Understanding Complex Systems

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Eve Mitleton-Kelly *Editor*

Co-evolution of Intelligent Socio-technical Systems

Modelling and Applications in Large Scale Emergency and Transport Domains

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Editor

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Modelling and Applications in Large Scale Emergency and Transport Domains

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Part I
Introduction and Literature Reviews

Introduction: The SOCIONICAL FP7 Project and an Outline of the Volume

Eve Mitleton-Kelly and Paul Lukowicz

1 The SOCIONICAL FP7 Project

SOCIONICAL is a socio-technical FP7 research project funded by the European Union with 14 Partners in ten different countries (www.socionical.eu); this volume captures some of the work that was done by the Consortium of Partners over the 4 year period, February 2009 to January 2013.

The project looked at the contribution Ambient Intelligence (AmI) technology could make to society. AmI technology is omnipresent and non-intrusive; the devices are part of networks within smart environments, which are context aware, in the sense that, they are sensitive and responsive to the presence and behaviour of people.

As AmI technology is deployed more and more widely, we need to develop a deeper understanding of the consequences it may have for society. SOCIONICAL is dedicated to fostering such an understanding through a study of the basic laws governing Ambient Intelligence based socio-technical systems. To this end it has developed modelling and simulation methods needed to describe, analyse and predict the behaviour of such systems and has applied them to two concrete scenarios: emergency response and traffic.

1. **Emergency scenario**. We considered an emergency evacuation situation where people are carrying sensor-enabled, communication devices. Typically this would be smart phones which can sense peoples' location, motion, meaningful sounds (e.g., panic, structures collapsing) and possibly environmental parameters such as heat and light intensity. They can also communicate with each other, either

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through infrastructure (3G networks) or, if infrastructure is not available, in a direct peer-2-peer manner based, for example, on built-in Wi-Fi radios. Within the SOCIONICAL project we investigated how:

(a) Global situation awareness can emerge from the individual sensor values being spread throughout the system, fused and collectively interpreted. This includes the question of how humans use the information provided by the technology and combine it with their own perception and the information received from other humans;

(b) The evacuation process is influenced and coordinated through such global awareness combined with dedicated suggestions made by individual devices to their owners. This includes the question of trust that people put in technology, the interaction of technical advice with effects such as emergent leadership, herding and possibly panic and the influence of uncertain or wrong information being derived from sensors.

Overall an evacuation aided by a distributed Ambient Intelligence system is a complex dynamic process that can lead to instabilities, oscillations (e.g., when people are sent from one exit to another) and a range of emergent effects, from a smooth exit to a chaotic state.

2. **Traffic scenario.** The flow of traffic is very much determined by the way drivers perceive, interpret and predict what other cars are doing and how they react to it. Often, traffic jams arise because drivers see cars in front of them slowing down and adjust their speed accordingly. However, in most cases, they will slow down more than is necessary, which means that each following car becomes slower and slower; with a high enough car density, the traffic comes to a halt without any ‘objective’ reason, because of interaction effects. Similarly one aggressive, driver can trigger a cascade, tipping an entire traffic system from a state where people cooperate (making, for example, a merging traffic flow into a smooth process) to a state where everyone is aggressive (making efficient merging impossible). The question that we asked in the project was how could Ambient Intelligence based technology be used to mediate the interaction and information exchange between drivers, to prevent and diffuse such negative effects. To this end we looked at the confluence of two core technologies: (a) sensing the driver’s state and intensions, and (b) peer-2-peer communication between cars (car-2-car systems).

In addition to the two individual scenarios, the project also considered their confluence in a large scale emergency situation (e.g. flooding) involving both pedestrians and traffic.

The aim of SOCIONICAL was not to develop concrete technical solutions that support the above scenarios (although some Partners are working on such technology in other projects) but:

- To have concrete examples of the general principles and phenomena expected in complex Ambient Intelligence based socio-technical systems; and
- To understand how technology that is currently becoming available, is likely to affect those two important domains and derive from this understanding recommendations for future research and policy.

In this volume we have collected some of the key insights that came out of the above approach. In doing so we have put an emphasis on showing different perspectives as seen by scientists coming from different disciplines and applying different research methodologies. Such heterogeneity is a hallmark of research in socio-technical systems and constitutes both a challenge and an opportunity.

2 Ambient Intelligence Based Socio-Technical Systems

Social phenomena are driven and determined by information flow and interactions between individuals. As the emergence of ubiquitous, instantaneous communication provided by mobile phones and the internet has drastically changed information distribution and human interaction patterns, modern society has started on a transformation process that is affecting virtually all areas of our lives. The freedom movements in the Arab world, the London riots of 2011, increased radicalization of public opinion, financial instability and unprecedented new economic opportunities have all been attributed to new information and communication tools.

While we are struggling to understand and harness this transformation, the next generation of even more disruptive technology is making rapid strides: Ambient Intelligence. Part of a broader research agenda involving related fields of Ubiquitous/ Pervasive Computing [5], the Internet of Things [2] and Socially Aware computing [3] is based on two main assumptions:

1. The ability of computer systems to perceive, analyze, and react to complex events taking place in the physical world (so called context awareness) [1];
2. The spread of computing devices with the above ability, embedded in everyday objects, leading to a virtual omnipresence of intelligent, connected, proactive systems.

Thus, modern cars cannot only sense road conditions and register car telemetry, but also interpret the driver’s emotional state, identify dangerously behaving pedestrians, and, if needed, autonomously trigger an emergency breaking to prevent accidents. With emerging car-2-car communication technology, the information can be distributed in a peer-2-peer manner creating, dynamic, distributed ‘global awareness’. Another example is the modern smart phone. With built-in sensors they can monitor user behaviour including travel patterns (through GPS), physical activities (through built-in motion sensors), and social interactions (through sound analysis, call pattern analysis or the detection of nearby Bluetooth enabled devices). Based on such an analysis, they can make shopping recommendations, link to social networks or try to influence user behaviour (e.g. towards a healthier or more sustainable life style).

What differentiates Ambient Intelligence devices from other technology is that they are not mere passive tools enabling people to gather information and communicate more effectively. Instead they autonomously gather, process, and deliver information actively, facilitating, shaping, and modulating human actions and interactions. In summary, we face a situation where:

1. Intelligent devices influence human actions and attitudes as well as the information flow and interactions between humans;
2. They do so based on a combination of (a) explicit human input, (b) their perception of human behaviour and (c) the situation in the environment;
3. They do so over different temporal (from immediate information delivery to long term persuasion and opinion influence) and spatial (from interaction with the device owner to complex information diffusion over the internet or peer-2-peer communication) scales.

The above has to be considered within a global, interconnected, dynamic ensemble of devices and users opening the way to complex, distributed feedback loops, chaotic evolutionary dynamics and emergent phenomena. As a consequence the interaction of humans and Ambient Intelligence devices cannot be described as simple cause-effect relationships between two independent systems. Instead we have to consider a unified, **tightly interweaved, dynamic socio-technical system that co-evolves** according to the laws of complexity theory.

A review of AmI literature is at Chapter 2 “Enhancing Crowd Evacuation & Traffic Management, Through AmI Technologies – A Review of the Literature” and a review of the literature on co-evolution is at Chapter 3 “The Concept of ‘Co-evolution’ and its Application in the Social Sciences – A Review of the Literature”. **Co-evolution is reciprocal influence which changes the behaviour of the interacting entities** [4] and in the context of SOCIONICAL it is viewed as the reciprocal influence between the information provided by the AmI device, the device itself, and human behaviour.

