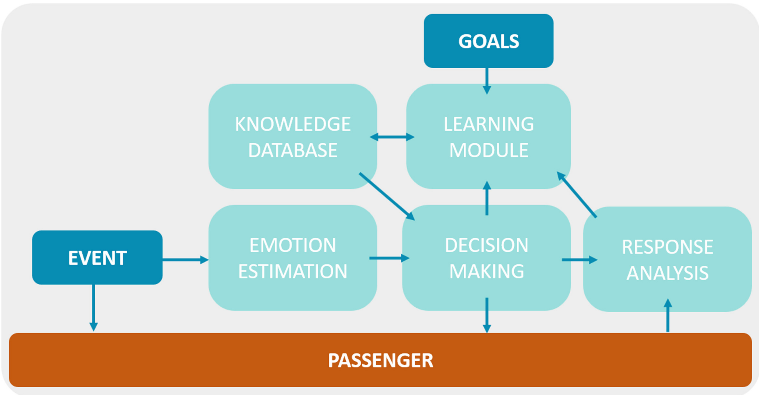

Fig. 4. Sc. Process template of the event – emotion estimation – learning algorithm.

The arrow that connects the passenger with the response analysis concerns the physiological response, together with the information captured through cameras. That information will help to validate if the decision made based on the actual event and the knowledge database is correct or not.

Focusing in the multi-dimensional, and concretely in the Valence-Arousal bi-dimensional model, scientific literature supports that it is possible to detect the emotional state measuring physiological signals:

- Heart rate variability (HRV) is associated with the balance between the sympathetic and parasympathetic nervous systems. HRV is inversely related to the intensity or emotional activation. When there is a high cognitive or emotional demand, the heart shows a steady rhythm to optimize performance, reducing heart variability. In contrast, when the person is in a state of relaxation or low activity, the heart rhythm is more variable, since it does not need to optimize the body's performance, thus increasing variability.
- Galvanic skin response (GSR) reflects the activity of the sweat glands, which respond to changes in the sympathetic nervous system. An increase in the level of emotional activation causes an increase in the level of GSR. The GSR signal has two components, a tonic component, which changes slowly, and a phasic component that is responsible for rapid variations, such as the response to a stimulus.

Shu et al. [20] reviewed signals that are being measured by different authors, and highlight the relevant properties from which the emotion can be detected with a certain percentage of accuracy.

In the case of SUaaVE, we will focus in the measurement and analysis of cardiovascular signals, electrodermal and respiratory.

The process from acquire data to launch an emotion guess, follows the steps shown in Fig. 5. Each signal will be studied and processed by different ways and it is of the core research work developed in the framework of the project.

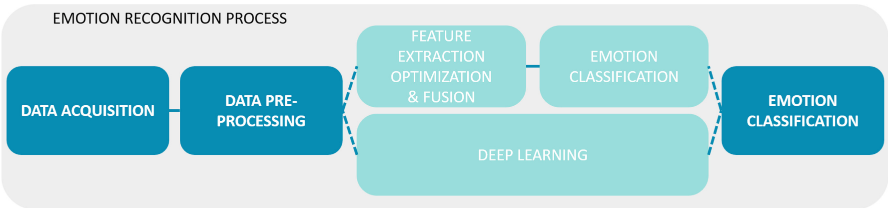

Fig. 5. Scheme of the human body with the zones from where the different physiological signals are the measured for the emotion detection.

In SUaaVE, several tests with subjects will be carried out to develop the dimensional model. These tests will consist in the elicitation of different emotions through the simulation of a set of self-driving scenarios in a realistic driving simulator, acquiring the physiological responses of the subjects through wearable devices and sensors. In the future, as technology advances, the monitoring of the occupants in CAV may be carried out in a non-intrusive-way, for example, heart detection and respiration rate by in-car embedded sensors and cameras. Therefore, the emotional model generated in SUaaVE shall be operational in the CAVs through the use of this future non-intrusive technology once it is considered sufficiently mature and reliable.

5 Definition of Strategies to Enhance a Positive State of the Passengers

Once the passenger's emotion is known the main question that arises is the adequate response of ALFRED for the improvement of passenger emotional state, depending this response on the goals of the trip for the passenger of the vehicle. By considering these goals, the emotional management will be in charge, not only of defining corrective actions on board in case an undesirable emotional state of the passenger is detected, but also acting before by means of the prediction of the emotional state of the passenger.

According to the modal model of emotions (Fig. 6) from Gross and Thomson [21], the emotion management can be performed in several places of the whole dynamic cycle of emotion elicitation (Fig. 7).

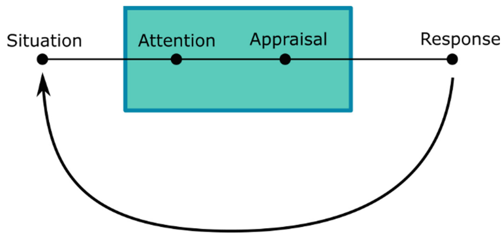

Fig. 6. Dynamic cycle of emotion elicitation based on the Modal Model of emotion [18].

The emotions are elicited from situations, the Attentional processes direct the emotions and are mediated by the goals of the person. Then the Appraisal model is where the emotion raises and a response is elicited. This response, dynamically changes the situation and influences the emotions. The green box is related to the driver intrinsic factors, while factors not directly related to the driver factors remain out of the box.

The strategies to be applied when the emotion has been already detected are Response Modulation, corrective actions, while the others imply understanding in advance what emotion will be raised in the passenger in order to be able to act before the elicitation of the emotion.

SUaaVE will use a repertoire of actions to incorporate all the strategies dealing emotion management. In particular, the dimensional model of emotion will be in charge of the strategies for *Response Modulation* while the Emotion Appraisal Categorical model will be in charge of the rest of the strategies.

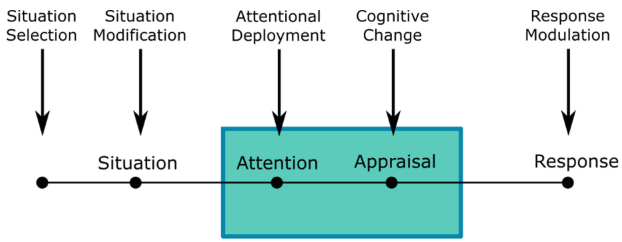

Fig. 7. Emotional management model [18], highlighting where the different strategies for emotion management are applied in the cycle of emotion elicitation.

5.1 Emotion Management with the Dimensional Model of Emotion

The emotion management will act as a predictive filter to deal with the dynamical aspect of emotions highlighted in the Model of emotion:

$$X(n+1) = F_1[X(n)] + F_2[U(n)]$$
$$Y(n) = H[X(n)]$$

Where $X(n)$ is the vector with the (emotional) state of the passenger; $Y(n)$ is the vector with the physiological parameters related with the emotional state of the passenger; $U(n)$ are the aspects of vehicle dynamics affecting the arousal and the valence of the passenger.

Therefore, we need to include to dynamics of the emotions (F_1), the relationship between the arousal and the valence with the physiological signals measured (H), and the relationship between vehicle dynamics and the arousal and valence (F_2) into the equation.

5.2 Emotion Management with the Categorical Model of Emotion

According to the OCC model [18], the emotions are related with goals and are elicited by events, agents and objects. Therefore, as ALFRED will be aware of the goal (the purpose of the trip) and the environment, ALFRED could anticipate the emotions of the passenger and apply strategies of *Situation Selection* and *Situation Modification.* Besides, ALFRED will be aware of the physiological measurements of the passenger, that will allow the system to refine their predictions of emotions and apply strategies of *Attentional Deployment* and *Cognitive Change.*

The responses of ALFRED will be feedback-based (providing feedback to the passenger) with a Machine Learning module to improve the response provided to each passenger of the CAV.

There would be four sources of feedback incorporated in ALFRED:

1. Information provided to the passenger.
2. Driving alternatives to be chosen by passenger.
3. Actions.
4. Modifications of feedback parameters.

The main pieces of information provided to the passenger will be the *state of the traffic* and *warnings and alerts*. The verbosity on the information about state of the traffic will be selected according to passenger preferences and the importance of the trip, and will include the information of changes in the estimation time for arrival. Warning and alerts will encompass information of external events such as accidents, traffic jams or forecasting of strong climate condition (blizzard, hail, etc.) and information of internal events such as breakdowns or malfunctioning of any of the subsystems.

The way the feedback is provided to the passenger will be also modified according to the emotional state of the passenger. In particular, the voice feedback would be modified in intonation and prosody and also, the audio feedback parameters such as volume and type of sound for alert (beeps, rings and alarms).

The driving alternatives to be chosen by the passenger will include, the selection of alternative routes, the selection of driving mode (i.e. sportive or relaxed) and to increase or reduce the safety envelop around the car.

Finally, there are a number of systems that ALFRED can actuate in order to improve the emotional state of the passenger. These actions are: switch on and off the multimedia system, actuate through the air conditioning system, through the communication system and even, safely stop the car.

6 Current Status and Future Steps

Current effort is focused on gather useful data of users to get deeper knowledge about driving and emotions:

1. Data acquisition of physiological signals during natural driving, without disturbing drivers and passengers in a non-obtrusive way.
2. Laboratory tests with driving simulator to assess the impact of different factors of AV in the emotional response of the user.

Along 2020, first results of the Emotional Model will be presented, combining categorical and emotional model.

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Electric Vehicles

Electric Wheel Dual Drive: Functional Integration for e-Vehicle

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Abstract. The EVC1000 project (Electric Vehicle Components for 1000 km daily trips) aims at developing brand-independent components and systems, and demonstrates them through an integrated wheel-centric propulsion architecture and EV (Electric Vehicle) management approach implemented on two different EVs.

The project relies on in-wheel motor and provides new chassis components and integrated controllers. Moreover a compact centralised drive for in-wheel motor axles, based on Silicon Carbide technology, targeting superior levels of functional integration and failsafe operation will be integrated in the EVs.

Keywords: Automotive · Electric vehicle · e-Mobility · In-wheel motor

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1 Introduction

Smart transportation is a key industrial sector for Europe [1] by securing 13.8 million jobs, producing 20% of the vehicle worldwide (out of 98.1 million vehicles produced yearly worldwide), and generating a yearly trade balance over €134 billion.

The automotive domain is currently facing two revolutions at a time: the shift towards electrification and towards autonomous driving. Both revolutions are tightly linked to societal challenges such as clean transportation [2], zero fatalities [3], mobility for an ageing population, as well as to customer needs towards more personalized mobility.

Both revolutions are strongly supported or even enabled by information and communication technologies and consequently result to a shift in the value creation as well as required skills in the automotive domain. New regulations and incentives for e-mobility are published to support this trend [4]; parallel to this, new business models such as car sharing are emerging [5]; connected car [6] is a further important driver in this context. Summarizing, the automotive market is currently being revolutionized and reorganized, electrification and autonomous driving supported by key digital technologies playing a central role.

With falling prices and recent technological advances, the second generation of electric vehicles (EVs) that is now in production makes electromobility an affordable and viable option for more and more people. With the help of strong governmental support (e.g., see Norway [7]), it appears that electromobility is on the verge of major expansion in Europe and the rest of the world. To maintain this EV momentum, the latest edition of ERTRAC's (European Road Transport Research Advisory Council) European Roadmap for Electrification of Road Transport [8] defines four big initiatives outlining the research and development needs. Under the initiative of "user-friendly affordable EV passenger car + infrastructure", the topics include:

- Electric motors, power electronics and charging systems with high impact on powertrain efficiency as well as reduced needs for raw materials and rare earths.
- Energy efficient control of electric vehicle (EV) operation (vehicle, powertrain, passenger comfort, traffic flow, charging and energy management) with high impact on the integration of the EV in the traffic environment.

The EVC1000 project addresses these challenges by developing brand-independent components and systems, and demonstrates them through an integrated wheel-centric propulsion architecture and EV management approach implemented on second generation EVs – from JAC (Anhui Jianghuai Automobile Group Corp., Ltd.) and AUDI respectively. The goals of the EVC1000 components are to match/exceed the ERTRAC efficiency targets for EV2030 + ; to reduce cost by at least 20%; and to increase convenience and comfort of long-range travel.

2 The EVC 1000 Project

At the core of EVC1000 is the in-wheel electric motor architecture because of its advantages in terms of active safety and drivability; and because of its unique benefits of packaging and modularity that will significantly enhance flexibility and adaptability of future EV architectures. For example, "design-for-purpose" vehicles built for dedicated usage models [8] can become reality more easily. At the same time, the EVC1000 participants acknowledge the perceived drawbacks of in-wheel motors – but the recent documented progress in terms of efficiency, durability, scalability and cost-reduction makes in-wheels motors a promising alternative to on-board motors [13–15]. In addition, the fact that two major car makers, AUDI and JAC, are investing resources here is a clear sign of the innovation potential of this technology.

To complement the in-wheel motor technology and exploit their full potential, EVC1000 provides new chassis components and integrated controllers. In particular, an efficient brake-by-wire system and electro-magnetic suspension paired with predictive controllers will be implemented to extend the driving range by up to 10%. What is more, the systems are selected to ensure relaxed, comfortable and safe driving on long journeys.

Despite the high level of integration within EVC1000, full flexibility in the commercialization of the individual components will be retained. This will facilitate the widespread introduction of the EVC1000 outputs on the automotive market in short term, and overcome the limitations of some of the previous integrated electric corner solutions. In summary, the main components/systems developed in EVC1000 (see Fig. 1) are:

- New components for in-wheel powertrains: i) Efficient, scalable, reliable, low-cost and production-ready in-wheel motors suitable for a wide range of torque and power levels; and ii) Compact centralised drive for in-wheel motor axles, based on Silicon Carbide technology, targeting superior levels of functional integration and failsafe operation – so called, eWD^2 (electric wheel dual drive). The designs consider electro-magnetic compatibility aspects, and include prognostics and health monitoring techniques of the electronic components.
- New components for electrified chassis control with in-wheel motors: i) Brake-by-wire system, consisting of front electro-hydraulic brakes and rear electro-mechanical brakes for seamless brake blending, high regeneration capability and enhanced anti-lock braking system performance; and ii) Electro-magnetic and electro-pneumatic suspension actuators, targeting increased comfort and EV efficiency, e.g., through the optimal control of the ride height depending on the driving conditions.
- Controllers for the novel EVC1000 components and new functionalities, exploiting the benefits of functional integration, vehicle connectivity and driving automation for advanced energy management, based on the results of previous projects and initiatives.

EVC1000 will assess the energy efficiency benefits of the new technologies compared to existing EVs. This will include demonstration of long-distance daily trips of up to 1000 km across different Member States with no more than 90 min additional travel time due to charging, and without additional degradation of the components.

3 The Corner Components

EVC1000 relies on dedicated and innovative corner components briefly described below.

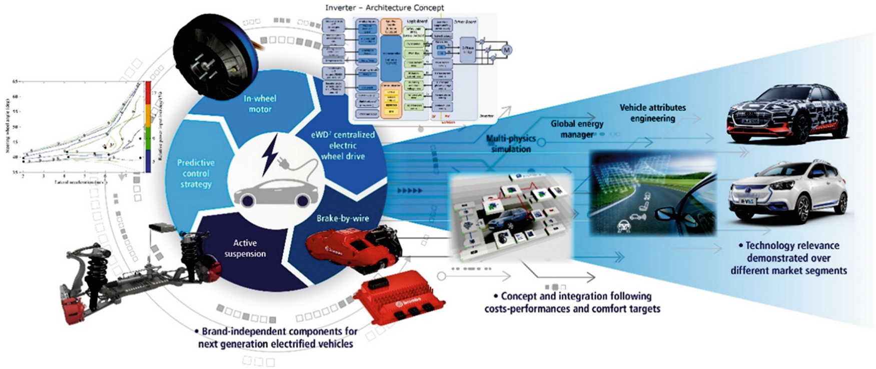


Fig. 1. EVC1000 project at a glance

3.1 Brake-by-Wire Components

The overview of Brembo Brake-by-Wire (BbW) system for EVC-1000 application, through its normally closed (NC) and normally open (NO) valves to switch from BbW mode to hydraulic backup mode, is provided in Fig. 2.

The system consists of the following components:

Brake Control Units - BCU (Fig. 2): Two BCUs, one for each axle, process an external braking request coming from the vehicle control unit and control the braking torque on the corners.

Driver Braking Interface DBI (Fig. 2): The brake pedal is connected to the push-rod which moves the master cylinder.

Corner Components: The four corners are responsible for generating the braking pressure/force in the calipers when requested by the system. In particular, each front corner is composed by Electro-Hydraulic actuators with hydraulic calipers, while each rear corner is composed by an Electro-Mechanical actuator integrated into a sliding caliper together with an EPB (Electrical Parking Brake) device. The rear corners are "dry" corners, as there is no use of brake fluid.

3.2 Advanced Suspensions: Linear Electro-Magnetic and Electro-Hydraulic

A first system will be experimentally assessed on the rear of JAC demonstrator. This will be in parallel to a conventional damper and coil springs. In the front, the compartment central electric motor will be removed together with gear box and inverter. Battery will be added in the space that will be made available. With EM (Electro Magnetic) suspension, Tenneco targets to lower the auto power density spectrum of the body acceleration, which is particularly challenging due to the higher unsprung mass by the in-wheel motors.

The solution proposed by Tenneco is coming from a patented solution (EFS ID: 35170917) claiming an "active damper system actuator arrangement" [9], where a conventional damper is placed in parallel with an electro-magnetic actuator. This could provide the trade-off of hydraulic systems between primary body control (large damping forces) and secondary comfort (low damping forces), by applying in real-time an

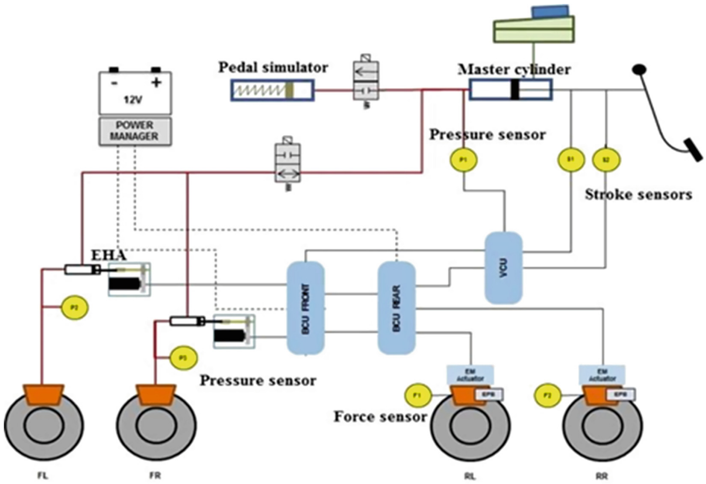
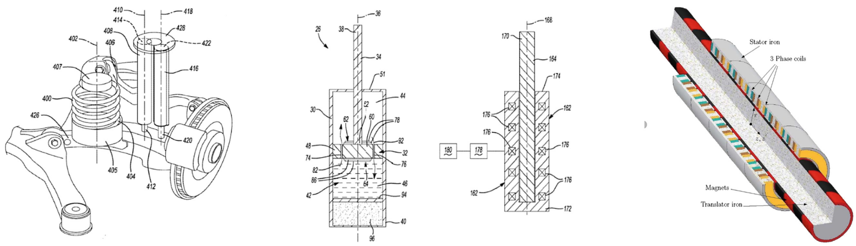


Fig. 2. Scheme of Brembo brake-by-wire system for EVC-1000 application

active force to the piston rod that is independent from the damping force generated by the compression and rebound valving.

The system is illustrated in Fig. 3: (a) the full system with a conventional (passive) and EM dampers in parallel and a coil spring, similar to the rear JAC configuration; (b) the conventional damper with piston assembly (compression/rebound valves) and piston rod and (c, d) the EM actuator with a stator and magnetized slidable armature disposed within the stator. From an electric current input, an electro-magnetic field is generated in the coils that will interact with the armature and create an active force to the body of the vehicle.



(a) (b) (c) (d)

Fig. 3. (a) complete system, (b) conventional damper, (c) and (d) electromagnetic actuator [9]

A second system will be assessed on the Audi E-tron for front and rear. It consists of Tenneco CVSA2 (Continuously Variable Semi-Active generation 2) air dampers connected with hydraulic lines between left and right and controlled via ECU. With this advanced suspension, Tenneco targets to improve handling and energy consumption compared to a full hydraulic active system reference. The generic design is presented in Fig. 4 (left). The complete concept with key elements is presented in Fig. 4 (right). They can be grouped in module with dampers, valve blocks and accumulators, and power pack with tank and pump.

An E /E concept is proposed with a central control unit as the derivation of an existing control unit as well as 4 actuator-related control units, which are interconnected by means of a bus system (CAN or FlexRay). The individual actuators receive the control information via a bus system. There is a central 12- or 48 V power supply. The actuator-related control units are operated with 12 V and the active power electronics with 12 or 48 V. Between the 12 V and the 48 V side, there is a galvanic isolation on the corner modules.

The sensor concept envisages a full sensor concept in the first development stage, consisting of 4 level sensors, 4 wheel acceleration sensors, as well as yaw rate and vertical acceleration in the center of gravity of the vehicle.

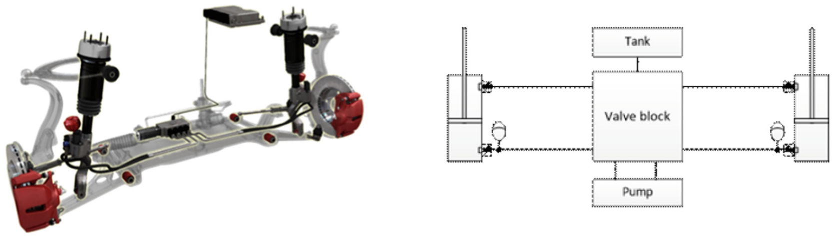


Fig. 4. (left) Generic design for the electro-hydraulic suspension, (right) Electro-hydraulic concept

3.3 e-Axle Components

The e-axle integrates the latest ELAPHE in-wheel motor technology and the eWD^2 provided by I&M, see Fig. 5. The eWD^2 is based on wide band gap switches, perfectly matching the requirements of the proposed in-wheel motors.

In order to accelerate the electric vehicle (EV), the e-axle system employs two electric motors directly coupled with the vehicle wheels to generate torque by converting electric energy into mechanical. The process is reversed during regenerative braking, when energy is recovered with braking torque that decelerates the vehicle.

Total requested torque represents a reference for the propulsion system control and is obtained from the driver over the accelerator and brake pedal positions. The in-wheel propulsion system enables an independent torque control for each driving wheel, whereas distribution of the torque between the driving wheels can be fixed or dynamic. The latter is used in the case of active propulsion systems with yaw control functions (torque vectoring) and/or anti-slip function. Active systems also employ steering wheel data as an additional reference for intended lateral motion from the driver.

The eWD^2 control board is based on latest Infineon 32-bit TriCore™ AURIX™ providing a top level computing performance and offering best in class features in terms of safety. Main microcontroller consists of different cores: two of them are fully dedicated

Fig. 5. e-Axle concept

to the motors control; the remaining cores are available to integrate application dependent control strategies. The EVC1000 E/E architecture has been designed to be flexible enough to guarantee a two steps approach during the development of the application. In the experimental phase, an external rapid prototyping unit is used in order to be faster in application update and tuning. Once the control algorithms will be stable enough the same application software will be synthesized. The resulting source code will be integrated directly on the eWD^2 control board.

3.3.1 L1500 In-Wheel Motor

For EVC1000 an efficiency optimized variation of the L1500 in-wheel motor has been developed. General project constraints are:

- 19-in. rims;
- Nominal Battery voltage 396 V;
- Peek current from the inverter 400 Arms;
- SiC inverter switching frequency will be 50 kHz;
- Two-wheel drive on rear axle.

Within motor design, electromagnetic part of the motor is developed through an extensive optimization process, which is focused to deliver efficient and high torque direct drive, with minimal mass and volume footprint within the wheel integration space.

In the first step electromagnetic design is optimized through genetic algorithms based on semi-analytical approach, which enable extensive number of motor design evaluations and rapid convergence of motor design to within few percent of final performance. Within this phase not only electromagnetic but also NVH (Noise, vibration and harshness), including airborne noise, and thermal motor characteristics are taken into consideration. Also coupling to inverter for system wide performance is accounted for. In the second step, performance of promising designs from the first step is confirmed by more extensive numerical simulations, also fine tuning of the models is done within this phase. In the final step the selected design is fully characterised by detailed numerical simulations.

In addition, coupling to mechanical models for detailed NVH, thermal and structural analysis is performed [16] (Fig. 6).

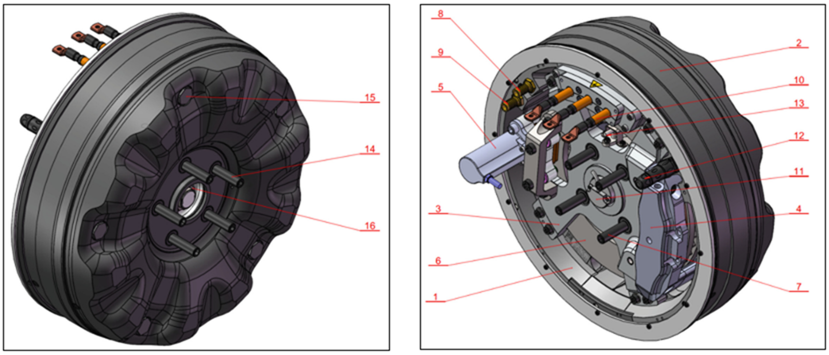


Fig. 6. Front view (left) and rear view (right) of the L1500.

3.3.2 Electric Wheel Dual Drive (EWD^2)

The eWD^2 is a dual inverter developed by Ideas & Motion aimed at integrating functionalities available on two separate inverters into a single unit. Integrating two inverters in the same box helps in sharing hardware resources, facilitating also software development and system control.

The idea is to target those applications where a pair of inverters can be packaged into one in order to bring packaging and functional safety benefits. The two devices need to communicate to synchronize their activity (e.g., in-wheel motors; engine and turbo compound electrification; benches for driveline testing; six-phase motors…).

The eWD^2 has a symmetric structure and the two parts composing it are equivalent: this helps optimizing size and room thanks to the sharing of several hardware components and connections to other parts of propulsion system. Moreover, coordination of the two motors is much easier than having two separate inverters, making this device more suitable for applications where reaction time between the two electric machines is important and safety has to be taken into account.

Total achievable power is 300 kW (peak for 10 s). Wide-bandgap power devices will be evaluated to provide high efficiency, a crucial point for e-mobility requirements. Its control unit is shared between the two inverters and it is able to coordinate the two electric machines connected with a high time resolution (Fig. 7).

The main target applications of the eWD^2 are Electric Vehicles (EV), but it may be adopted as well in Hybrid Electric Vehicle (HEV) or in Plug-in Hybrid Electric Vehicle (PHEV). The drive and management of the two in-wheels motors of an electrified axle has very strict requirements in terms of safety. Indeed, a failure might cause an abrupt change of torque delivered by a single wheel or, in the worst case, a change of its direction. This could lead to a momentum on the yaw angle of the vehicle, making the vehicle instable and complicated to be controlled for the driver. To overcome similar situation, I&M developed the idea of a fail-safe dual inverter.

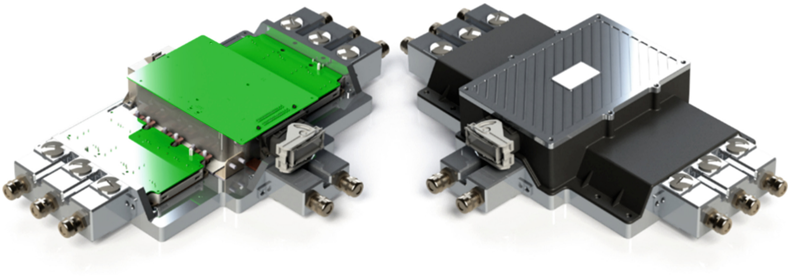


Fig. 7. Electric wheel dual drive

3.3.3 Wheel Slip Control

The wheel slip control (WSC) functions in the target EVC1000 vehicle are realized for a braking mode with the combined use of three different actuators: four in-wheel motors, electro-hydraulic brake-by-wire system actuating front friction brakes, and electro-mechanical brake-by-wire system actuating rear friction brakes. Such a configuration makes possible different brake blending options to be used in WSC including pure regenerative ABS braking, pure friction ABS braking as well as several hybrid variants with regenerative /friction ABS braking.

A general WSC architecture, Fig. 8, consists of several parts as follows. The value of the slip for each wheel for given manoeuvres and road conditions is defined by the reference slip generator. The difference between the reference slip and the actual slip is processed by the wheel slip controller producing the limitation to the traction or braking torque demanded by the driver. For a traction mode, the WSC is working as the traction controller operating in-wheel motors only. For a braking mode, the WSC includes the brake blending controller defining the share of the brake demand to be realized by both electric motors and friction brakes. To compensate undesired difference between the dynamics of wheels and in-wheel motors, the active vibration control functions are also included into the overall architecture. In addition, to calculate vehicle velocity and derive the actual vehicle slip, a corresponding vehicle state estimator is also an inherent WSC part.

The qualitative WSC targets in the EVC1000 project are (i) to ensure smooth tracking of the reference wheel slip, also for severe road conditions, with maximizing the tire friction utilization, (ii) to reduce essentially the vehicle jerk by braking or harsh accelerating, and (iii) to guarantee the control robustness in the presence of uncertainties caused by the road conditions and actuator dynamics. These targets are addressed

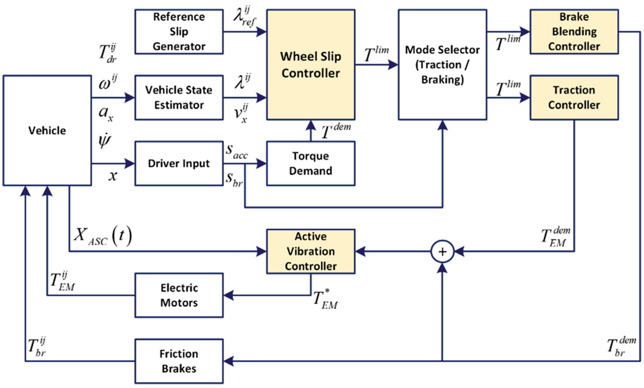


Fig. 8. WSC Architecture (by M. Heydrich, TU Ilmenau)

through the meaningful selection of the control methods. Based on previous studies of the consortium participants, the proposed WSC is being realized as the combination of PI and sliding mode control methods, which demonstrated required performance by applying to the SUV with electro-hydraulic brake-by-wire system [10] and to the AWD vehicle with in-wheel motors [11].