3 The Volume as a Whole

The volume is presented in three sections. Chapters 4, 5, and 6 “Using Mobile Technology and a Participatory Sensing Approach for Crowd Monitoring During Large-Scale Mass Gatherings”, “Agent-Based Modelling of Social Emotional Decision Making in Emergency Situations”, and “Designing Complex Socio-technical Systems: Empirically Grounded Simulations as Tools for Experience-Based Design Space Explorations” discuss emergency-related approaches: Chapter 4 discusses the use of a smart-phone app designed to be used during an evacuation and tested during crowded events. Chapter 5 discusses agent-based modelling of decision making during emergency situations, involving emotions and the contagion of those emotions, which could spiral out of control. Chapter 6 describes a computer simulation approach to aid fire-fighters. Chapters 7, 8, and 9 “Enhancing Future Mass ICT with Social

Capabilities", "Emerging Phenomena During Driving Interactions", and "Effective Assessment of AmI Intervention in Traffic Through Quantitative Measures" discuss traffic: Chapter 7 explores how 'socially aware cars' could be making use of their social environment. Chapter 8 investigates AmI technologies, in the form of advanced driver assistance systems. Chapter 9 considers the challenge of quantifying the benefit of AmI within a complex system, specifically a motorway traffic system. The third section includes only Chapter 10 "City Scale Evacuation Simulation: A High-Performance Multi-agent Simulation Framework" as a first step in integrating the other two scenarios in a city-scale evacuation simulation, as well as addressing modelling and simulation at a massive scale.

Neither the smart phone app described in Chapter 4 nor the city-scale evacuation simulation described in Chapter 10 were anticipated in the original Description of Work and emerged as the project progressed and evolved. The app was developed as a natural consequence of looking at safe evacuation following a disaster. Two of the partners ETHZ and DFKI had the necessary technical expertise, while LSE in London and the University of Malta had the right connections with policy makers to organise the first two trials of the app, described in Chapter 4. The city-scale evacuation simulation evolved to address simulation of a complex system at a massive scale. However it also offers a means of integrating the two scenarios of evacuation and traffic; although the chapter focuses primarily on pedestrian evacuation, the simulation can also be extended to include traffic.

A summary outline of each chapter is given below.

4 Chapter 4: Using Mobile Technology and a Participatory Sensing Approach for Crowd Monitoring and Management During Large-Scale Mass Gatherings

Chapter 4 describes a framework that helps organisers of crowded events to infer and visualize crowd behaviour patterns in real-time, using a specially developed smartphone app. The SOCIONICAL app shows the density of a crowd, its direction and movement as a heat map superimposed on a Google map. Attendees at an event voluntarily download the app, which when active, allows the sending of location updates of the device; in return app users receive information about the event, transport advice, and background on historic/interesting buildings within their immediate vicinity; as well as the location of first aid stations and toilets. In the event of an emergency, app users will receive timely and location-targeted notification and advice directly from security/emergency personnel to help with the potential evacuation of the area.

The chapter is based on two trials; one conducted during the Lord Mayor's Show in London, UK in November 2011 and an earlier trial at the Notte Bianca festival in Valletta, Malta, in October 2011. Apart from verifying the technological feasibility, the chapter also reports on interviews conducted with app users and police forces that were accessing the monitoring tools during the event. The researchers worked closely with policy makers, the emergency services and event organisers and policy implications of using the SOCIONICAL app are discussed; as well as the response of users to being guided by an AmI device during a possible emergency.

Although the app was developed primarily to be used during an emergency, its trials during crowded but peaceful events have highlighted other useful features. For example attendees arrive at an event at different times, but tend to leave at the same time creating congestion and crowding at the most popular train and tube stations. The app can therefore be used to advise users that a particular station is very crowded while another one close by is not. The combination of interviews and the heat map also highlight potential changes in planning (e.g. the position of barriers) to make the following year's event safer.

The use of such apps, that provide information on the location of users, has ethical considerations and these were taken very seriously by the SOCIONICAL Consortium. For example, the data was anonymous, could only be accessed in aggregate and the identity of the user was protected at all times. Furthermore, the app was only active within the immediate geographic area of the event and only during that one day. The survey and the telephone interviews were also anonymous. The SOCIONICAL Ethics Committee was consulted and the criteria of the European Commission and the Ethics Committees of the relevant Institutions were also respected.

The chapter is based on the 2011 Lord Mayor's Show, but since then a second trial has taken place during the 2012 Show. During the second trial, the app was made available both for the iPhone and the Android. Furthermore, information on all the floats was provided which made the app particularly useful and attractive to users. The organisers of the Show intend to continue using the app in future Shows, after SOCIONICAL itself has ended on 31 January 2013. In addition, a different kind of app has been developed for the City of London Police, which provides regular up-dates on what is happening within the City of London (the financial district known as the Square Mile) to City businesses and residents. This version is for information only, but if there is an incident within the City, then app users will be asked to enable the location-sensing feature to enable the app to be used for location-targeted information and advice during the emergency. During the London Olympics, the app was also used by the City of Westminster Council to provide information on the events happening within the City of Westminster and continues to be used by Westminster City Council. The Lord Mayor's Show app, the City of London Police app and the Westminster 'What's On' app will be part of the legacy of the SOCIONICAL project.

Although most of the trials took place in London, there were also trials during the 2012 Vienna Marathon and the 2012 New Year's Eve celebrations in Zurich, apart from the pilot trial in Malta in 2011.

Since the app is based on interaction between users, an AmI device and information provided through that device, it provides a context for socio-technical co-evolutionary dynamics.

5 Chapter 5: Agent-Based Modelling of Social Emotional Decision Making in Emergency Situations

Chapter 5 looks at social decision making under stressful circumstances, which may involve strong emotions and contagion from others. For example, during the evacuation of a crowd, in an emergency, the quality of such decision making processes could make a difference to the survival of individuals. Decision making under stress involves high levels of emotions, adequate predictive capabilities, and social impact from other group members.

Recent developments in Social Neuroscience have revealed neural mechanisms by which social contagion of cognitive and emotional states can be realised. Mental states of individuals making a decision in a social context are not static. They often show high levels of dynamics due to social interaction. Neural mechanisms can account for mutual mirroring effects between mental states of different persons; for example, an emotion expresses itself in a smile which, when observed by another person, automatically triggers certain preparation neurons (also called mirror neurons) for smiling within the other person, and consequently generates the same emotion. Similarly, mirroring of intentions and beliefs may be taken into consideration. Chapter 5 is based on these mechanisms, and proposes an agent-based computational model, which is biologically plausible. Such a model may be useful not only for purposes of prediction, but also to gain deeper insights into the dynamics of the social mechanisms and their emergent properties as described in a non-computational manner in Social Neuroscience.

The computational model called ASCRIBE (Agent-based Social Contagion Regarding Intentions, Beliefs and Emotions) not only incorporates mechanisms for mirroring emotions, intentions and beliefs between different persons, but also addresses how within a single person beliefs and emotions affect each other, and how they both affect the person's intentions, in other words how they co-evolve.

As a case study the model was evaluated based on empirical data for crowd behaviour. Behavioural patterns emerging in large crowds are often difficult to regulate. Various examples have shown how things can easily get out of control when many people come together during large events. The consequences can be devastating when emotions such as aggression or fear spiral out of control within a crowd. A computational analysis is presented of the incident that happened at the Dam Square in Amsterdam on the 4th May 2010 and the authors show how the model is able to simulate an outburst of panic and its consequences.