3.3.4 Torque-Vectoring and Active Suspension Control

Within EVC1000, a torque-vectoring controller with the following features will be developed:

- Multi-layer control structure for ease of integration with other controllers, such as: i) the wheel slip controllers for traction and braking, based on the actuation of the in-wheel motors and friction brakes; and ii) advanced drivability controllers, using the in-wheel motors for the compensation of the longitudinal jerk induced by road irregularities
- Generation of a reference yaw rate that allows a safe vehicle cornering response while reducing the power losses in cornering. The off-line reference yaw rate generation process will account for the electric motor power losses as well as the longitudinal and lateral tyre slip power losses
- Variation of the reference yaw rate as a function of the estimated sideslip angle to keep stable cornering response
- Capability of varying the understeer characteristic, i.e., the graph of steering wheel angle as a function of lateral acceleration, depending on the driving mode selected by the user
- Increased yaw and sideslip angle damping in transient conditions, with respect to the same vehicle with even wheel torque distribution
- Seamless integration of torque-vectoring with the stability control function based on the actuation of the friction brakes (commercially known as Electronic Stability Program or Electronic Stability Control)
- Ease of integration with the active suspension system, through a multi-variable control structure to be developed in EVC1000. The suspension controller will vary the front-to-rear anti-roll moment distribution to facilitate the yaw rate tracking control action of the torque-vectoring system

4 Preliminary Simulation Results

The on-board powertrain layouts of the original baseline configurations of the two EVC1000 target vehicles (Audi e-tron and the JAC iEV7) have been modelled with the vehicle simulation software AVL VSM 4™[1]. The vehicle models have been extensively experimentally validated with data from: i) vehicle dynamics tests in steady-state and transient conditions (Fig. 10); and ii) driving cycle tests carried out on a rolling road facility (Fig. 11).

[1] https://www.avl.com/de/web/guest/-/avl-vsm-4-.

The validated simulation models for the two baseline vehicles have been further upgraded to the in-wheel motor driven powertrain proposed by the project. The energy consumption of the upgraded powertrains has been evaluated using the WLTP driving cycle. The results have demonstrated that the upgraded Audi e-tron with in-wheel motors could save up to 12.56% of energy, and the upgraded JAC iEV7 with in-wheel motors could save up to 9.1% of energy.

5 Conclusions

The European project EVC1000 introduces an integrated corner solution featuring in-wheel motor, brake-by-wire and active suspensions. The approach relies on innovations both at component level - electrified chassis components, e-axle – and at system level with the use of advanced control strategies taking advantage of the new controllability of the introduced components. Hence, the in-wheel motors with the dual inverter, the brake-by-wire systems and the active suspensions provide new degree of freedom that can be efficiently combined through advanced and tightly integrated wheel slip control, torque vectoring and active suspension control strategies. Preliminary results already indicate a significant increase of energy efficiency.

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Prediction, One of the Key Points in the Development of Electric Vehicles

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Abstract. With the increasing adoption of electromobility, it has become crucial to balance the consumer demand and offer from electric vehicle charging points. To improve end-users' electromobility experience and access to related services, the NeMO project developed a Hyper-Network of tools and services. As a service, this paper describes the artificial neural network (ANN) models that are built to predict the occupancy statuses of electric vehicle charging points in Barcelona. The models are designed to do both short- and long-term predictions of the next 2 h and next week, respectively, considering the different power levels. We propose to combine similar charging points by behavior with no geolocational information to reduce the computational cost by considering the high number of charging stations in the future.

Keywords: Electric vehicles · Occupancy prediction · Time-series prediction · Clustering · Dimensionality reduction · Urban mobility · End-user services

1 Introduction

A drastic evaluation in the mobility ecosystem has been triggered by technological advancements and societal changes. Alongside other mobility-related trends such as autonomous driving and shared mobility, electric mobility is also gaining momentum and attention [1]. Electric vehicles deserve a significant amount of attention since they will help cities to reduce emission levels, air pollution, noise and dependence on oil. Although the electric vehicles have received attention, and have been used for a while, the cities are not well prepared to balance the demand and offer, or provide advanced services and tools.

To tackle the described problems, NeMO [2] as an EU Horizon 2020 project funded by European Commission provides a fully open ecosystem allowing a continuous and uninterrupted provision of electromobility data and services. The aim was to extend the range of current electric vehicles by creating an umbrella ecosystem that would unify the access to versatile charging networks and ancillary services and would extend the horizon of charging and mobility serviceability for electric vehicle users seamlessly and transparently. As one of the provided services in the project, the short- and long-term

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occupancy status (i.e. occupied, free) predictions of electric vehicle charging points in the city of Barcelona are done considering also the different power levels (i.e. fast, slow).

In order to have accurate predictive models, understanding the problem and dataset itself is quite important. Considering the fact that the charging points are in different locations and their temporal behaviors can be affected by many factors. Thus, one model for each charging point can be built. However, the computational cost that will be born is complex to deal with. On the other hand, the increasing number of charging points will bring more complexity in the future. For these reasons, we propose to cluster charging points based on their temporal behaviors without including any geolocational information after a dimensional reduction step. Then, with the reduced complexity, there is one model for each cluster.

With using the advantage of reduced cost, the prediction of occupancy statuses for both slow and fast charging points are done using the sequential nature of ANN [3] including both short- and long-term predictions for next 2 h and next week, respectively. Exogenous variables are also added into modelling to increase the explanatory power of the model. The model parameters are tuned by having error and trials. Then, the performance of models is calculated using MAE (Mean Absolute Error).

The paper is organized as follows: In Sect. 2, there is a brief overview of related projects. The underlying problems and their definition of the study are presented in Sect. 3. The practical experiment of the prediction model is explained and detailed in Sect. 4. Finally, in Sect. 5, we conclude the outcomes of our study and discuss the possible future improvements.

2 Related Work

Each charging point usage can be affected and shaped by different kind of variables. It is quite complex to define all of these variables and deal with them in a model. Without identifying these variables, one can use one specific model for each individual charging point. However, this is not reasonable considering high computational cost including the fact that the increased number of charging points in the future. Thus, some studies gave more attention to the clustering algorithms that are unsupervised learning methods to discover unknown dataset patterns by separating the dataset into subgroups. Clustering methods and electric charging points came together in different studies and different problem scopes. Some of them focused on the optimal placement of the charging stations, and used coordinated cluster algorithms [4], whereas the others attempted to solve the same problem with clustering the charging station demand locations [5]. On the other hand, some studies focused on only categorizing the charging stations based on their usage purposes (home, work, or other) [6]. As the next step, more advanced clustering algorithms are chosen to have better results for similar goals from different domains. For instance, there is a study that presents a clustering-based strategy to identify typical daily electrical usage profiles of multiple buildings, used a GMM (Gaussian Mixture Model) based clustering to identify the profiles of each individual building [7].

Some other studies bring clustering and multi-step-ahead prediction methods in order to reduce the computational cost and having fewer models where one model is applied to one cluster. For short-term load forecasting in smart grids, a combined CNN

(Convolutional Neural Network) and K-means clustering approaches are combined in such a way that the dataset is clustered into subsets, and then the obtained subsets are used to train the CNN model [8]. Additionally, some other ANN models are built to forecast the next day charging demand [9].

In our work, we introduce twofold contribution where we do clustering on reduced dimensions, and then, built ANN predictive models for each cluster considering the different level of charging points' powers.

3 Problem Definition

Based on the dataset, the occupancy forecasting model predicts the future occupancy status (i.e. occupied (1), free (0)) of the electric vehicle charging points in Barcelona considering also their different power levels (i.e. fast, slow). Before getting into more detail, let us define the concepts and problems.

3.1 Charging Points Session Data

The dataset R comprised of charging point, type, plug-in and plug-out records without any user-related information.

$$r = (P, d, \tau_s, \tau_e)$$

where r represents each individual record in the dataset R, P is for the charging point ID where N represents the total number of charging points, d is for the type of the charging point (slow or fast), τ_s and τ_e represent plug-in (start) and plug-out (end) DateTime, respectively. The binary occupancy status λ for all N charging points is produced (1: occupied, 0: free) based on each record's τ_s and τ_e. The dataset is divided into two sets based on the charging point type d. In other words, one dataset is for the fast charging points, whereas the other one is for the slow charging points.

We group the charging operations into 10 min bins by average to observe if the charging point was occupied in that 10 min (1: occupied, 0: free). Since we take the average of the values of 0 and 1, the average as the outcome ranges between 0 and 1. As a result, for each charging point, the process creates 1008 variables $\left[6(1\ hour) \times 24(1\ day) \times 7(1\ week)\right]$.

3.2 Dimensionality Reduction

In order to have a high-level pattern detection for the distributions that are further to be used for dimensionality reduction algorithm, we re-bin the 10 min bins by average into a predefined 3 h (b). As a result, the number of variables for each charging point P will be reduced from 1008 to 56 $\left[8(1\ day) \times 7(1\ week)\right]$(Fig. 1).

To be ready for clustering, the principal components will be detected by PCA (Principal Component Analysis). With PCA, we are able to understand the relationships between each variable, avoid the danger of overfitting the model to the data, and handle "curse of dimensionality". The purpose of reducing the dimension of the feature space

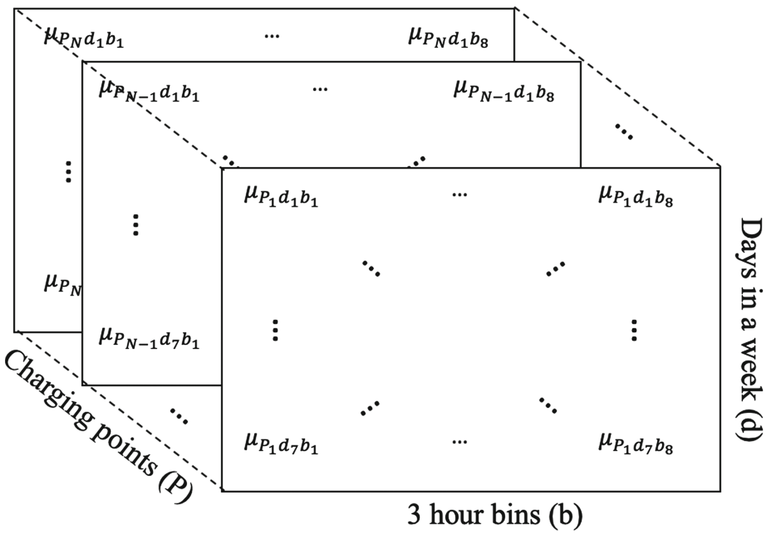

Fig. 1. Charging points' average usage representation

is to have fewer relationships between variables to consider and avoid overfitting. With PCA application on a standardized dataset, a matrix that summarizes how the variables all relate to one another will be calculated. Then, this matrix will be broken into two separate components to see how important each direction is: (1) direction, (2) magnitude. The data will be transformed to align the important observed directions that are combinations of original variables. The less important directions will be dropped so data projection into a smaller space will be done, whereas the most important components by considering the cumulative variability will be chosen as the number of principal components. The PCA will be applied to both datasets (slow and fast charging points).

3.3 Clustering: Characteristics of Charging Points' Usages

Since each charging point station is located to a different place in the city, they carry different usage characteristics hence different usage distributions. Having one prediction model for the whole dataset is not realistic in this case to provide meaningful results and satisfying accuracies, and the increasing number of charging points are considered for future implementations. On the other hand, having a different model for each charging point in the city rises the computational cost.

Thus, we cluster both datasets (slow and fast) for the charging points based on their usage distributions, and the observed clusters are used for predictions. The (GMMs) [10] are chosen as the method since the GMMs assume that there are a certain number of Gaussian probability distributions, and each of these distributions represents a cluster. Hence, a GMM tends to group the data points belonging to a single distribution together. Each of these distributions has a certain mean and variance values. The GMM identifies the probability of each data point belonging to each of these distributions.

We apply the GMM based clustering to the output of PCA analysis (principal components) to cluster the charging points based on temporal patterns of average occupancy over a standard week period from Monday to Sunday. The observed clustering results are applied to the previous datasets that contain 10 min bins.

3.4 Occupancy Status Prediction

In this work, we harness the sequential nature of neural networks for occupancy status prediction for the charging points. We study both short-term (next 2 h) and long-term (next week) predictions for both slow and fast charging points datasets using Keras [11] that is a tool for constructing an ANN. In both predictions, we create the sequential models, use 1 hidden layer and fully connected (dense) structure. The 10 min bins nature is used for the predictions: (1) each bin is used for short term prediction, (2) each 6 bins is used by taking the average for long term prediction.

The output neurons are the predicted occupancy status (1: occupied, 0: free) for the charging points. The results evaluation is based on the MAE [12],

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|y_i - x_i|$$

where N is the number of absolute errors $|y_i - x_i|$, y_i denotes the prediction and x_i the real value.

The multi-step occupancy status prediction $\lambda_i(t-n+1), \ldots, \lambda_i(t)$ for the past n intervals, the purpose is to predict the future occupancy statuses $\lambda_i(t+1), \ldots, \lambda_i(t+m)$ for each station C_i in the next m time intervals.

4 Experimental Evaluation

Our study is based on the dataset that is provided by Barcelona City Council (Ajuntament de Barcelona) [13]. The original dataset consists of both slow and fast charging points with 31535 records in total with plug-ins and plug-outs recorded at 45 charging points over the period between September 11th, 2017 and March 30th, 2018. Each plug-in and plug-out event is recorded with the related charging point ID, type (slow or fast), and DateTime. Since the data provision from the API (Application Program Interface) is for every 10 min, the data is binned into 10 min by taking the average of the occupancy statuses. Later the dataset is subsetted based on the power of charging points, and all charging points are labeled as "slow" (27 charging points) or "fast" (18 charging points). In order to have a high-level pattern detection, the 10 min bins are re-binned into 3 h and the PCA is applied for dimensionality reduction. The results of PCA is used for GMM based clustering. Then, the cluster results are applied to the previous datasets (both for slow and fast charging points) that hold 10 min bins. In the end, 3 clusters are observed for slow charging points, whereas 4 clusters are observed for fast charging points (Fig. 2).

For each dataset (slow and fast charging points), and each observed cluster, one ANN model is built. Thus, the model configurations differ for each cluster. As an addition to

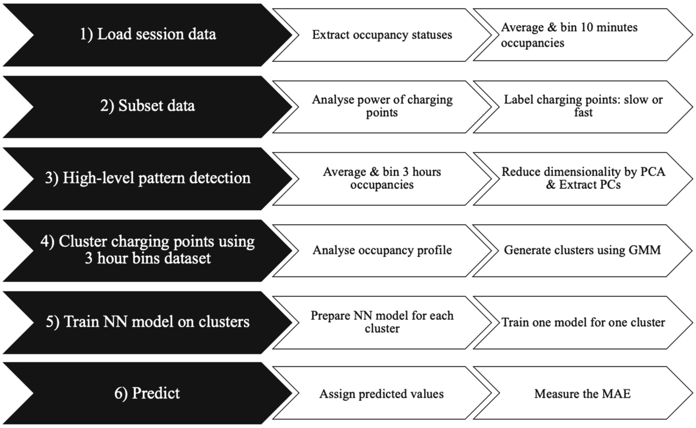

Fig. 2. Workflow of the study

the time-series, the days of a week and hours of a day are one-hot encoded and added into the models as exogenous variables. After the predictions are made, for both slow and fast charging point datasets, from all clusters, the MAE are observed.

4.1 Short-Term Occupancy Status Prediction

The GMM based clustering after the dimensionality reduction step gave 3 clusters for the slow charging points (C1: 9 charging points, C2: 10 charging points, C3: 8 charging points), whereas it gave 4 clusters for the fast ones (C1: 11 charging points, C2: 4 charging points, C3: 1 charging point, C4: 2 charging points). The slow charging points' clusters have well balanced numbers of charging points. On the other hand, we see that some of the fast charging points' clusters have only a few charging points. This is not the concern here since in the future there will be more charging points.

The 10 min intervals are used for short-term occupancy status predictions. Exogenous variables for the days of week and hours of the day are added into the model. The input sequences composed of n = {1, 7, 13} past and m = 12 future 10 min interval. Notice that 12 steps equal to 2 h and we formulated the input sequences before by $\lambda_i(t - n + 1), \ldots, \lambda_i(t)$. Then, the datasets are randomly split into training (70%) and test (30%). The performance of the models is measured using MAE.