Experiments were performed in which the ASCRIBE model, adapted to show crowd behaviour when a panic spiral occurs, was compared to three other models: (1) a baseline model where the agents do not move at all; (2) a model developed by Helbing and colleagues; and (3) a variant of the model where parameters related to contagion were set in such a way that there was no contagion at all, in this case the movement of individuals is only determined by their individual state. Contagion of emotional or other mental states is not present in these three models; and no evaluation with real qualitative data has been performed. By contrast, in the full

ASCRIBE model, mutual influencing did take place because emotions, beliefs and intentions were spreading to persons nearby. The results of the model analysis show that the inclusion of contagion of belief, emotion, and intention states of the agents, results in a better reproduction of the real incident than non-inclusion.

6 Chapter 6: Designing Complex Socio-technical Systems: Empirically Grounded Simulations as Tools for Experience-Based Design Space Explorations

Designing complex socio-technical systems poses significant challenges due to the large number of design options and the interdependency between the societal and the technical systems, resulting in a co-evolution of the two. This is particularly true for the Ambient Intelligence technologies, which couple the two systems more intimately than before. Chapter 6 proposes empirically grounded simulations as tools for the experience-based exploration of the design spaces of socio-technical systems. A case of such an exploration is presented, namely the design of advanced tactical navigation support for fire-fighters during search and rescue operations. Based on this case, the potential and limitations of experience-based simulations are discussed.

There are two aspects of particular interest when designing complex socio-technical systems. The first aspect is the experience that humans undergo, because their ability to assess them and provide feedback is at least partially embedded in their ability to act within a particular context, as it involves in part tacit knowledge. This is a general consideration that is valid for even the simplest use of tools. But one of the most significant differences of the emerging technologies of ubiquitous computing and ambient intelligence compared to tools in general and traditional computing in particular is that they can integrate more closely and more intimately into the relation of human beings with their respective context. As a consequence, using them can take on more thoroughly a quality of implicit interaction and designing them more deeply depends on experiencing their use in action.

The second relevant aspect for designing complex socio-technical systems comes about through the other new and emerging characteristic of ubiquitous computing and ambient intelligence, namely that they exist in the form of numerous interconnected devices that are embedded in the environment and provide services collectively and transparently. This makes recreating the context of use particularly challenging.

Chapter 6 discusses these approaches as tools for experience-based innovation processes or of simulation-based innovation. These approaches do have limitations, which are addressed by the FireSim approach, presented in the chapter, which has been developed to assist fire-fighter navigation.

The design process consists of a series of simulation techniques that allow groups of users to play out and experience scenarios while using increasingly sophisticated prototypes of novel technologies. The foundation of all of these simulations is created through empirical studies of the context of use in order to identify relevant and necessary aspects for inclusion in the simulations. The first technique is a role-playing simulation; the second technique is a virtual simulation in which multiple players can interact with interactive virtual prototypes of the technologies under consideration; the third technique is a mixed-reality simulation in which users play out scenarios in a real-world setting partially using systems and services that are already available as functional physical prototypes and partially using systems and services that are being injected from a synchronized virtual simulation.

FireSim was also developed to study large scale interventions, by modelling firefighter agents, using the empirical data obtained through the other techniques. Simulation techniques for the design of socio-technical systems cannot be judged independently of their context of application. They are used in a process involving human beings and they form a methodological ecosystem with other techniques. A given technique may be insufficient if used alone, but may become valuable when used in the right combination. The chapter emphasises that applying simulation techniques requires embedding them in the given design context.

7 Chapter 7: Enhancing Future Mass ICT with Social Capabilities

Next generation socio-technical systems research is challenged by the complex interactions of technological progress and the social nature of individuals using and adopting technology. For example, most recent advances in automotive technologies, together with the massive deployment of vehicles worldwide, indicate a different understanding of traffic, not as a collection of cars, but as a web of social connections. Chapter 7 seeks to adopt the capacities of socially aware interactions among individuals to vehicles engaged in mass traffic. The authors discuss how ‘socially aware cars’ could be making use of their social habitus, i.e. any information which can be inferred from all of its past and present social relations, social interactions and social states when exposed to other vehicles in live traffic. Examples such as ‘socially inspired lane changes’ and ‘socially controlled hazard zone avoidance’, evidenced by large scale agent based simulations, show that socially capable vehicles represent a potentially effective way to avoid undesirable mass traffic phenomena. A prospective is given on how to make social awareness an underpinning design principle for ICT deployed at a massive scale, in general.

Chapter 7 is not addressing social interaction between drivers, but focuses on the automotive domain as one field with significant potential in enabling social interactions. It would be relatively easy for a car to provide status information continuously (location, speed, driving destination, etc.) using on-board information systems, navigation devices, and GPS information. Furthermore, it would be possible for the car to exchange a type of social information (e.g., feelings and emotions) by taking information from diagnostics systems such as the engine control unit (ECU) or the powertrain control module (PCM) into account (error codes, condition of engine, clutch, etc.); and last but not least, the mental/social state of the driver could be determined and used for car status adaptations. The chapter considers some issues associated with the above:

- A car's social status update might be used to advise other drivers in its vicinity of an icy road ahead, or to recommend re-routing because of a traffic jam or blocked route.
- A social car, like a human, would require a social environment such as intelligent roads with dynamically changing lanes; road signs adapting to the driver, etc., and would function less well in isolation.
- Capabilities of social cars: (i) 'learning', e. g. a jam every workday on the same route and at the same time can be learned and the car would recommend an alternative route (particularly relevant for drivers using a rental car in an unknown area); (ii) 'remembering' road signs with certain speed limits in association with low temperatures, which mean ice on the road. This linked to 'learning' could lead to slowing down around a sharp bend in icy conditions; (iii) 'forgetting' these conditions during the summer.
- 'Smart road concept': Dynamic reconfiguration of the road network, for example, by changing lanes according to direction inbound/outbound and depending on the time of day or road usage.

The authors highlight the potential impact of such an approach. By focusing on the driver rather than the technology, with regard to complexity reduction in vehicle operation, they see great potential in revolutionizing traffic in Europe and in achieving the long term visions and road safety goals of the European Union. In particular, they expect that drivers will have a more relaxed driving experience and feel pleasure, while controlling their cars. A further expected impact is that collective understanding of the traffic situation together with concerted behaviour modification of the drivers could potentially facilitate the reduction of global fuel consumption or CO_2 emissions.

The authors have identified some of the most crucial problems in vehicle operation and have proposed a number of possible solutions to establish human-computer confluence in the automotive domain. This concept should be understood as a specific instantiation of human-computer interaction, working towards the goal of understanding the symbiosis and co-evolutionary dynamics between drivers, cars and infrastructure. This covers not only the sharing of information about an oil spill on the road, but also includes reasoning about driver states and social or emotional interaction, and can be achieved, for example, by modelling driver behaviour, studying distributed negotiation processes, performing driving studies and simulations, and relating their results to observations made in reality.

8 Chapter 8: Emerging Phenomena During Driving Interactions

AmI technologies, in the form of advanced driver assistance systems (ADAS), can be used to deliver information, give recommendations and assist drivers. Chapter 8 describes potential emerging effects of future ADAS (e.g. efficient cruise control) on driver behaviour (including cognitive-emotional mechanisms) by experimental studies using driving simulators.