The ANN model hyper-parameters are tuned manually by trial and error. The number of neurons in the hidden layer is defined as {10, 20}. The batch size is 32, whereas the number of epochs is 40. As the loss function, the binary cross entropy, as the activation function Sigmoid, and as the optimizer ADAM [14] is chosen to be used.

For the short-term occupancy status prediction of slow charging points, the lowest MAE errors for all three clusters are captured using 10 neurons in the hidden layer and going back only one-time step back (10 min) in the sequence.

In Fig. 3, the best ones from Table 1 are represented. The MAE errors increase over time as they expected. One of the important results here is that the 3rd cluster (C3) has the lowest error that is far from the other cluster errors. The reason can be the fact that

Table 1. Short term prediction errors for slow charging points

Input (n)	Hidden layer	C1	C2	C3
1	10	**0.1858**	**0.1084**	**0.0339**
1	20	0.2732	0.2083	0.1352
7	10	0.2600	0.2037	0.1361
7	20	0.2541	0.2054	0.1392
13	10	0.2441	0.1921	0.1290
13	20	0.2444	0.1942	0.1359

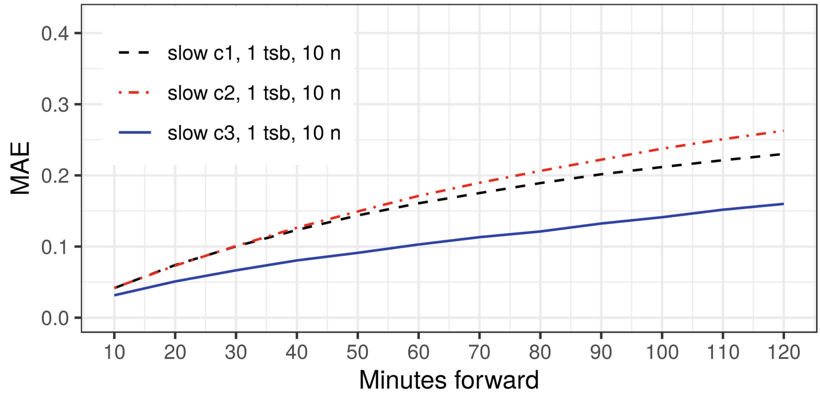

Fig. 3. Cluster-wise MAE errors of next 2 h (short-term) prediction for slow charging points

the GMM based clustering locate the charging points that have similar behavior. This behavior also includes similar statuses over time. In other words, these charging points can be the ones that are usually occupied, or usually free. Thus, we introduce an average overall MAE for the predictions. This average value is calculated with the best results (lowest errors) from each cluster. In this case, it is 0.10937. Since the value range differs from 0 to 1, the observed results can be interpreted as a percentage as well, so the average error is 10.937%.

For the short-term occupancy status prediction of fast charging points, the lowest MAE errors for all four clusters are captured using different configurations. Cluster 1 (C1) and Cluster 2 (C2) received the lowest errors using 10 neurons in the hidden layer and going one-step back in the sequence, whereas Cluster 3 (C3) and Cluster 4 (C4) received the lowest errors using 10 neurons in the hidden layer but going 13 steps back (120 min) in the sequence.

In Fig. 4, the best ones from Table 2 are represented. The MAE errors increase over time as it expected. The average error comes from the best tuned models for each cluster is 28.96%.

Table 2. Short term prediction errors for fast charging points

Input (n)	Hidden layer	C1	C2	C3	C4
1	10	**0.1618**	**0.3010**	0.4246	0.3573
1	20	0.2083	0.3416	0.4231	0.3559
7	10	0.1917	0.3178	0.4024	0.3346
7	20	0.1937	0.3211	0.4090	0.3406
13	10	0.1794	0.3091	**0.3821**	**0.3138**
13	20	0.1862	0.3145	0.3925	0.3293

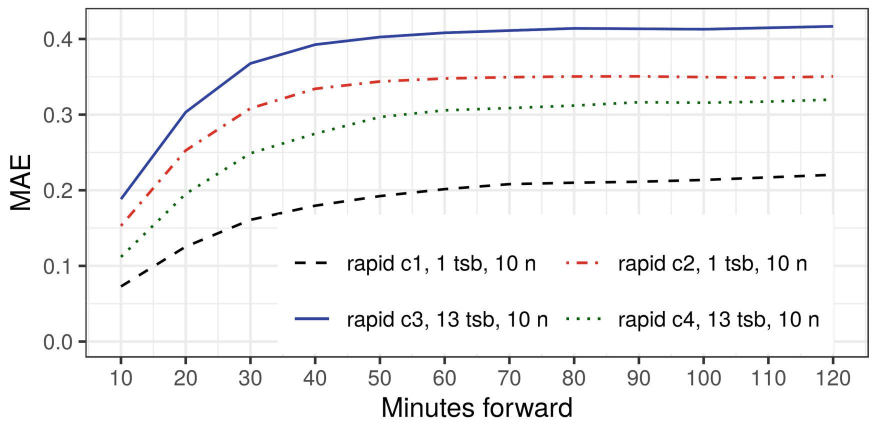

Fig. 4. Cluster-wise MAE errors of next 2 h (short-term) prediction for fast charging points

4.2 Long-Term Occupancy Status Prediction

The GMM clusters that are applied for the short-term prediction are used also for the long-term occupancy status predictions.

The 10 min intervals are re-binned into 1 h (6 bins) by average to be used for the long-term occupancy status predictions. Exogenous variables for the days of week and hours of the day are added into the model. The input sequences composed of n = {1, 25, 169} past and m = 168 future 1 h interval. Notice that 168 steps equal to 1-week and we formulated the input sequences before by $\lambda_i(t-n+1), \ldots, \lambda_i(t)$. Then, the datasets are randomly split into training (70%) and test (30%). The performance of the models is measured using MAE.

The ANN model parameters are tuned manually by trial and error. The number of neurons in the hidden layer is defined as {20, 70, 120}. The batch size is 32, whereas the number of epochs is 50. As the loss function, the binary cross entropy, as the activation function Sigmoid, and as the optimizer, ADAM is chosen to be used.

For the long-term occupancy status prediction of slow charging points, the lowest MAE errors for all three clusters are captured using different configurations. Cluster 1 (C1) received the lowest error by having 70 neurons in the hidden layer and going 1-week

Table 3. Long-term prediction errors for slow charging points

Input (n)	Hidden layer	C1	C2	C3
1	20	0.2176	0.0795	0.0132
1	70	0.2152	0.0793	0.0134
1	120	0.2158	**0.0789**	0.0134
25	20	0.2112	0.0818	0.0126
25	70	0.2082	0.0813	0.0122
25	120	0.2080	0.0818	0.0131
169	20	0.2094	0.0845	0.0117
169	70	**0.1960**	0.0831	0.0115
169	120	0.1974	0.0839	**0.0111**

in the past (168 h); Cluster 2 (C2) received the lowest error by having 120 neurons in the hidden layer and going only one-step back; Cluster 3 (C3) received the lowest error by having 120 neurons in the hidden layer and going 1-week in the past. Here, again we see that the error in Cluster 3 (C3) is the lowest.

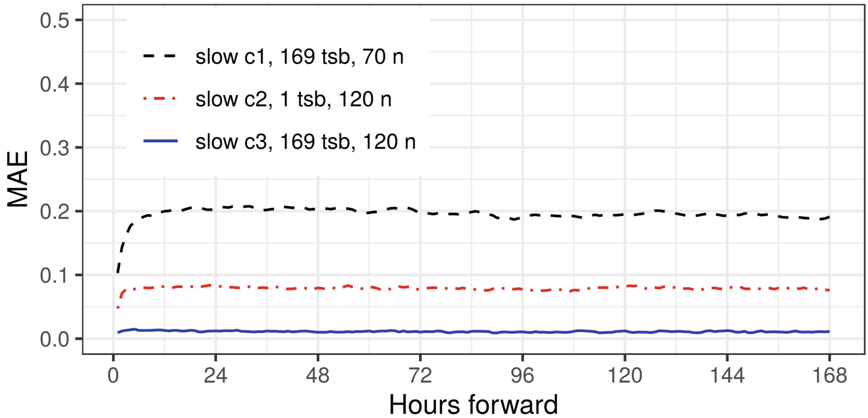

Fig. 5. Cluster-wise MAE error of next week (long-term) prediction for slow charging points

In Fig. 5, the best ones from Table 3 are represented. The average error comes from the best tuned models for each cluster is 9.53%.

For the long-term occupancy status prediction of fast charging points, the lowest MAE errors for all four clusters are captured using different configurations. Cluster 1 (C1), Cluster 2 (C2) and Cluster 3 (C3) received the lowest errors by having 130 neurons in the hidden layer and going 1-week back in the sequence, whereas Cluster 4 (C4) received the lowest error by having 70 neurons in the hidden layer and going 1-week back in the sequence.

Table 4. Long-term prediction errors for fast charging points

Input (n)	Hidden layer	C1	C2	C3	C4
1	20	0.1089	0.2000	0.2811	0.1851
1	70	0.1075	0.1979	0.2763	0.1837
1	120	0.1081	0.1984	0.2755	0.1846
24	20	0.1080	0.1973	0.2796	0.1672
24	70	0.1071	0.1955	0.2746	0.1668
24	120	0.1060	0.1956	0.2737	0.1665
168	20	0.1074	0.1991	0.2767	0.1561
168	70	0.1056	0.1924	0.2710	**0.1467**
168	120	**0.1049**	**0.1909**	**0.2694**	0.1473

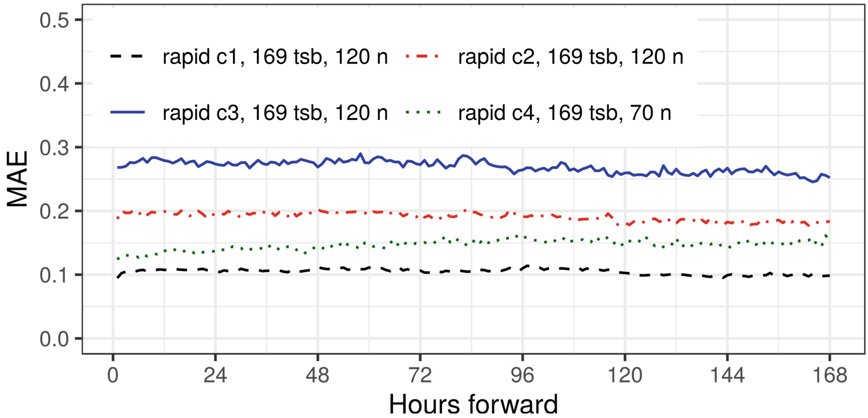

Fig. 6. Cluster-wise MAE errors of next week (long-term) prediction for fast charging points

In Fig. 6, the best ones from Table 4 are represented. The average errors come from the best tuned models for each cluster is 17.8%.

5 Conclusion and Future Work

Predicting the future occupancy statuses of the charging points using multi-steps from past for both short- and long-term considering different level of power of the charging points is important by the consumer and provider side. The prediction models can be productized into a user-end service such as a mobile phone application to show the predicted availability of the charging points in the near future to the users (2 h, etc.). The provider side will take advantage of knowing the occupancy statuses of the electric vehicle charging points in the near (2 h) or far future (1 week). Thus, this will allow the operator of the charging points to have more accurate planning to balance the demand and the offer. Furthermore, they will be able to investigate the need for increasing the number of charging points through the occupancy statuses. We showed that the electric vehicle charging points can be clustered based on their temporal behavior without including any geolocational data. The clusters give us the advantage of having only one model for each cluster, so the computational cost is reduced significantly. In the time to come, when there are more charging points, the algorithms will be run again to re-cluster them. We also presented the fact that the occupancy status prediction for the fast charging points is less accurate than the slow ones both in short- and long-term. For the future work, we plan to have different configurations to improve the models and improve the modelling in such a way that it will be able to capture the fast and slow charging points in training without defining them at the beginning in different datasets.

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Eco-Routing Android Application to Promote the Usage of Light Electric Vehicles in Urban Environments Within the Framework of the STEVE European Project

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Abstract. Nowadays, the high level of atmosphere pollution strongly influenced by industry and transportation is one of the most relevant social problems. In order to reduce the amount of pollutant discharged into the atmosphere, some technological breakthroughs have been developed in vehicle electrification area. The main objective of the European project STEVE is to introduce Electrified L-category Vehicles in urban transport systems. However, the main drawback is their limited driving range thus, optimal energy management systems are crucial here. In this paper the newly developed Eco-navigation Android application, which generates the most optimal route based on speed and elevation profiles for use in e-bikes, will be presented. The Eco-routing app is going to be implemented in Calvià (Mallorca, Spain) during 2020.

Keywords: Electric vehicle · Android application · Eco-routing · Eco-driving · Gamification

1 Introduction

Currently, the high level of pollution in the atmosphere, mainly generated by the industry and transport in large urban areas, is an outstanding problem. Some technological advances have been developed in vehicle electrification area, which have managed to reduce the amount of pollutants discharged into the atmosphere [1].

The limited driving range is the main technical constraint to the widespread adoption of EV (electric vehicles). EV manufacturers and research institutions are intensively addressing this issue, being mainly focused on the enhancement of battery technologies [2] and the systematic introduction of superfast charging stations on the road network [3]. In addition, the driving range increase is supported by the progressive enhancement of energy efficiency of electric powertrain components and the performance improvement allowed by predictive energy management and optimal speed profiling [4].

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On the other hand, thanks to all the traffic condition information nowadays accessible, energy efficient routing optimization has become a crucial research topic. It has also a high impact in the energy consumption [5]. Furthermore, in [6] it is concluded that the driving style of the driver has a great impact on the energy consumption, getting energy consumption prediction with a mean relative error of 6.8%.

As a solution, the European project STEVE, intends to introduce EL-Vs (Electrified L-category Vehicles) in urban transport systems, with the aim of sensitize citizens to the use of electric vehicles. For this purpose, an Eco-navigation application (hereinafter SAMAY) has been developed. This application generates the most energetically optimal route based on speed and elevation profiles. SAMAY is going to be used in the island of Mallorca during 2020.

The rest of this paper is organized as follows. The framework of the paper is presented in Sect. 2. The description of the application is designed in Sect. 3. The application operation phase is provided in Sect. 4, followed by the conclusive remarks.

2 Framework: STEVE

In order to sensitize citizens to the use of electric vehicles and giving a system solution to future mobility, the European project STEVE (http://www.steve-project.eu/index.php/en/) is being carried out with the main objective to introduce EL-Vs in urban transport systems. In addition, it should implement new energy-efficiency and customer-oriented services for EL-Vs moving from the concept of owning something to the use of services (eMaaS – electric Mobility as a Service), and demonstrate the wide range of EL-Vs typologies and analyse the operation of EL-Vs in real scenarios.

STEVE brings together cities, industrial companies, small and medium enterprises, and academic institutions from seven European countries, for the demonstration of the integration of EL-Vs in different European cities - called pilot sites - as shown in Fig. 1, where the system will be operated in real life traffic conditions.

Fig. 1. Pilot sites in Austria, Italy and Spain

This paper is focused on the use case of Calvià. The implementation of the demonstration activities in the City of Calvià is mainly focused on the use of 2-wheeled EL-Vs in the tourism sector with the aim of encouraging eco-friendly tourism-related transport and business.

The Calvià use-case differs from the other pilots as it does not involve STEVE vehicles but rely on EL-Vs already available in the region and developed SAMAY application. Therewith, the focus will be mainly placed on e-bikes from rent-a-bike companies. Thus, Calvià's demonstration is going to focus on urban population such as daily commuters, tourists, and municipality workers.

This case will be using three types of e-bikes (mountain bike, racing bike and urban bike) of the different e-bike rentals in the municipality with the purpose of achieving a wider impact of the project.

3 SAMAY Android Application

The proposed application is an Eco-routing navigation application, which generates an energetically optimal route based on speed and elevation profile and the analysis of driver behaviour. The app provides a navigation screen where the route selected, the SoC (State of Charge) of the battery and actual vehicle speed and the optimal speed are shown. During the route, if there is not enough battery to complete the route, the app automatically adds a stop in a charging station.

In this application, different agents take part, as shown in Fig. 2 - an eBike, HERE routing services, SAMAY application and a database.

Fig. 2. General diagram

The eBike is the EL-Vs type used in the use case of Calvià. HERE routing API (application programming interface) [7] is going to be used to obtain a route, introducing the route's waypoints information into the application. SAMAY will collect data from

HERE and the eBike to make the eco-navigation possible. Finally, all the data will be collected in a database for a future analysis. When the user logs in, the first name, last name, date of birth, email of the user, gender and registration password will be saved at the Tecnalia server. In addition, when the user configures the parameter to make a new route, information such as the age of the user and the selected route sections, will be required. When the navigation has finished and the route completed, the recommended speed specifications and the speed that the user applied, will be saved in the backend.

SAMAY's main features are: 1) Login, 2) Create a route, 3) Navigation, 4) Gamification and Navigation statistics and 5) Acquired data. The following sections will describe each feature in a separate manner.

Log In

When a new user starts, the first step in the app is a log-in-screen. Then, the two options appear to create a user account or try to the application's trial option.

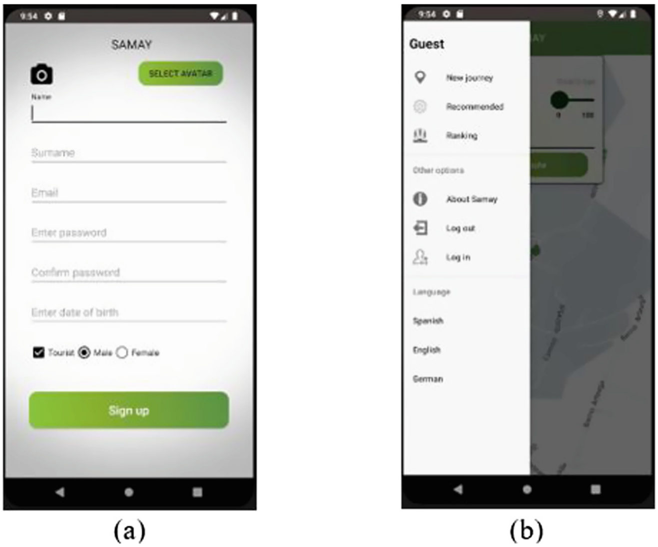

Fig. 3. Different log in options

In the case of the first option (see Fig. 3a), the application requires personal information about the user. In addition, a difference between controlled users or not controlled users can be made thus, in case of being a not controlled user; user must tick the tourist option box. If the user chooses the trial option, no personal information will be asked (Fig. 3b). In that case, to create a route the user must insert the information about the age and the weight.

Depending on which kind of login the user chooses, the main menu will appear in a different style. If the user registered, the application will show the full menu allowing him/her to make a new route or see all the previous results, such as statistics, global rankings or awards. If the user chooses the trial option, the main menu will look differently, allowing the user to choose between a new route, a recommended route and visualization of the global ranking, only.

Create a Route

Once the registration process is completed, the user will be able to make a new route. If this option is selected the user must insert some additional information such as destination address, type of vehicle and the actual vehicle's battery level. HERE API will then create the most energetically optimal route based on selected parameters.

Alternatively, one will be able to choose between three different predefined routes, which are saved and available via data server.

Navigation

Before the route navigation starts, the application processes two intermediate operations. The first one is to save the description of the route with all the route sections, and the second action is to calculate whether it is possible to reach the destination with the actual battery charge.

When the route navigation starts, the co-called efficient driving assistant appears – the navigation screen, similar to ones available on the market. The screen allows the user to select the preferred destination and provides a desired route on a map. Likewise, while the user is on the way and cycling, the map on a display will be steadily updated depending on the current location.

The energy-efficient driving assistance system is based on the development of a speed profile. This indicates to the driver the most suitable speed, considering safety and the energy consumption. Since predicting how familiar users are with EL-Vs is quite difficult, some recommendations can be given to them on their driving behaviour. Recommending an optimal speed, make users aware on how to save energy or regenerate energy when braking, only in the case that the vehicle has regenerative braking.

In Fig. 4 the speed indicator with its representation of green zones for the indication of optimal speed range, is shown. In accordance with the energy consumption during the route, the battery indicator will be steadily modified. In addition, during the route, the remaining distance is reflected on a progress bar. With the aim of stopping the route, a stop button has been added, as well.

During the route, if there is not enough battery to reach the final point of the route, the app will suggest the user to deviate from the route and the app adds automatically the nearest charging point (Fig. 5). This feature allows users to be informed about the planning of the route and enables an estimate of the exact travel time. Since in Mallorca no specific charging points for e-bikes exist, the Municipality of Calvià is currently looking for options to facilitate the uptake of this kind of mobility in the Municipality.

Gamification and Navigation Statistics

Since one of the main objectives of the application is to rise citizen's awareness of electric mobility and to promote a greater use, the Eco-routing app has two different functionalities.

The first one is a so-called Gamification approach. This functionality is for registered users, who can see and study their results (statistics and awards) when the route is

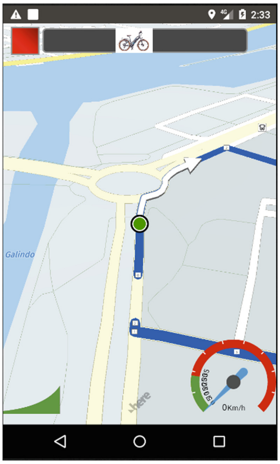

Fig. 4. Navigation screen

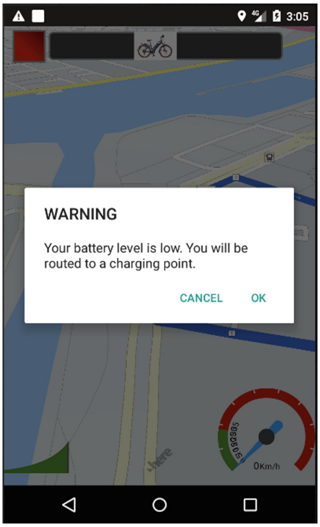

Fig. 5. Efficient driving assistance system suggestion

finished, as showed in Fig. 6a. The gamification consists of three main elements: a) ranking where every user sees the score and an overall position with respect to other users (Fig. 6b), b) the awards screen (Fig. 6c), and c) the statistics screen of all the routes made (Fig. 6d).

The second functionality is a survey for proving the acceptance level of the end-user regarding Eco-routing application. Furthermore, the survey should collect user's opinion on whether the application encourages and supports the usage of EL-Vs in urban areas. This information will be required with the following questions:

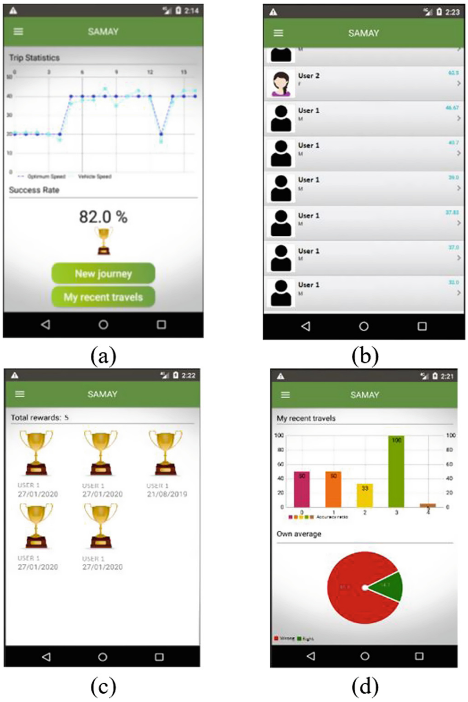

Fig. 6. Gamification screen

- Would you recommend the SAMAY app?
- Did you find the SAMAY app useful?
- How satisfied are you with the SAMAY app?

4 SAMAY Operation Phases

During the operation phase of the app, one can distinguish between three phases. As shown in Fig. 7, first phase is called "Ready phase" and is one month long. The second phase is the "Running SAMAY" and is six-month long whit the main objective to validate the application and to get additional feedback from users in order to eliminate possible failures of SAMAY. The last phase is called "Analysing data" and is responsible for the analysis of the collected data.

Fig. 7. Operation phases

Participants of this Operation phase are divided in two groups. The first group will be comprised of controlled users, i.e. ones who have participated directly or indirectly in the project itself. For instance, project partners with specific tasks or rental bikes companies count as controlled users. The second group consists of "not controlled users" as for instance, tourist or daily commuters.

Within the project duration, different kind of data will be generated. This information, after being post processed will be shared with the project partners. During this phase, the application uses a backend service to save all the information collected from the app. Data can be divided in two different groups: measurements and subjective data. Measurement data will be the user's data, collected from the registration feature, i.e. information such as users age, gender, etc. In addition, applications measurement data will be including in the first group, i.e. SAMAY will collect technical information like vehicles battery SoC, optimal speed and current speed during the navigation, etc. On the other hand, participants' acceptance of the Eco-navigation application is assessed after the navigation. Subsequently, by evaluating the survey, the users' acceptance will be analysed.

With the collected data, the main questions STEVE project wants to answer are divided in three categories. The first category encompasses environment analysing whether given solutions decrease ICE vehicles fuel consumption also CO2 emissions. The second category encompasses mobility and analyses if have had any impact on traffic flows and travel times. The third category encompasses driver behaviour analysing how STEVE can change the behaviour and perception of drivers into an eco-friendlier driving style. For that purpose, a set of indicators divided into the three different categories can be set as:

- ENVIRONMENT
  - Total energy consumption of the system
  - Energy consumption per passenger km
  - CO2 emissions saved
- MOBILITY
  - Number of uses per user
  - Total number of gamification users
  - Share of tourist of the total users
- DRIVER BEHAVIOUR
  - Changes in road capacity and traffic flow
  - Number of EL-Vs available for sharing per 100.000 inhabitants
  - Gamification change in driving behaviour over time

5 Conclusion

In this paper, functionalities of the SAMAY Eco-navigation application has been introduced. The aim of SAMAY is to sensitize citizens to the use electric vehicles in everyday life. The application has been developed within the European project STEVE whose demonstration will involve well-defined target groups in four European cities called pilot sites. This paper has been focused on the use-case in the municipality of Calvià where SAMAY is going to be used along with eBikes during the next two years.

Meanwhile, collected data will be analysed to learn whether the Eco-navigation application has sensitised users for the use of EL-Vs, already. With that purpose, indicators like number of application users and number of actions per person are going to be analysed.

The main expected results are an increase on the use of e-vehicles for promoting sustainable mobility and tourism. In addition, thanks to the analysis of electric vehicles in the city, the pilot will enable the implementation of an efficient and flexible network of charging stations, within the Calvià territory.

Four main results are expected from the pilot:

1) Positive impact on environment through reduction of CO2 and number of vehicles transiting in the natural areas of the region,
2) Increase of user acceptance on EL-Vs and improvement in driving behaviors,
3) Promotion of smart and sustainable mobility through improvement of its associated infrastructure, and
4) Improvement of road safety through smart integration of EL-Vs within the Calvià transport system.

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A Robust and Ultra-Fast Short Circuit Detection in Half-Bridge Using Stray Voltage Capture: Applied in Electromagnetic Suspension

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Abstract. The paper proposes a robust and ultra-fast short circuit detection method based on the voltage dip in the half-bridge due to the presence of stray inductance. For the application of the inverter in electromagnetic suspension, the short circuit is detected in less than 100 ns, which is a promising solution against the Fault Under Load due to a Single-Event Burnout failure type.

Keywords: Single-Event Burnout · Fault Under Load · Half bridge · Stray Voltage Capture · Stray inductance

1 Introduction

In recent years, there has been a growing concern about vehicle road comfort and safety. On the suspension level, these requirements translate to the usage of electromagnetic (EM) suspension, as it can respond to the road condition quickly. However, the inverter used in the EM suspension poses a problem, namely the possible failure of the power switches [1]. One of the most probable failure types that can happen in the system is a short circuit in one of the converter's Half-Bridges (HB), which is illustrated in Fig. 1. It is necessary to have a robust and fast short circuit detection to prevent further damage and fault propagation in the system. In literature, some short circuit detection schemes such as desaturation circuit, current sensing, *di/dt*, and gate voltage sensing have been proposed [2]. Among these schemes, the desaturation circuit is the most widely used solution, as it is easy to implement and uses a voltage measurement, which does not insert any resistive or inductive component in the power loop. However, this circuit needs a certain blanking time to avoid a false alarm, which slows down the detection time [3]. In addition, this circuit is not very robust as the performance depends on the saturation voltage characteristic of the switch, which varies according to the junction temperature [4].

This paper proposes a method for robust and ultra-fast short circuit detection at Fault Under Load (FUL). FUL appears when a power switch is shorted by an unintended turn-on of the complementary switch in an HB [5]. The method described here is intended to detect the most challenging situation, that is, a FUL due to Single-Event Burnout (SEB).

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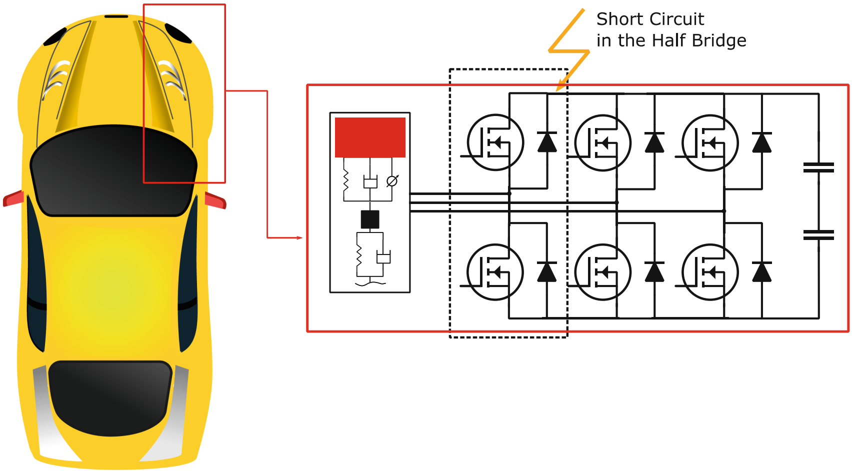


Fig. 1. The top view representation of a car. On each corner, the EM suspension is installed with the configuration, as shown in the circuit on the right.

SEB happens because of secondary cosmic particles that hit a power switch when it is blocking [6]. It causes deposition of tens to several hundreds of MeV energy over a few micrometers distance and happens in less than one nanosecond [7]. This paper proposes an indirect short circuit detection by measuring the HB voltage-dip during a short circuit due to the stray inductance (L_σ) between the DC-Link capacitor and the HB. This method is dubbed as Stray Voltage Capture (SVC). As it is impractical to measure the voltage across L_σ, the HB voltage is measured instead. A High Pass Filter (HPF) is used for passing through the voltage dip and filter out the DC component. Additionally, a Low Pass Filter (LPF) is implemented to avoid a false-triggering alarm during the HB switching transition.

In order to show the merits of SVC, some key performance indicators (KPI's) are compared with those from the other short circuit protection methods from reference [11]. This comparison is shown in Table 1.

From Table 1, it can be seen that the SVC method is superior in the term of detection speed. Therefore, SVC is suitable for detecting a SEB as will be discussed further in section III. Furthermore, SVC detects the short circuit from a system point of view. Hence, the SVC implementation reduces the circuit cost, as it only needs one protection circuit for a three or more phase system.