ADAS often promise to make traffic smarter, but is this promise true? The chapter investigates whether drivers and traffic profit from such systems and which (possibly negative) side effects could emerge. These questions point to the methodology to be used to evaluate driver interactions and road traffic and the influence of new ADAS. The chapter uses three criteria for analysis, which often influence each other and co-evolve in the process: traffic safety, energy efficiency, and emotional climate (including driver stress, workload, and comfort), at three levels: individual, group and system level. This provides a 3 × 3 analysis matrix.

The analysis identified one crucial aspect that the technical development of ADAS has to be tailored to the skills and limits of the driver. Assistance systems must be developed that are easy to learn, comprehensible and usable. The driver is confronted with many new demands, such as learning the usage and functionality of the system, while at the same time many drivers could be helped by compensating individual limitations and handicaps (e.g., automatic parking for older drivers).

The chapter presents several examples for emerging phenomena during driving interactions studied by using driving simulation, especially the innovative approach of multi-driver simulation. Regarding ADAS, three systems were under study: hazard warning, merging assistant and efficient cruise control. All three have the potential to improve driving on an individual, group, and system level.

A systematic analysis of the effects and implications of such systems, however, needs an interdisciplinary approach involving traffic engineering and driving psychology. Furthermore, it requires the integration of diverse methodologies such as experimental runs in driving simulators, studies in real traffic and traffic simulations to provide a comprehensive picture.

The chapter explores the following exemplary studies of emerging phenomena, during driving interactions, using multi-driver simulation. The main focus of each study is given within the brackets:

- Braking convoy (study of indirect and emerging effects in a complex traffic situation)
- Group driving (study of driver-to-driver effects in a group of drivers)
- Braking car (study of safety effects of ADAS on a group of drivers)
- Merging assistant (study of emotional effects of ADAS on a group of drivers)
- Efficient Cruise Control (development of an innovative ADAS and study of effects on energy consumption)

The braking convoy study highlighted that non-trivial interactions between road-users could emerge that are not easily predictable. In this experiment, the effects of right lane events on the behaviour of drivers in the left lane of a motorway were studied. The results indicated that events in the right lane of a motorway could have effects on the driving behaviour of the drivers in the left lane. Most of the current traffic simulation models do not include such lane-to-lane influences.

The second study focuses attention on the effects that emerge within a group of real drivers during relatively simple driving manoeuvres. It asks what kind of influence does the position in a group of drivers have; how and by which parameters this influence, if any, can be described. An analysis of driving parameters showed that in multi-driver conditions, the speed variation depends on the group position. Drivers who are at the back of the group show more variation of speed than drivers further ahead. As a consequence, the last driver has to accelerate strongly, in order to catch up with the other drivers or has to brake significantly, in order to avoid an accident.

The braking car experiment analysed the effects of a system that warns the driver that a hazard is likely to emerge (hazard warning system, HWS), when for example a leading vehicle brakes abruptly. It found that the use of such AmI technology could lead to safer roads, especially if the first driver following the hazardous vehicle is able to anticipate and to respond by increasing the time headway. As a consequence, this driver does not need to brake as fast as would be the case without assistance.

The merging assistant study looked at the effect that using a merging assistant could have on drivers' interactions and emotional response. The findings showed that a merging assistant could lead to significant improvements of traffic safety and traffic climate by reducing the potential for conflicts during merging interactions on the motorway.

The fifth study analysed a new type of cruise control system called Efficient Cruise Control (ECC). This system's aim is to make driving smarter and greener and can be characterised as an enhanced ACC system, which actually reduces the energy consumption of a fully electric vehicle.

9 Chapter 9: Effective Assessment of AmI Intervention in Traffic Through Quantitative Measures

Chapter 9 considers the challenge of quantifying the benefit of Ambient Intelligence (AmI) within a complex system, specifically a motorway traffic system. By its nature, the deployment of AmI is distributed and inconsistent. Hence, an evaluation strategy must consider the individual to ensure desired or undesired effects are not hidden by only measuring at the whole-system level. For the evaluation the authors use *quantitative measures for self-organizing properties of socio-technical systems*. Although the measures are defined analytically for micro-level models, the systems are usually too complex to evaluate the measures analytically. Approximation methods are therefore used based on simulations, such as time series, which are used for the approximation of the measures for self-organizing properties. The results of the evaluation can be used for the analysis of the scenario, for the optimization of system parameters and for the assessment of AmI intervention in the system. For the considered devices, the main goal is the increase of safety in traffic by allowing system designers and infrastructure-operators to implement or dynamically choose the most appropriate device and parameters.

The chapter looks at traffic on a motorway as the domain of study, and at vehicle breakdowns and crashes on motorways, as the specific problem, as they have direct and indirect impacts on traffic flow (e.g. efficiency and economy) and traffic safety.

The loss of a lane available to traffic can create a sudden drop in traffic flow and make driving conditions dangerous through the sudden change in traffic speed and the requirement of many braking and merging maneuvers within a confined region. These changes often result in follow-on accidents. Recent developments in vehicle-to-vehicle and vehicle-to-infrastructure communication technologies have made it possible for incident information and driving instruction to be delivered to motorists far more rapidly than it was traditionally possible. Hence, it is now technically plausible that a vehicle-communication based system could allow even a small number of equipped and compliant drivers to rapidly improve the driving situation for others by taking appropriate action. This could happen without the aid of any infrastructure.

Two broad types of system for the AmI devices were tested by the authors. The first was a fine-grained speed reduction system (also known as harmonization (HAR) or speed ‘funnel’) where the (desired) speeds of vehicles are set individually by an on-board system according to the distance from a point of danger. The second system was an adaptive cruise control (ACC) system, when following another vehicle in range. Here, the acceleration is set in order to maintain a specific time headway. Both systems feature a common danger point detection algorithm that decides whether alerts are generated, forwarded, and whether a system is activated. Thereafter the control of the vehicle is governed by the HAR algorithm or ACC algorithm until the origin of the alert is passed.

Based on the two properties of traffic harmonization and safety in general, sought from the systems, the authors examined three measures. With measure #1, bad states are situations where velocities have a high variance coefficient, because a high variance of velocities implies that many different speeds are present in the system. Analogously, measure #2 specifies a good state by a low variance coefficient for the velocity changes that each vehicle makes from one time step to the next. These measures express the “system goals” of motorway speed management, namely to see less variance in the overall speed, and to prevent drivers from having to adjust the speed suddenly. Measure #3 attempts to examine the safety effects more directly by using a simple safety ‘proxy’ indicator, ‘Time-To-Collision’ if one vehicle is closing in on another.

The results show that the influence of the system parameters differs according to the measure used, even though ideally all measures, which are examining desirable states, should show similar results. Intuitively, a higher equipment rate should lead to a situation, which is safer. But the simulation results show, that while this often works for measure #2, which pertains to individual driver experience, it rarely holds for measure #1, which examines the entire analyzed area. Measures #1 and #2 suggest that the HAR system is often better than the ACC system, especially for a high input traffic flow. For measure #3 there is so little improvement to be made that the use of any of the systems usually seems unnecessary.

Overall, the results are mixed and cannot be used to choose one measure as the ideal or one system as better than another. None of the measures bring a noticeable benefit at low equipment rates. This may serve as a warning: Systems that seem sensible for a single driver may only bring about benefits for all traffic when high equipment rates are ensured.

The authors emphasise that the evaluation methodology used in this chapter is not restricted to the special scenario of an accident on a highway, but can be used in any other context of self-organizing systems where input data can be measured.

The chapter also has a very useful appendix which discusses modelling of a socio-technical system and defines quantitatively the following concepts: autonomy, emergence, target orientation, resilience and adaptivity.