Table 1. Comparison of KPI's between existing and proposed short circuit detection method

Methods	Parameter	Detection time	Detecion level	Comments
Current mirror	*Ids*	~100 ns	Device protection	Expensive, not all devices have a port for current mirror
Source current detection by resistor	*Ids*	~100 ns	Device protection	Increases resistive loss and parasitic inductance in power loop
Source current detection by Rogowski coil	*Ids*	~100 ns	Device protection	Expensive
Desaturation circuit	*Vds*	~ 1 µs	Device protection	Depend on the device saturation voltage characteristics
Desaturation circuit with adaptive blanking time	*Vds*	~ 250 ns	Device protection	Many additional components (reducing robustness), adaptive with the changing of the transistor
Gate driver voltage sensing	*Vds*	~100 ns	Device protection	Needs two op-amps and a logic circuit for ignoring switching transient
Stray voltage capture (Proposed solution)	*Vdsds*	<100 ns	Subsystem protection	Use LPF and HPF for capturing voltage dip

2 Fault Under Load and Single Event Burnout

A MOSFET in an HB can be subjected to FUL/SEB, as illustrated in Fig. 2.Typical waveforms for this event are shown in Fig. 3a. At t_1-t_2, the T_{A-} is already on and carrying a load current (I_{Load}). At t_1, a FUL happens when T_{A+} is unintentionally shorted by one of the short circuit failure mechanisms, as presented in [1]. In this stage, the drain-source current of T_{A-} increases very rapidly with L_σ being the only limiting factor until the MOSFET reaches its saturation at t_2. A rise in the V_{ds} of MOSFET T_{A-} leads to the rise of its V_{gs} through the Miller capacitance C_{gd}. Therefore, the I_{ds} keeps increasing, and at some point, it will decline as the V_{gs} is going back to the normal on-state value. From t_2-t_4, the MOSFET reaches its saturation region. At t_4, the short circuit protection is triggered by the conventional detection, i.e., desaturation circuit, which discharges switches V_{gs} of T_{A-} to zero. This hard-switching turn-off gives an overvoltage spike in V_{ds} due to L_σ.

As depicted in Fig. 3b, the I_{ds} of Silicon (Si) and Silicon-Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) continues to increase with the rise of

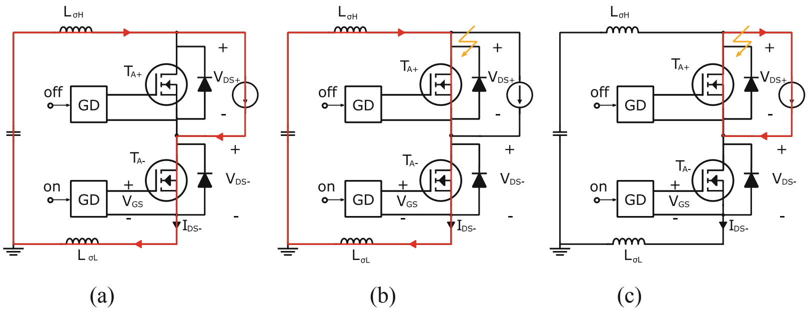


Fig. 2. A sequence of FUL in a Half-Bridge (a) TA− is already on and is conducting the load current (b) The unintended turn on of TA + causing the short circuit to happen (c) TA− is turned off by the protection circuit after the short circuit has.

V_{ds} for a long time due to the large ohmic region. As a result, the short circuit withstands time of a MOSFET is, in general, lower than that of an Insulated Gate Bipolar Transistor (IGBT). A SiC MOSFET can only sustain around 7µs during a short circuit event [8].

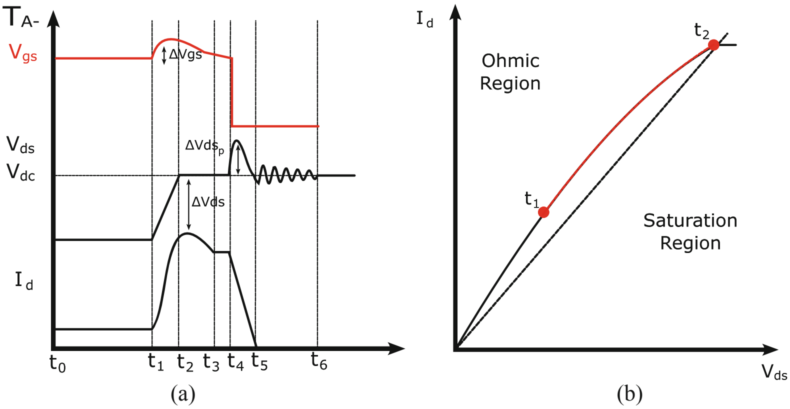
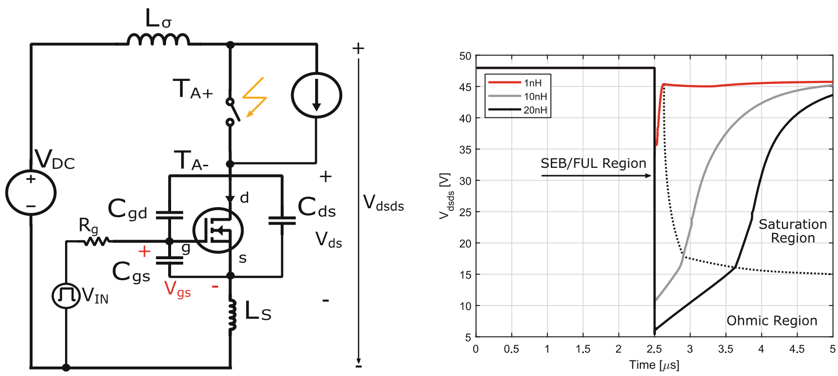


Fig. 3. (a) MOSFET behavior at FUL by using conventional short circuit protection scheme, (b) MOSFET region during FUL/SEB event.

It is aforementioned that there is a voltage dip due to L_σ during the FUL/SEB event. The HB simulation during FUL/SEB is conducted in SPICE and illustrated in Fig. 4a. Here, an ideal switch is used to mimic the SEB occurrence. Figure 4b shows the SPICE simulation of V_{dsds} with the variation of L_σ.

From Fig. 4b, the region of detection is divided into a SEB/FUL, an ohmic, and a saturation region. A higher value of L_σ gives a higher voltage dip magnitude in the SEB/FUL Region. Therefore, a minimum value of L_σ is necessary to achieve an optimum trade-off between the switching and detection performance. SVC is able to detect a short circuit in the SEB/FUL region, with some uncertainty (ex: component-time delay). Thus,



(a) (b)

Fig. 4. (a) The illustration of simplified HB during FUL/SEB event (b) SPICE simulation by varying Lσ and its detection region

the SVC method guarantees detection, while the MOSFET is operating in the ohmic region.

3 Stray Voltage Capture Principle

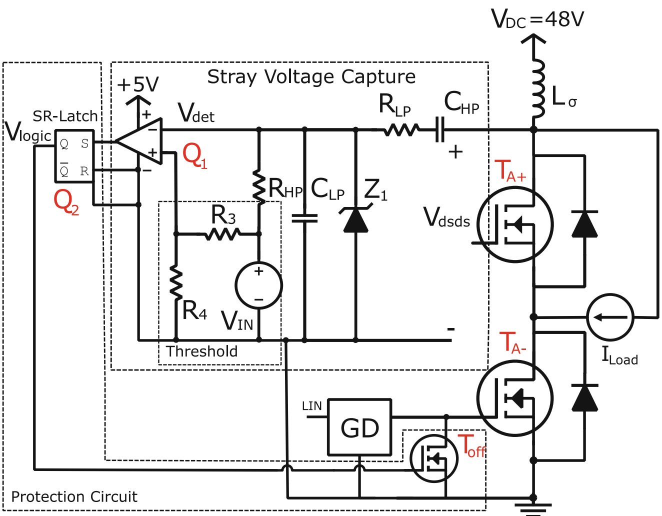


Fig. 5. Stray Voltage Capture implementation for short circuit detection in a Half-Bridge

Figure 5 shows a possible circuit implementation of the SVC method as a combination of an HPF and a LPF, which together are realized by a two-port RC network. It consists of C_{HP}, R_{HP}, C_{LP}, R_{LP}. The output of the network is given an offset by V_{IN} to match the comparator input. The transfer function from the HB voltage measurement V_{dsds} to the network output V_{det} can be written as

$$V_{det} = \frac{s}{C_{LP}R_{LP}s^2 + \left(1 + \frac{C_{LP}}{C_{HP}} + \frac{R_{LP}}{R_{HP}}\right)s + \frac{1}{C_{HP}R_{HP}}} V_{dsds} + V_{IN} \tag{1}$$

A Zener diode (Z_1) is placed in cascade with the RC network to protect the comparator from a huge undershoot and overshoot of V_{det}. The SVC performance at SEB and FUL is examined in the SPICE environment, with the result as depicted in Fig. 6.

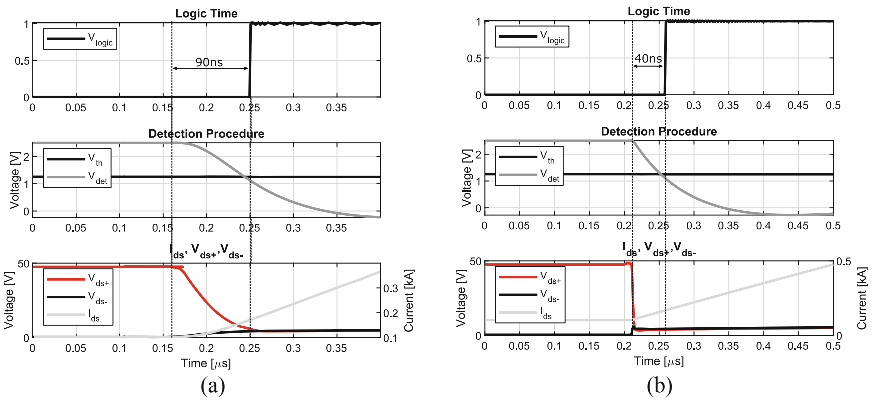


Fig. 6. The Waveform of Vds−, Vds + , Ids, and the logic output of SVC (a) during FUL (b) during SEB

In the SPICE model, a-Si MOSFET 48V/180A IPB024N10N5 is used as an example. The SEB is realized by turning on an ideal switch located in parallel with T_{A+}. Meanwhile, a "normal" FUL is realized by turning on the gate driver logic input of T_{A+}, which is acting like a normal MOSFET. If a SEB or normal FUL occurs, the input signal of comparator V_{det} will become lower than V_{th}. The SPICE circuit parameters are listed in Table 2.

Table 2. SPICE SVC parameter values

L_σ	30 nH	R_{HP}	100 Ω	Q_1	LT1721
V_{IN}	2.5 V	C_{HP}	1 nF	T_{off}	RJK005N03
R_{LP}	1 kΩ	C_{LP}	1 nF	Q_2	SN74LS

The signals in Fig. 6 show that the SEB and normal FUL are detected after 40 and 90 ns, respectively. It should be noted that the detection speed also depends on the comparator and SR-latch time delay. In this simulation, this time-delay is 6ns as an ultra-fast comparator (Q1) is used. The simulation of the full protection scheme during Single-Event Burnout is presented in Fig. 7.

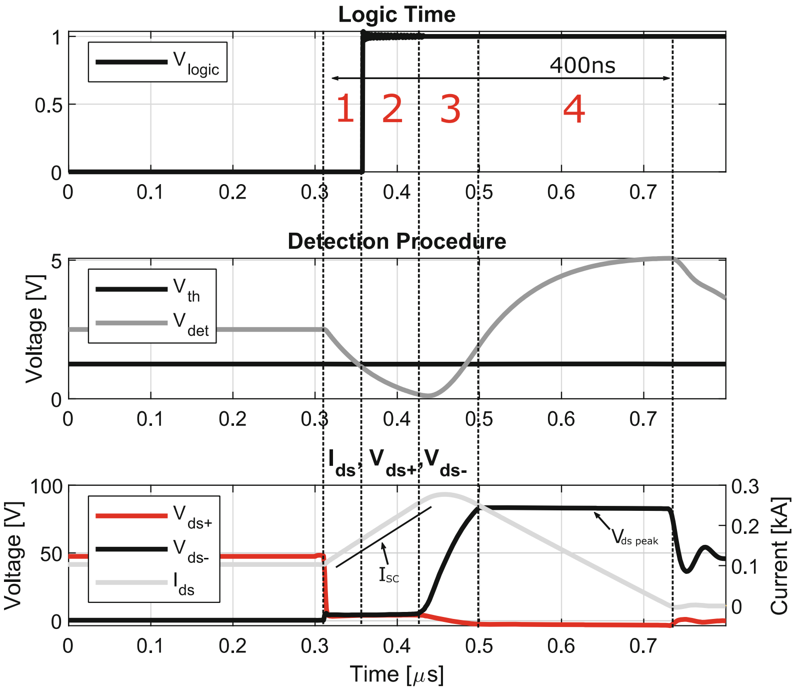


Fig. 7. The protection of Single-Event Burnout, which is divided into four working areas.

The signals in Fig. 7 show that the short-circuit protection scheme which works in the ohmic region of the switch is realized. The working area can be divided into four regions. The first region starts when a short circuit occurs, which results in the rapid rise of current with L_σ is the limiting factor. Mathematically, the short circuit current is expressed as

$$V_{DC} = (L_\sigma + L_s)\frac{dI_{SC}}{dt} + 2R_{dson}I_{SC} = \frac{V_{DC}t}{L_\sigma + L_s}e^{-\frac{2R_{dson}t}{L_\sigma + L_s}} + I_{Load}, \tag{2}$$

where I_{sc} is the short circuit current of the HB, R_{dson} is the on-resistance of T_{A+} and T_{A-}, L_s is the stray inductance of the MOSFET source, and I_{load} is the load current. The second region starts when the SVC detects the short circuit; there is an additional delay due to the protection circuit. Therefore, the current is still increasing, as formulated in (2). The total short circuit time (t_{total}) is thus:

$$t_{delay} = t_{comp} + t_{latch} + t_{prot}, \quad t_{total} = t_{SC} + t_{delay}, \tag{3}$$

where $t_{comp,}, t_{latch}$, t_{prot} are time delays due to comparator, SR-latch, and protection, respectively. The third starts at T_{A-} where, as $V_{gs} < V_{TH}$, V_{ds} is still rising while I_{ds} already starts falling. The final region starts, where I_{ds} keeps falling until MOSFET is completely turned off and V_{ds-} starts its oscillating period. In this area, there is an overvoltage of V_{ds-} due to the energy stored in $L_{\sigma.}$ Note that this overvoltage should be limited to prevent the secondary breakdown of the MOSFET. During the I_{ds} current falling period, the behavior of the circuit Fig. 4a is analytically modeled by using a similar technique as in [9] and [10], leading to:

$$V_{gs} = \left(\frac{I_{SC}(t_{total})}{g_{fs}} + V_{TH}\right)e^{\frac{-t}{T}}\left(\cos\omega t + \frac{\sin\omega t}{\omega t}\right), \text{ underdamped response} \quad (4)$$

$$V_{gs} = \left(\frac{I_{SC}(t_{total})}{g_{fs}} + V_{TH}\right)\frac{1}{T_2 - T_3}\left(T_2 e^{\frac{-t}{T_2}} - T_3 e^{\frac{-t}{T_3}}\right), \text{ overdamped response} \quad (5)$$

where

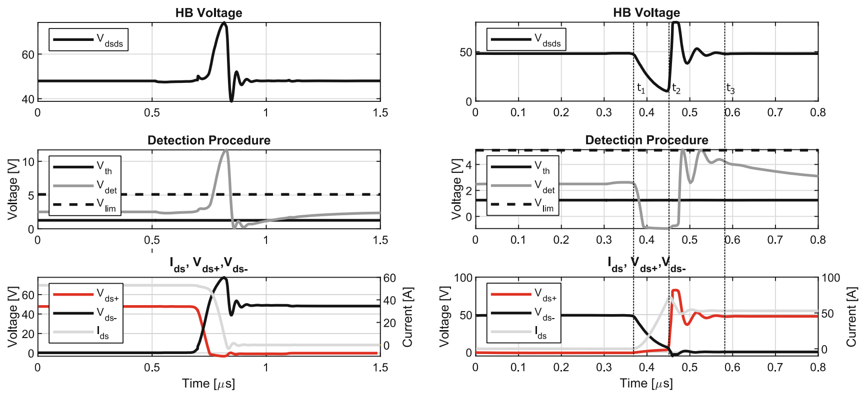
$$T = \frac{2A}{B}, \omega = \sqrt{\frac{4A-B^2}{4A^2}}, T_2 = \frac{2A}{B+\sqrt{B^2-4A}}, T_3 = \frac{2A}{B-\sqrt{B^2-4A}},$$
$$A = R_g g_{fs} C_{gd}(L_\sigma + L_s), B = R_g(C_{gs} + C_{gd}) + L_s g_{fs},$$

Here, R_g, C_{gs}, C_{gd}, g_{fs} are extracted from the MOSFET datasheet. The underdamped response occurs when $4A-B^2 \leq 0$ while overdamping occurs when $4A-B^2 > 0$. The V_{ds} overvoltage peak can be written as

$$I_{ds}(t) = g_{fs}(V_{gs}(t) - V_{TH}), \ V_{dspeak} = \max\left(V_{DC} - (L_\sigma + L_s)\frac{dI_{ds}(t)}{dt}\right). \quad (6)$$

4 Limitation of Stray Voltage Capture

As an example, consider a change of the LPF parameters from Table 2, with C_{LP} and R_{LP} are 330pF and 10 Ω, respectively. Results of circuit simulation are shown in Fig. 8 for a normal HB switching transient.