10 Chapter 10: City Scale Evacuation: A High-Performance Multi-agent Simulation Framework

Understanding the dynamics of urban evacuation systems – due to disasters such as flooding or tsunamis, terrorism or nuclear power plant accidents – has elicited massive interest in the past few years. In Chapter 10 simulation models of social agents at massive scale are presented and high performance simulation experiments are conducted, to analyse realistic evacuation models at city level. Variations of demographics and the morphology of cities, together with population densities, mobility patterns, individual decision making and agent interactions are analysed.

The main focus of this Chapter 10 is to present generalization techniques to address the challenges of modelling and simulation at city scale with individual and functional diversity, which results in unpredictable and emergent behaviour patterns with active co-evolutionary dynamics as a result of the macro-to-micro feedback loops. To be useful, the simulation should not be specific to one city and its features. To address this problem, the authors have investigated the main typological features of European cities and settled on 5–6 main city types and their features. A city type represents many cities of the same genre, hence eliminating the need to model each city separately.

The authors use an Aspect oriented Modelling (AoM) paradigm, which allows for agent interaction at different scales. Simulation is performed at a real physical and demographic scale after converting a high resolution city map into grids of cells. The Cellular Automata (CA) describing the space, allow the mobile agents to be manoeuvred. It also provides a natural way to link an agent to a real space. However, a city-scale simulation at this scale, in terms of space and number of agents, cannot be handled without explicitly employing a Parallel and Distributed Simulation (PDS) hardware and software platform. Chapter 10 works with a sociotechnical system for urban mobility with geo(graphic)-simulation capabilities, which is referred to as a geo-socio-technical-urban-mobility simulation.

There is an increasingly strong relationship between urbanisation and disasters which is the focus of the chapter. A city or an urban area is constituted by a specifically designed infrastructure, other supporting structures, and buildings that create an environment to serve a population living in a relatively small and confined geographical area. There is a tight interrelationship and interdependence of systems within a city and a disaster often affects many related systems. Although urban areas are particularly vulnerable to disruptions from extreme events, the evaluation and management of disaster is the most underestimated issue in urban development, yet the threat of such disasters is increasing.

The 2003 World Bank report "Building Safer Cities: The Future of Disaster Risk" categorizes the impacts at four levels: Globalization and the Economic Impacts of Disasters; Environment, Climate Variability, and Adaptation; Social Vulnerability to Disaster Impacts; and Vulnerability of Critical Infrastructure to Disasters. According to the report, there is a need to manage the urban hazards at two levels: developing innovative approaches to disaster risk reduction and changing people's perception of risk. In addition to recognizing the importance of new and innovative approaches, several risk management techniques are recommended, including: investing in improved data and indicators of disaster risk, developing community participation programs, creating new risk transfer and risk reduction mechanisms, and reinforcing partnerships among stakeholders to reduce communities' vulnerability to risk.

The discussion in the chapter makes it evident that a city (or a city type) defines its vulnerability towards a disaster. It also defines its capability to cope with a disaster. Hence it is necessary to understand city types in greater detail and in particular the factors describing the city's vulnerability towards disasters and its capability in facing them. Chapter 10, therefore, presents a typology of cities based on general and qualitative features. The former include purpose, architecture and history, topography and culture. The qualitative features include knowledge-based economy, smartness, urban mobility and polycentricity. Different city types are defined and specific examples given.

The authors describe in detail how the modelling and simulation of cities is approached. The simulation is performed at two scales: small-scale and city-scale. Since the basic purpose of the simulation is evacuation, the analysis of the results is anchored at evacuation patterns and efficiency.

The chapter concludes by pointing out that the potential of parallel and distributed simulation for an agent-based geo-simulation can only be materialized if in addition to an efficient hardware architecture, the algorithmic optimization is also taken care of in order to fully utilize the agent-based modelling strength in which each agent may potentially have a unique behaviour pattern. Scale becomes a real issue if the focus is an urban space with billions of space agents in addition to millions of mobile agents. Simulation of urban mobility is a complex task with a variety of important aspects. The authors have tried to conceptualize these aspects into categories and have designed an agent-based PDS framework to simulate. They emphasise however, that this is on-going research and that they intend to enrich the agents' models with more data, information and behavioural rules in future work.

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Enhancing Crowd Evacuation and Traffic Management Through AmI Technologies: A Review of the Literature

Eve Mitleton-Kelly, Ivan Deschenaux, Christian Maag, Matthew Fullerton, and Nihan Celikkaya

1 Introduction

This document is a review of the burgeoning literature on the utilisation of AmI (Ambient Intelligence) technology in two contexts: providing support and enhancing crowd evacuation during emergencies and improving traffic management.

The review opens with a brief introduction to the field of AmI, which emerged as a synthesis of several prior areas of research. A list of key elements for a definition of AmI is established, and the opening section ends with a survey of some recent contributions concerning the direction of future research on AmI, as well as some of its important, non-emergency related applications, to provide the broader context of AmI research and application.

The following section turns to the utilisation of AmI technologies for the improvement of evacuation during disasters and emergencies. It is worth emphasising that this is both a specialised and recent field of research. The earliest publications we found that make more than anecdotal mention of AmI's potential for improving evacuation date back only to the 2000s. Earlier research on crowd evacuation, sensor networks, and computing does exist, but it rarely uses the term 'AmI' explicitly. Indeed, this terminological issue is important: there are forms of research which operate under assumptions similar to those of AmI, yet do not use

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the same denomination.[1] We distinguish two types of research: that which uses AmI as a technology for crowd monitoring, and that which uses AmI to modify crowd behaviour. There is some overlap between these types, and we found in particular that research of the latter type often comprises aspects of crowd monitoring. First, we review a selection of articles concerned with computer-vision techniques for crowd analysis. Within these, ‘holistic approaches’ to crowd behaviour are the most relevant to the issue of emergency detection. This is the case because they have been the most concerned with the detection of anomalous behaviour in crowds, of which behaviour during emergencies can be understood as a subset. Second, we turn to non-vision based approaches for crowd monitoring, i.e. approaches that do not use cameras. We focus in particular on research being led by SOCIONICAL partners in which location-aware smartphones are being used to monitor crowd behaviour [76–79]. Third, and finally, we turn to another AmI technology developed by SOCIONICAL partners, known as the LifeBelt [25–27]. This research aims to optimise crowd behaviour during evacuations without necessarily requiring external monitoring.

The review then turns to traffic monitoring. Advanced driver assistance systems (ADAS) and intelligent transportation systems (ITS) are mentioned as utilisation areas. These systems support traffic safety and efficiency since they provide warning or information about the surrounding situation (e.g. congestion level, weather conditions) and as they increase comfort (e.g. ACC), safety or the ease (e.g. navigation) of driving action. Future developments are anticipated to be in many aspects of transportation, but especially in ICT systems (particularly in “cooperative” systems) in which great potential for improving traffic safety and efficiency is seen. In this section, the expected development in the level of interaction between infrastructure and drivers and its consequences are emphasized. Finally, challenges and key considerations for the implementation of new systems are mentioned. These include concrete factors such as costs or technical problems and more strategic factors such as data privacy and awareness of the effects and efficiency of the newly introduced systems.

The last section of this review concerns a problem faced by most researchers trying to optimise AmI systems for crowd evacuation, viz. the fact that it is impossible to test new technologies during real emergencies, and expensive and impractical to run large-scale ‘fake’ emergencies (on this issue see e.g. [59]). Computer simulation is often resorted to in order to test hypotheses on crowd behaviour and on how AmI might influence it. Simulating crowd behaviour is a vast topic and it cannot be surveyed exhaustively in this document. Instead, we narrow the focus to publications which are strongly related to research on evacuation.