(a) (b)

Fig. 8. The limitation due to the switching transient (a) comparator input overvoltage, (b) false-triggering alarm.

Here, V_{lim} is the comparator input limit from the datasheet. From Fig. 8, it is shown that too low LPF component values give catastrophic events in the SVC, namely, comparator input overvoltage and false-triggering alarm. The former occurs due to the overvoltage turn-off of T_{A-}. The latter could be analyzed from Fig. 8b. At t_1-t_2, the fault-alarm is triggered because of the V_{dsds} voltage dip during the hard commutation of the

MOSFET T_{A+}. This makes the V_{det} fall and quickly surpass the V_{th}, which is limited by the forward voltage of the Zener diode (Z_1). At t_2, I_{ds} has a peak overshoot due to the T_{A+} body diode's reverse recovery. After t_2, there is an overvoltage turn-off of T_{A+}, which can harm the comparator. Therefore, it is necessary to choose the right value of Zener diode (Z_1) clamping voltage for limiting the maximum voltage input to the comparator. It is important to consider that the event depends on the I_{Load} direction. If the I_{Load} direction is reversed, the transient behavior of V_{dsds} in Fig. 8a will follow the same pattern as in V_{ds-} transient behavior in Fig. 8b. Similarly, it also happens for the transient response of V_{ds-} in Fig. 8a.

To test the dependency of SVC with L_σ, consider a change of L_σ value into 2nH. In Fig. 9a, Δ_{mp} is introduced and expressed as $\Delta_{mp} = \min(V_{det})\text{-}V_{th}$.

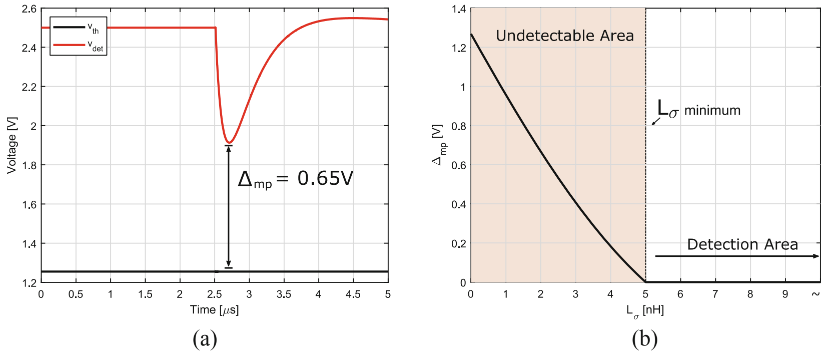


Fig. 9. The limitation due to (a) the introduction of Δmp with Lσ is changed to 2nH, (b) value with the variation of Lσ.

In Fig. 9a, an SEB is introduced at t = 2.5μs. If Δ_{mp}, > 0 a FUL/SEB is not detected by the SVC. Note that the magnitude of V_{det} is reduced as the value of the LPF component, i.e., C_{LP} and R_{LP} increases. Therefore, it is necessary to have a compromise between the L_σ and false-triggering limitations in choosing the LPF parameters. Figure 9b shows the operating area of SVC. As shown, Δ_{mp} is reduced linearly with the increase of L_σ. We conclude that in this application, the minimum value of L_σ is 5nH to ensure the correct operation of SVC.

5 Conclusion

SVC is proposed as an ultra-fast and robust FUL/SEB detection. By using SVC, the FUL/SEB detection in the ohmic region of the MOSFET is realized. The results show that the SVC can detect the FUL/SEB very quickly, with response times in the order of less than 100ns.

The limiting factors of the SVC are the false-triggering due to the switching transient, the comparator input overvoltage, and the minimum value of L_σ. In the example application for electromagnetic suspension, the minimum value of L_σ is 5 nH.

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Policy Strategy

Preparing Testing and Learning Requirements for the Automated and Connected Age

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Abstract. Automated driving will significantly influence our society. The development towards connected and automated mobility offers solutions to many of today's societal challenges. The further development of automated and connected vehicles to market maturity requires extensive test procedures that meet the highest safety requirements. This paper will highlight key activities, which are necessary from a public authority's point of view to test and implement them on domestic roads. It describes Austria's strategy including its concrete measures and criteria to fulfill a holistic approach for enabling car manufacturer and scientific institutes to test and further develop technologies under real conditions, based on the active steering role from the public authority to ensure the safe and sustainable implementation.

Keywords: Automated and connected vehicles · Performance criteria catalogue · Learning requirements · Test environments · Test on public roads · Test regime

1 Introduction

The development towards self-driving vehicles has the potential to make the transport system significantly more efficient, safer and secure and can help to lower emissions. It can also be a key enabler towards accessibility and inclusion [1]. A study made by HIS Markit forecasts a total global sale of autonomous cars of 21 million in the year 2035. Between now and 2035 there will be nearly 76 million vehicles with some level of automation [2]. Despite several other optimistic statements in 2016, it seems that some of the hype surrounding autonomous vehicles faltered [3]. The challenges related to the introduction of this technology are manifold and not necessarily technological but instead based on regulatory limitations, the lack of harmonization and the underestimation of the human being. Furthermore, the speed of technological advance outpaces the regulators' attempts to keep up. However, tests of automated or even autonomous vehicles under real conditions are crucial for car manufacturers to evaluate best settings and conditions for sensor fusion and data from multiple sensors. Given the fact that neither autonomous nor highly automated vehicles are still available for consumer purchase, the collection of data and experience under real-world conditions are limited at this time and a standardized vocabulary and methodology for evaluating and regulating are under development by

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regulators on a national and international level [4]. Additionally, local authorities and regulators have to face the challenge that each car manufacturer has unique specifications compounded with different operating environments that are constantly changing [5]. However, as automated vehicles must interact safely with pedestrians and human drivers to operate in a mixed transportation ecosystem, there is a need for safe and reliable tests under real conditions. This has to be managed by public authorities and regulators to ensure a safe and transparent procedure especially when thinking about different penetration scenarios. Hence, public authority's play a major role by defining steering mechanism, enabling tests on public roads, evaluating effects and preparing the society for the mobility of the future.

2 Strategic and Legal Framework for Testing in Austria

The Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK) established a controlled process to develop the Austrian Action Programme on Automated Mobility [6]. More than 300 experts and stakeholders from various sectors like industry, science, business, infrastructural operation but also local citizens, civil engineers etc. have been included to enable a holistic approach. This process enabled the establishment of mayor goals and the definition of three prioritized use-cases for the next years: security through an all-round view to increase road safety, new flexibility to include on-demand services to enable last mile solutions and efficient mobility of goods and people.

The Action Programme addresses automated mobility in respect of all modes of transport for mobility of persons and goods. Between 2019 and 2022, the ministry will invest more than 65 million euro to enable a safe, sufficient and reliable implementation of automated mobility solutions. In order to realize that seven concrete deliverables (including 34 measures) have been defined to maintain or regain a public space worth living in and on high quality. These deliverables are shown in Fig. 1.

Back on August, 2016, a general legal framework to allow experimentation with automated vehicles in real traffic conditions was adopted in Austria. This was possible due the 33rd Amendment to the Motor Vehicle Act. Based on this amendment, the BMK issued the "Automated Driving Regulation (AutomatFahrV)", which specifies the conditions under which tests of automated vehicles on public roads can take place. The regulation defines three applications: Autonomous Minibus, Motorway Pilot and Autonomous Military Vehicle. It also defines general rules like there must always be a driver (operator) in the vehicle in order to be able to take over as well as an event data recorder (black box). Interests of testing institutes or research and innovation (R&I)-companies in the field of vehicle development can apply for time-limited tests on public roads after a successful evaluation by the BMK. The BMK receives support by an independent council of experts.

Since 2016, more than 40 permits have been issued for testing on public roads. Most of them represent organizations dealing with first-/last mile minibuses. With the corresponding prerequisites, the BMK enabled tests of driving functions within a safe and controlled environment on a liberal and transparent base. While the ministry is willing to enable tests under highest safety criteria, testing companies are required to submit a test

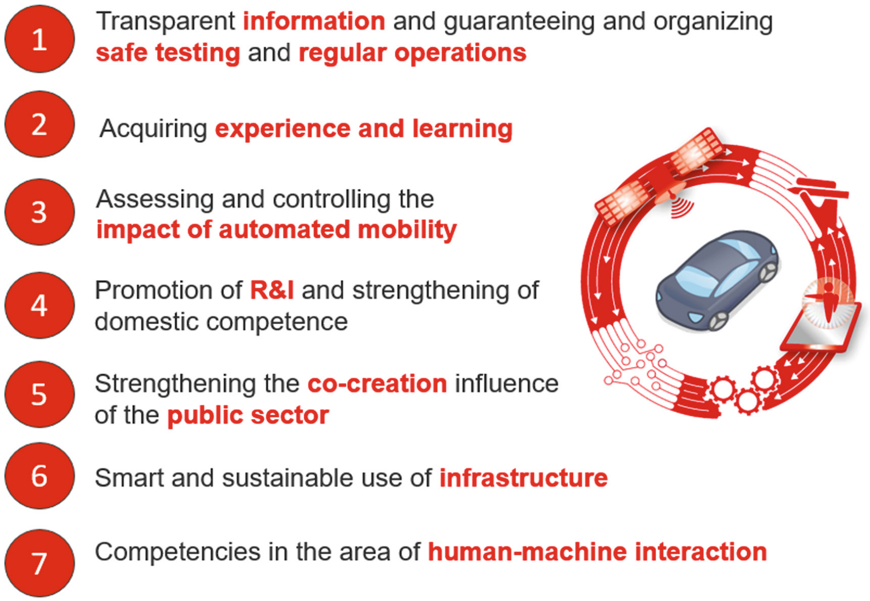

Fig. 1. Deliverables of the Austrian action programme on automated mobility

report on a regular basis. After an evaluation by the ministry, the reports will be published for the public on the website of the BMK[1]. This process is not only strengthening the co-creation influence of the public sector it also enables required measures for the safe and sustainable deployment and supports the industry with target-oriented R&I-funding [7].

3 Test Environments and Flagship-Projects

Several studies have determined that highly automated and connected vehicles (CAV) would need to travel hundreds of millions of kilometers, to demonstrate their reliability. As this process could take several decades there is a need for combined solutions of the real and the virtual world. In order to enable test of new technologies under real conditions the BMK supports the development of test environments, representing a combination of test bench, simulation, test scenarios of hardware in the loop as well as software in the loop, closed tracks and real time experience on public road with a total funding of around seven million euros. Additionally, the BMK funds the development of flagship projects to ensure clusters of high impact projects that develop, test and deploy innovations in essential areas of interest.

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[1] https://www.bmk.gv.at/themen/mobilitaet/alternative_verkehrskonzepte/automatisiertesFahren.html.

3.1 ALP.Lab

ALP.Lab (Austrian Light Vehicle Proving Region for Automated Driving)[2] – includes a sophisticated environment for testing and verifying the components and systems of automated driving in complex scenarios. It aims to set up a test center and innovative environment for automated and connected driving passenger cars in Austria. ALP.Lab offers a comprehensive range of private and public test tracks with focus on traffic situations specific to Austria (e.g. tunnels, mountain roads, etc.), as well as on Austrian specific weather conditions. Further, the consortium is in a strong cooperation with ASFINAG, the national highway and motorway operator, which supports the development of the test environment with additional infrastructure. Tests on public roads can be made on a nearly 30 km long test track highway section of the A2 as well as on the highway section A9 from St. Michael to the Styrian-Slovenian border, which allows cross-border tests. Several test sections are equipped with additional infrastructure by ASFINAG. Traffic-management enables to record individual vehicle data as well as overall traffic analysis and guarantees the recording of test vehicles trajectory.

3.2 DigiTrans

DigiTrans[3] aims to set up and operate a test environment for automated and connected driving with a focus on the transport of goods in the central area of Upper Austria. Based on company-oriented applications, it supports the implementation of test tracks for freight-mobility service providers, which are open for all vehicle manufacturers that have committed themselves to novel forms of mobility of goods with assisted and autonomous vehicles. It also aims to maintain a test infrastructure, in order to provide the framework conditions for the validation of innovative developments in the area of automated and connected mobility of goods. By developing a platform for data & development support new, digital business models for logistics service providers will be enabled. DigiTrans thus offers a test environment that enhances transportation and traffic safety through sustainability.

3.3 DigiBus®Austria

Digibus®Austria[4] pursues the goal to research and test methods, technologies and models for proofing a reliable and traffic-safe operation of automated shuttles on open roads in mixed traffic in a regional driving environment based on different levels of automation. Expected results address the fields of driving environment and digital infrastructure, driving scenarios and interaction with other traffic participants as well as passenger interaction during driverless operation. The results form the basis for an Austrian reference model for the real testing and operation of highly or fully automated vehicles in local public transport.

[2] https://www.alp-lab.at/#about.
[3] https://www.testregion-digitrans.at/en/downloads/.
[4] https://www.digibus.at/en/.

3.4 Connecting Austria

Connecting Austria[5] brings technology leaders and end-users together to demonstrate and evaluate specific use-cases for semi-automated and energy-efficient truck platoons. Key objectives is the evidence-based evaluation of energy-efficient truck platoons as a prerequisite for competitive strength of Austrian industries. Its unique contribution is the specific focus on infrastructure issues and on parameterized traffic perspectives. This particularly includes platoons at intersections before entering motorways and after leaving motorways.

4 Key Findings from Tests on Public Roads and Test Environments

Tests on public roads as well as the buildup of test environments and flagship projects are one of the key deliverables defined in the Austrian Action Programme. Its 34 measures can be clustered into three main fields of action.