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[1] In fact, this sometimes rendered the choice of publications to be included in this review problematic. In part, the fact that the review contains important amounts of research led by SOCIONICAL partners is an effect of their more frequent, explicit utilisation of the term ‘AmI’. In the absence of this term, we opted for a somewhat conservative view, including only those publications in which the connection to AmI is obvious.

2 AmI: Main Characteristics and Recent Suggestions

AmI is a recent field of research. The term ‘Ambient Intelligence’ came into use during the late 1990s [8,80]. The inaugural issue of a journal dedicated to the field was published in 2009 ([40], Aghajan H. & Augusto J.C. chief eds.) and a comprehensive handbook covering advancements in AmI was published the following year [55].

Some authors [64, p. 1] cite Norman [57] as having developed certain ideas in which it is rooted. More often, its early origins are situated in a well-cited paper by Mark Weiser [74], in which it was suggested that computing devices in the twenty-first century would become so ubiquitous that people would slowly stop noticing them. In other terms, Weiser predicted that various elements of hardware would reach a level of miniaturisation and interconnectivity so advanced that their users would engage with them quite naturally, without any strong, conscious realisation of doing so. This proposal is usually recognised as having provided the original impetus for the development of the fields of ubiquitous and pervasive computing. The field of AmI emerged in turn by calling for an understanding of the total integration of intelligent devices in the physical environment [1,2]. This can be interpreted as an evolution of Weiser’s initial vision: where he announced high levels of integration of computer networks in physical environments, AmI brings the crucial idea that these very networks can display intelligent characteristics. The term itself, ‘ambient intelligence’, was introduced by Emile Aarts ([80, p. 475], footnote 1). It came into use during the late 1990s and grew in popularity during the 2000s. [8, p. 2]

2.1 Definition

AmI is a field of research and technological development in which several prior fields of research converge: artificial intelligence and robotics, multi-agent systems (MAS), sensor networks, human-computer interaction (HCI), and pervasive computing (PeC) [8, p. 3]. As such, it is often recognised as inherently multidisciplinary [64]. Perhaps this explains the high number of definitions of AmI given throughout the literature. It is clear, however, that this plurality of definitions draws a coherent portrait of AmI, which has recently been concisely summed up by Aaarts and Ruyter [2, p. 5]: “In short, Ambient Intelligence refers to electronic systems that are sensitive and responsive to the presence of people.” Some noteworthy characteristics of AmI are given below, and a more detailed explanation of the concept features in the Introduction chapter “The SOCIONICAL FP7 Project”, to this volume.

- The AmI vision relies on the **miniaturisation of computing devices**. This is essential for their seamless integration into the environment, so that they may be ‘forgotten’ by users. The non-intrusiveness and omnipresence of computing devices is what is picked out by the term ‘ambience’ [2, p. 6]. Ultimately, the hardware layer becomes nearly invisible, leaving only the user- interface evident to the user [8, p. 1, 18].

- AmI devices form a **network that is embedded in the physical environment** and that is sensitive and responsive to people’s presence and behaviour [2, p. 5]. The number of devices that compose an AmI network is usually high, and they can be of various different types. [58, p. 1]
- The intelligent networks formed by AmI devices are often dubbed ‘**smart environments’** (see e.g. [8,20]). Such environments are meant to provide support for the people who live in them on a daily basis, with an emphasis on preserving ease of use. [2]
- The networks that compose smart environments are **context-aware**; they respond to new situations in a context-sensitive way. Put differently, they are sensitive and responsive to events in the physical world, which can be both complex and dynamic [4]. Such networks include vision and other sensor capacities to acquire information on the environment in which they are embedded.
- As well as a capacity to respond in function of context, ‘intelligence’ in an AmI context refers to **social awareness**: smart environments and AmI devices are capable of responsive interaction with the user [2, p. 8]. This feature has led to developing the concept of ‘socially aware computing’ [47]
- The interaction between technologies used in AmI and humans takes the form of a **feedback loop**: “the system reacts to human behavior while at the same time influencing it” [84, p. 103]

2.2 Exploring the Research Space

AmI is not a rigid or fixed discipline, but an evolving field of research. Some areas which are being explored include:

Synergetic prosperity: It has been suggested that the development of AmI has been mainly technologically motivated, rather than truly attending to user requirements. To counter this undesirable effect, Aarts and Grotenhuis have proposed the ‘synergetic prosperity’ model, which is more sensitive to users’ wants and well-being [1].

Human-centric computing: Similarly, researchers in AmI are now sensitive to the issue of human-centricity. The guidelines of Human-Centric Computing (HCC) potentially apply to all disciplines which involve computing. However, authors working in the field of AmI have called for investing the concept with new meaning, enabling the user to truly tailor an AmI network or Smart Environment to his personal requirements, so as to avoid any form of invasiveness [8, p. 7].

Pervasive Computing at Scale (PeCS) and the Internet of Things (IoT): The scale of the networks envisioned in AmI and the associated fields has grown immensely.

> This change of scale represents a new challenge for those working in these disciplines, especially insofar as it is crucial to maintain efficiency while scaling up networks to the size envisioned today [21]. The Internet of Things (IoT) [33] allows us to picture a world-wide network of billions of different objects all interconnected in one universal network.

In addition to these contributions, it should be noted that even when changes aren't delineated as drastically, AmI is being taken into many new directions: ambient control, tangible interfaces, end-user programming, sensory experiences, social presence, trustful persuasion, e-inclusion and ethics are just some examples of the many domains AmI researchers are exploring [2, p. 9ff].

2.3 Applications

Apart from crowd evacuation and traffic, which are discussed in the following sections, a number of applications of AmI are being developed.[2] Among these, some noteworthy examples are:

- *Health monitoring and assistance* [20, pp. 66–68]: Homes can become smart environments, providing health monitoring and assistance to those who need it. Two categories of population are targeted in particular: elderly people (e.g. [61]) and those with disabilities (e.g. [3]). Hospitals can also benefit from the introduction of AmI: "Applications of AmI in hospitals can vary from enhancing safety for patients and professionals to following the evolution of patients after surgical intervention" [19, p. 20].
- *Smart classrooms and smart offices*: Research on smart classrooms has shown various ways in which AmI can assist speakers and lecturers, and improve distance learning [29,62], while smart offices can accelerate decision making processes [67,81].
- *Entertainment and education*: Ndiaye et al. have developed "COHIBIT, an AmI edutainment installation that guides and motivates visitors, comments on their actions and provides additional background information while assembling a car from instrumented 3D puzzle pieces" [56].
- *Smart cities, AmI in urban environments*: As pointed out by Hollands [38, p. 303], the term 'smart city' has yet to be defined clearly. It has been noted, however, that "Cities are complex systems, composed of myriad biological and non-biological components that function and interact within multiple coincident spatio-temporal scales" [12, p. 1744] and that "'smart city' concepts are not just a vision but are currently being deployed in cities like Brisbane, Glasgow, Amsterdam and Helsinki" [12, p. 1760]. For a recent overview of AmI in urban environments, see Böhlen and Frei [15].

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[2] For a more comprehensive overview of the diversity of applications of AmI, see [8] and [69, pp. 73–74].

- *Emergency situations not related to evacuation*: There are forms of emergency response other than crowd evacuation, which can be improved through AmI. For example, tracking the location and health status of patients is a process that can be facilitated by the introduction of appropriate wireless sensor networks. Such networks could comprise "vital sign sensors, handheld computers, and location-tracking tags" and "have the potential for enormous impact on many aspects of disaster response and emergency care" [45, p. 22]. It is suggested that this may be particularly useful in situations where the health status of multiple victims needs to be rapidly assessed. In crowded environments, the improvement of evacuation is not the only issue that can benefit from AmI. Gerritsen [32] discusses aggression control, suggesting that equipping police officers and other individuals involved in aggression control with AmI devices capable of intelligently predicting high-risk zones will help reduce aggression and riots.

2.4 Measurement Approaches

When a complex system is designed, implemented or used, there are many situations, where an evaluation of the system is necessary. During the design phase, different high level models may be evaluated and compared to predict the behaviour of the system and to decide which model leads to the desired results. During the implementation of a system, many decisions have to be made about system parameters and local rules for the components, so an evaluation of different settings is necessary to achieve the desired results. During the run of an existing system, an evaluation can be used for an optimization of the system. For all these evaluations, the goal has to be specified in advance, such that the design, implementation and optimization can be done with respect to the specified goal. The challenges are:

- How can the goal be formalized in the mathematical model of the system?
- How can the mathematical model be evaluated with respect to the specified goal?
- How can the results of the evaluation be used to improve the design and implementation of a new system or for the optimization of an existing system?

In SOCIONICAL, different state of the art evaluation approaches have been explored.

2.5 Some Criticisms

Although the majority of publications are enthusiastic about the development of AmI, it is worth noting that some researchers have expressed doubts as to whether its goals are realistic [39]. Others have envisioned frightening 'dark scenarios' that AmI could bring about, in order to create a set of safeguards for its development [80].

3 AmI for Crowd Evacuation

Before discussing the way in which AmI can be used for the improvement of crowd evacuation, it is worth noting that the following operational understandings have been offered:

- **Crowd:** "a large number of people (and/or) things considered together" [26]
- **Evacuation:** the process whereby the crowd can be directed "towards safe exit(s) as fast and as calmly as possible" [26, p. 19].

These are quite clearly minimal definitions. For an extensive literature review on the meaning of crowds, see the *'Social Science Literature Review: Emergency, Queue and Crowd: Definitions and Cultural Comparisons'* prepared by the SOCIONICAL LSE team, 2012 (www.lse.ac.uk/complexity) [70].

Broadly speaking, two types of research on AmI technologies for the prevention of crowd disasters and the improvement of evacuation can be distinguished. First, AmI can be utilised to *collect* real-time information on crowd behaviour and to *detect* crowd emergencies, so that the prevention and response to such emergencies can be ensured through external means. This is typical of research which uses computer vision to monitor crowd behaviour, i.e. research in which computing is used to analyse data provided through cameras. There is an extensive literature on this topic, and a very brief overview is given in Sect. 3.1. In the second type of research, AmI technologies are used to *influence* crowd behaviour directly. Research with such an objective appears scarcer, although some SOCIONICAL partners have been exploring its potential. Section 3.2 reports on forms of crowd monitoring, which do not rely on cameras. Although these might be thought to fall under the first type, in which AmI is not used to influence crowd behaviour, there is an emergent trend (led by SOCIONICAL partners at DFKI, ETHZ and LSE) in which location-aware smartphones are used as the primary source of data on crowd behaviour. Since this allows for feedback and advice to be sent to individual devices (anonymously), the method potentially allows for direct improvement of evacuation processes [79]. Finally, Sect. 3.3 reviews research conducted by SOCIONICAL partners at Linz University on the LifeBelt, a wearable device capable of improving crowd evacuation by providing haptic feedback to its user, i.e. feedback through the sense of touch.

3.1 Approaches Based on Computer Vision

The bulk of the research in which sensor networks are used to monitor crowd behaviour and detect crowd-related emergencies is based on computer vision. Two literature reviews on this topic were published recently: Zhan et al. [82] and Silveira Jacques Junior et al. [69]. The former lists the multiple applications of computer vision for crowd analysis: public space design, virtual environments, visual surveillance, and intelligent environments. Of particular relevance to the present document is the application called ‘crowd management’. Indeed, “crowd analysis can be used for developing crowd management strategies, especially for increasingly more frequent and popular events such as sport matches, large concerts, public demonstrations and so on, to avoid crowd related disasters and ensure public safety” [82, p. 345]. The second review makes a similar point: “[The behavioural analysis of crowded scenes] can be used for developing crowd management strategies, to avoid crowd related disasters and insure public safety” [69, p. 66].

Both documents survey various techniques and algorithms that have recently been developed in order to improve crowd tracking and analysis, pointing out that “The approach favored by psychology, sociology, civil engineer and computer graphic research is an approach based on human observation and analysis” [82, p. 345], whereas “computational methods such as those employed in computer graphics and vision methods focus on extracting quantitative features and detecting events in crowds, synthesizing the phenomenon with mathematical and statistical models” [82, p. 346].

[69, p. 68] opt for a tripartite division of the field of computer vision for crowd monitoring: ‘People Counting’ (which can be achieved through pixel-based, texture-level or object-level analysis), ‘People Tracking’, and ‘Behaviour Understanding’ (which can be studied using either object-level or holistic approaches). The topic of emergency detection appears most often in the sub-field of computer vision concerned with ‘Behaviour understanding’. Indeed, crowd emergencies can be understood, to a certain extent, as cases of abnormal crowd behaviour.[3] Research on abnormal crowd behaviour detection using object-level approaches is described by e.g. Cheriyadat and Radke [18] and Ma et al. [48], however, it is an issue that is mentioned more frequently by researchers using holistic approaches. Some examples are given below,[4] however, we do not aim to provide a comprehensive overview of the algorithms used in computer vision to detect emergencies.

Boghossian and Velastin [13] note that “Closed Circuit Television (CCTV) systems are widely employed by police and other local authorities to monitor public events that involve crowd interactions in confined areas. The early detection, and so the prevention, of crowd-related emergencies are the main aims of CCTV operators.” [13, p. 961]. They present a method whereby computer vision can assist CCTV operators in the early detection of crowd emergencies. The method is based principally on a motion-based approach to detect three critical indicators of crowd emergencies: circular flow paths, that “originate close to scene exits when large crowds attempt to evacuate the scene” [13, p. 962], diverging flows, an indication of local threats, and obstacles.

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[3] Although the study of abnormal crowd behaviour is not limited to emergencies, but rather, touches upon other subjects such as surveillance (see e.g. [42]).

[4] A number of the articles we mention below are reviewed in more detail in Silveira Jacques Junior et al. [69].

In a similar vein, Andrade et al. [6] present an automated, unsupervised solution for the detection of abnormal events in crowds. They note that "in scenarios where hundreds of cameras are monitored by a few operators, behavioural analysis of crowds is useful as a tool for video pre-screening" [6]. They propose a method based on an analysis of the optical flow of crowds involving unsupervised feature extraction and fitted hidden Markov Models (HMM) to extrapolate 'normal crowd behaviour' from video streams in which no abnormality occurs. This allows for the development of an algorithm capable of detecting abnormal situations in crowded contexts. The efficacy of the proposed technique is confirmed through computer simulation.

Ali and Shah [5] introduce a method using the principles of Lagrangian particle dynamics to detect instabilities in the flow of crowds, which functions by overlaying a grid of particles on video data to detect crowd flows and irregularities in these flows.