4.1 Transparent Information, Active Participation of the Public Sector and Strengthening of Societal Dialogue on Automated Mobility

Several measures have been implemented like knowledge transfer and experience for the general public citizen dialogues, debates as well as regular surveys on the acceptance. The results of these measures emphasized the uncertainty of the public regarding automated driving in general as well as a desensitization of the public based on promised deployment achievements in 2020, without a general commercial availability in sight. While almost everybody has still heard about autonomous driving, there is no common knowledge about the different levels of automation or even the difference between automated and autonomous. It turns out that industrial media presentation leads to wrong expectations, which can be dangerous in some way. For example by using the term ‘autopilot-system’, which has been understood as fully autonomous by users and hence have been wrong used by them. Dangerous situations, accidents, mistrust and rejection are the results which hind the sustainable deployment and hence delays the technological development. This counts also for automated shuttles where people are trying to jump in front to test the systems reliability. Surveys regarding acceptance, fears and hopes also demonstrated that there is currently no understanding for the need for automated mobility which also leads to a hesitate attitude. A recent worldwide Deloitte study found a high degree of consumer hesitance of 60–80% regarding the safety of automated driving depending on region [8]. Surveys based on national citizen dialogue highlighted that safety was the highest ranked followed by hope and fear. Regarding highest hopes, safety was followed by gain of leisure as well as life quality and sustainability, while technology dependency, supervision and increase of traffic have been ranked as highest fears. 88% of all persons interviewed are concerned about their personal information being shared with others [9]. Several measures demonstrated that the human factor was underestimated in respect of acceptance and use. Users as well as local authorities emphasized that they are missing the users and authority’s perspective in terms of deploying automated vehicles. This results in a skeptical fundamental position and the need for a user-centered approach.

[5] https://connecting-austria.at/#/project/general.

4.2 Guaranteeing and Organizing Safe Testing and Regular Operations

Since 2016, it is possible to test on domestic roads under specific conditions, as described in the previous section. Organizations are obligated to submit their test reports to the BMK to enable a transparent information for the public. The following key findings are based on these reports.

4.2.1 Tests with Motorway Pilots

Primary representatives from the Austrian supply industry as well as car manufacturers received a test certificate for testing on domestic roads in Austria. Within the scope of their tests Advanced Driving Assistance Systems (ADAS), like Lane Change Assistant, Blind Spot Assistant or tests scoping the emergency corridor have been analyzed and verified. So far, no accidents or dangerous situations have been reported. However, the results are far behind the expectations of testing companies as they expected a much more advanced technological progress. In many cases, a permit for tests on public roads was available but tests could not be done due to bad weather conditions or increased traffic. Further, the large amounts of data generated during the validation of automated driving functions pose a particular technical challenge for real time analysis. The results demonstrate that even on less complex environments like highways, the topic of collecting and processing data and data management plays a central role, which emphasizes the need of cooperative support by the infrastructure.

4.2.2 Tests with Autonomous Buses (Shuttles)

Shuttle-projects in Vienna, Salzburg and Carinthia are currently testing automated driving functions in urban and suburban areas. The aim of these tests is the evaluation of the user's acceptance and reaction, operation in mixed traffic solutions and required infrastructural components. In total, several thousand kilometers have been absolved with an average driving speed of about 11 km/h. In many cases, this slow speed resulted in dangerous situations because other road user often reacted impatiently and hindered the flow of traffic. Obstacles and complex situations required manual control by the operator as artificial intelligence is not available yet or at a very low level. Tests have successfully demonstrated that the shuttles can stop reliable in front of obstacles or adopt their speed. Apart from that, this passive driving mode proved to be problematic because of the very sensitive sensor alignment, which causes the immediately stopping of the shuttle in any cases. In some cases, shuttles stopped due to falling leaves or waving branches, based on minimal changes between the virtual mapping and the actual on-side situation. This often caused an immediately breaking of the shuttle. In some cases, this caused dangerous situations for involved passengers, as they did not expect an emergency break of the system. Tests on suburban areas also highlighted the necessity of additional physical and digital infrastructure based on inaccurate mapping or lost mapping signals. Cooperative traffic light systems have been implemented to avoid critical situations like turn left at unregulated crossing or at unobservable crossings. Additionally, human-machine-interactions as well as the reactions of road users and passengers have been evaluated. In some kind of unexpected "stress test", pedestrians and cyclists tested the limits of the vehicle by deliberately entering or crossing the lane just in front of the vehicle. This reactions demonstrate a certain curiosity but also reluctance of the system. This counts especially for the first contact with a shuttle. During the long-term tests, this attitude has changed and the participants have learned to accept the shuttle. Numerous questions raised regarding human behaving in respect to driverless shuttles. In order to address that, different situations of everyday life have been tested, e.g.: how passengers on board react when the limit of maximum capacity is already reached and an additional passenger want to get into the bus or how to deal with aggressive passengers. The results emphasized that even the shuttles are at a very low technological level and there are still causing dangerous situations in real world traffic.

4.2.3 Tests with Autonomous Military Vehicles and Platooning

The Austrian department for defense is testing automated and connected military vehicles and trucks in special. Related ongoing R&I-projects are focusing on the development of teleoperation, hybrid-communication technologies and the deployment of Platoons on private and domestic roads and their required infrastructure. Platooning in this context means a convoy with a maximum of three vehicles with a driving distance of about 20 meters, including commercial line-haul trucks and tractors. Ongoing R&I-projects are dealing with driverless technology maneuvers in addition to the standard leader-follower.

All submitted test reports demonstrated current challenges and hurdles for the implementation and deployment of highly CAV in respect of technological development, system and services, society and human beings. Tests with shuttles and Motorway Pilots highlighted the challenges in terms of human-machine-interaction and the need for additional infrastructure in order to enable a safe and secure operation. Additionally they emphasized danger situations on public roads and the need for improved tests of such scenarios. This proofs the maturity of extensive test procedures, which are required for further development of advanced automated vehicles. As the exciting possibilities of this new technology unfold, there is a growing need for testing and verifying the components and systems of automated driving in diverse and complex scenarios but not in real traffic. This results in a specific conflict potential, as the development of new technologies can be a risky project. In the perspective of a local authority, this obliges highest safety requirements and performance criteria. As local authorities are facing the challenge of making decisions without profound knowledge there is a need for test environments to test under safe conditions, based on the harmonization of data and standards between cross-boarders as well as between car manufacturers and infrastructure operators.

4.3 Acquiring Experience and Learning

Initial findings from both Austrian test environments show the need for cooperation and connection in respect of automated mobility. The large amount of data generated during the validation of automated driving functions pose a particular technical challenge for real time analysis. Data processing based on onboard sensoric and processing units is hardly manageable without excessive effort and investments. This does not support making real time decision based on low latency requirements. Decisions being made by the vehicle itself would not help to improve the overall system in terms of sustainability, safety and security. Cooperative, connected and automated mobility is thus requisite and require a strong support by the road infrastructure and its interface with the vehicle [10]. Standardization of communication between the infrastructure and the vehicle itself is still an ongoing process and requires further investments. In order to handle the large amount of data, generated by the vehicle, ALP.Lab has already developed a cloud-based solution, which has been also made available for other test regions and scenarios.

5 Future Testing and Learning Requirements Steered by Public Authorities

Local authorities are facing the challenge of dealing with validation and verification of CAV and solutions. Test scenarios based on defined use-cases like in Austria enable first trials for industry and R&I and support authorities by gaining experiences with new technologies. As this procedure is limited to defined operational design domains and conditions it reduces the risk of accidents and incidents for governments and authorities to a minimum as it only allows tests under 'known' conditions. Safe testing requires more than the evaluation of 'autonomous' vehicles or systems. It can only be ensured by combing vehicle components (e.g. sensors, or maneuvers); context and environment (e.g. weather or mixed traffic); infrastructure (e.g. digital and physical) and (test-)driver (e.g. skills or handover-procedure). The combination of all factors mentioned has to enable a monolithic process. Since the first test-trials in Austria under real conditions, this process is based on the definition of Society of Automotive Engineers (SAE) levels (0–5). However, public citizen dialogues as well as tests on domestic roads back in 2019 emphasized the lack of understanding the differences between the SAE levels in terms of responsibilities and take over requests. While this starts at the general distinction between automated and autonomous for the public, it ends at the question of responsibility for local authorities in cases of an accident. For local authorities this issue got much more complicated as it is not possible for them to adopt the legal framework based on SAE-definitions, neither for tests nor for regular use. Much more, the adaption of the legal framework has to be done in respect of automated vehicles as well as conventional ones. Based on this experience, future test procedure require the definition of operational design domains (ODD) as additional explanation to the SAE-levels. This will support a better understanding and the safe use of the technology for all stakeholders involved. Further, it will increase decisions regarding legal adaption by local authorities.

As technology for automated vehicles is still behind expectations, cooperation and connection with the physical and digital infrastructure turns out to be unavoidable and necessary. While the need of additional support by the infrastructure depends on the use-case and ODD, this support has to be defined in detail. For example, automated shuttles in (sub-)urban areas require additional navigation support and landmarks, while highway pilots have other needs. Defining the infrastructure support levels for automated driving (ISAD) will support the process of decision making for infrastructure managers and local authorities. Within the INFRAMIX (Road INFRAstructure ready for MIXed vehicle traffic flows) project, first steps have already been made by defining classification levels for automation support by the infrastructure – from Level A to Level E. Considering the ODD of the vehicle as well as the ISAD-level, future test procedure will benefit from this cooperation mechanism by enhancing interoperability and synchro modality. This will also enhance the European industry by harmonizing legal frameworks and traffic regulations all over Europe.

The combination of SAE, ODD and ISAD levels will be the core element for testing on public roads and the adaption of the Austrian legal framework. This requires not only a better cooperation between car manufacturers/suppliers and the infrastructure operator; but also a better cooperation with local authorities and governments. This cooperation mechanism is crucial for progress and will lead to a development of a more well-rounded view of automated vehicles. Regulators require knowledge and information based on facts, which cannot be gained through crucial field operational tests, being mostly not allowed under international law yet. This results in a conflict, as highly automated vehicles require extensive, real-world tests to become safer and to reach their full potential. Hence, tests in controlled fields, dynamic driving simulator and simulations are necessary for testing. By supporting the development of test environments, this will help to support up a common understanding about CAV and will demonstrate the technological state of the art, further requirements but also wrong paths of development. With ALP.Lab and DigiTrans, the BMK has already started to support the development of such test environments for further tests. Through their strong cooperation with infrastructure operators such as ASFINAG they enable a holistic approach and a common view. This collaboration covers the expertise of all thematic areas regarding automated driving. While both test regions are accessible to all researchers and industries, R&I-projects focusing on major challenges like over the air updates, mixed traffic, human-machine-interaction, safety and security, hybrid communication, etc. can be implemented and tested there. A large amount of required tests can be simulated instead of real driven. This enables a safe, repeatable and efficient testing of path planning on anything by generating several scenarios with no need for expensive field tests. Further, it enables the creation of a digital twin of the real world, which provides a flexible and risk-free environment including changing parameters and a multitude of variables. Companies can create a digital copy of a real world environment to find the pain-points of their technology and take steps to correct them. Errors, which are sometimes referred to the industry as edge cases, can be produced in the digital environment and then tested physically on the track [11]. It is of importance to share national best practice examples on an international level and enable cross-border experiences. Cross-border cooperation will support decisions maker on European and international level and thus will push forward a harmonized traffic regulations framework as well as the homologation process.

Test environments will definitely pave the way towards CAV. For this reason, the BMK will increase their involvement within the test regime in the near future. The current legislation process, based on use-cases, will be adopted in such a way, as testing organizations will have to define the vehicles ODDs as well as the required ISAD-levels by the infrastructure in a first step. Secondly, licensed test regions, such as ALP.Lab or Digitrans, could further evaluate the proposed test regime and define edge cases based on different criteria (as described in Fig. 2).

This enables the specification of a validation and verification framework for CAV. This framework will add evaluation and management of data by the vehicle itself and the infrastructure, test automation and results, definition of edge cases and requirements for testing areas, into a seamless workflow. To ensure this workflow, highly accurate

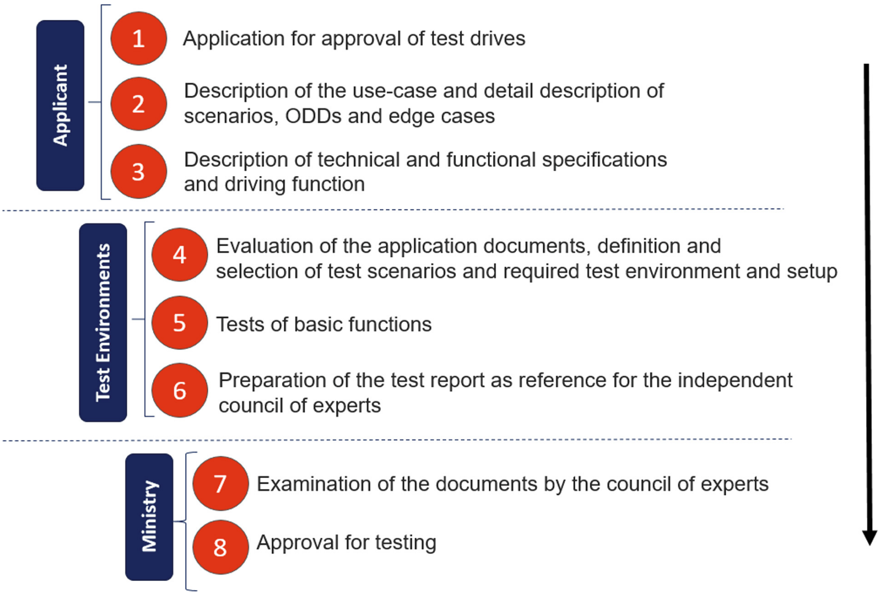

Fig. 2. Holistic approach for a further test regime on public roads

simulation services, digital twins and virtual tests under several situations and conditions are required and can only be accomplished by the independent test-regions. This validation and verification framework enables industries to see how their products are going to perform under real conditions and regulators to evaluate the impact of new technologies, required conditions and edge cases. The results of this process will support the independent expert advice and the BMK by making a decision regarding the approval of tests.

The use of digital twins and simulation will be vital for testing automated vehicles but real world tests remains a priority. By adding the test regions in the loop of approval, critical situations can be defined in advance as well as edge cases can be named. This is special of interest for new technologies without any human driver involved or technologies without experiences yet. Regulatory frameworks should enable tests without human drivers on domestic roads in the near future. Regulators need to be involved in the automated testing process to have a better understanding of the technology.

6 Summary

Automated and connected or even autonomous vehicles are one of the most disruptive technologies of today's world and have the potential of improving safety on our roads. Safety also remains the highest priority by introducing new mobility solutions. As fully autonomous driving is still at a vision level, the ongoing automation requires support in terms of cooperation and connection by the infrastructure and a holistic test approach. While simulation, software tests or digital twins will dominate further test activities, tests on public roads will still play an essential role in the future. However, the rate at which highly automated or even autonomous vehicles are developing is so fast that the rules that govern the roads are not keeping up – which results in a major problem for regulators. Test environments, such as the Austrian ALP.Lab and DigiTrans, will therefore play a crucial role for enabling local authorities to gather experience as they leverage unique physical and digital assets for testing CAV. New legal frameworks, processes and European standards will have to be put in place assuring the smooth implementation of innovative technologies, enabling cross-border cooperation. Harmonization and standardization is a crucial step in this context. As Austria still plays an active role in international forums to ensure the safe and sustainable deployment of CAV, the proposed validation framework could be a base for common European activities. Despite all visions about autonomous or even driverless driving a human-centered approach should not be forgotten most advanced unmanned space missions required human interaction on a regular basis, which emphasizes human beings still be required to be in the loop in the foreseeable future.

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