Mehran et al. [51] propose a method relying on the Social Force model [36] to detect crowd abnormalities that is specifically capable of detecting escape panic. The technique uses a combination of optical flows and a grid particle overlay in order to estimate the interaction forces between those particles. The technique is shown to be "effective in detection and localization of abnormal behaviors in the crowd" [51] and to outperform techniques based on pure optical flow analysis.

Kratz and Nishino [43] take on the challenge of producing an algorithm capable of computer vision based crowd analysis in extremely crowded situations. They point out that extremely crowded environments are difficult to analyse not only for computers, but also for human operators of video-surveillance systems, and therefore, a successful automated method would represent an important contribution. In the method they propose, which utilises "3D Gaussian distributions of spatio-temporal gradients" and Hidden Markov Models, the "key insight is to exploit the dense local motion patterns created by the excessive number of subjects and model their spatio-temporal relationships, representing the underlying intrinsic structure they form in the video" [43].

3.2 Non-vision Based Approaches

A considerable amount of research is being conducted on the utilisation of AmI in urban environments (see Sect. 2.3 above). In such environments, there is a trend in which non-vision based approaches are used to monitor crowds. This usually relies on aggregated data provided by location-aware devices such as mobile phones or GPS devices. Some examples follow.

The MIT SENSEable City Lab achieved real-time mapping of fluid components of Rome, i.e. of people and of traffic [17]. The collected data to achieve this came from devices such as mobile phones and GPS devices. Locational data was aggregated from a cell phone company, a bus company and a taxi company. Among the many applications of this technology, the authors cite its relevance to crowd monitoring. The study looked at people's behaviour during two very crowded events: "Viewing the World Cup final match between Italy and France on July 9, 2006, and celebrating the arrival in Rome of the winning Italian national team on July 10", and "Madonna's concert in Rome on August 6, 2006" [17, p. 252]. This real-time mapping of Rome was discussed further in a later paper, in which the authors point to some of the other potential applications of the technology: "The platform has potential applications in a variety of areas, including urban management, route planning, travel-time estimation, emergency detection, and general traffic monitoring" [16, p. 142]. Some technical details on the data collection for the Real Time Rome project as well as discussions of the directions the research might take are given in Reades et al. [63].

Even if they do not always explicitly mention emergencies and evacuation, researchers have investigated the possibility of using data provided by location-aware devices to map and monitor activity in urban environments. For example, such data collection processes have been used to understand the behaviour of spectators during sporting events [54], the way spaces are occupied during other important events [72], and a number of authors have discussed the application of this type of technology to traffic regulation [14,37,75].

SOCIONICAL partners Wirz et al. [76] have proposed utilising wearable acceleration sensors to detect group formations, arguing that "static infrastructure (e.g. cameras and communication system) may not work reliably or may not be deployed in the possibly unforeseen critical areas" and that "Current mobile phones provide sensors and local communication. Their prevalence may allow them to play a decisive role in the future to understand individual and collective behavior in real-time". Initial trials were run to demonstrate the potential of a proposed three-step procedure to infer crowd characteristics on the basis of the data delivered by wearable acceleration sensors. The validity of this method was further demonstrated in Wirz et al. [79], in which some further limitations of vision-based approaches are signalled: "Vision-based approaches face several limitations: Cameras cannot capture elements outside their fields of view or occluded by other obstacles and it is still difficult to fuse information from many cameras to obtain global situational awareness. Another drawback is the need for good lighting conditions. Furthermore, as many events happen during the night, the application of a vision based approach is limited" [79]. As an alternative, data collected from smartphones allowed the monitoring of several factors relevant to the prevention of crowd emergencies: crowd density, crowd velocity, crowd turbulence and crowd pressure. Trials using this technology were conducted during real-world gatherings: the Lord Mayor's Show in London, 2011 and the Notte Bianca festival in Malta, 2011. A promising feature of this research is its potential to go beyond information gathering and start influencing behaviour: "Police forces and event organizers are able to send push notifications directly to the users' mobile phone to inform them about critical crowd situations in certain areas and provide them with advice on how to avoid them e.g. by recommending alternative routes. Hereby, notifications can be targeted to people in a specific area so that only they receive the information, avoiding confusion among other, not affected users" [79]. Such targeted feedback might be crucial in speeding up evacuation processes, since people need to be distributed across different exits. A single message displayed on e.g. a screen or conveyed through loud-speakers could not achieve this goal as satisfactorily as a personalised message delivered through a smartphone (Wirz, personal communication).

3.3 LifeBelt: A Wearable Computing Device to Enhance Crowd Evacuation

There are cases in which AmI is used not primarily for monitoring purposes, but rather in order to influence people's behaviour in crowded situation in order to improve the evacuation process. One such project is the 'LifeBelt'. This device was initially developed by Fersha et al. without explicit mention of AmI or emergencies, but rather as a way of raising humans' attention to their spatial environment through haptic (mediated through the sense of touch) feedback, a channel that may solve the saturation problem affecting the visual and auditory senses [25]. The mechanism used is a vibro-tactile belt which is sensitive to local spatial information (as opposed to global, GPS-like information). The belt can indicate to its user both the position and proximity of obstacles through several vibrating segments which can operate at different levels of intensity.

The utility of the LifeBelt for crowd evacuation was demonstrated in Ferscha and Zia [26]. A 'next-step' model was created to simulate agents' decision processes regarding the direction in which to proceed during an emergency evacuation. This model was validated through three experiments involving 30 persons. While a number of these were instructed to evacuate a classroom as promptly as possible, the rest were told to act as motionless obstacles. Once validated, the model was used to parameterise a cellular automaton (CA) computer simulation system for large-scale evacuation (up to 2,000 individuals). This demonstrated that the feedback the LifeBelt provides on neighbouring obstacles can significantly accelerate the evacuation process. A later paper provided additional evidence for the effectiveness of the LifeBelt in evacuation processes [27]. More complex simulations were run, in which the evacuation of actual railway stations was tested.

4 AmI for Transportation

4.1 Advanced Driver Assistance Systems (ADAS) and Intelligent Transportation Systems (ITS)

A variety of ADAS [46,71] and ITS [52] have been employed to improve road safety and management.

ADAS range from safety systems that support drivers in safety-critical situations and stabilize the car (e.g. anti-lock brake system and electronic stability control), through comfort systems that reduce the workload of the driver (e.g. adaptive cruise control (ACC)), to information systems that carry out secondary tasks and give the driver important information (e.g. navigation system). Another categorization of ADAS is based on the level of intervention from information over recommendation and assistance to control [60]. Besides the intended safety and comfort issues, such systems are discussed because of their effects on traffic flow and environment [10].

ITS use sensors in the infrastructure to ascertain critical measures of road weather conditions and/or traffic flow. When a certain critical threshold is reached, the road regulations or warnings are altered via overhead signs (freeway traffic) or through traffic signals (urban traffic). This same information, especially concerning congestion, is communicated to the driver through radio announcements, a radio data channel for car radio or navigation device display and over the web to cell phones. Hence ITS could supply an input to ADAS. The combination of GPS tracking devices in navigation systems and phones has led to a number of systems where car positions are regularly transmitted using the mobile phone network to a central traffic information repository (e.g. Google Lat Long Blog, 2009[5]).

4.2 Future Developments

A study predicted the future developments in the area of information and communication technology (ICT) [85]. By asking more than 400 international experts from science, politics, and economics using the Delphi method (experts are asked in a multi-step approach, giving them information about the results of the previous step), future ICT innovations were prognosticated. Concerning the automotive area – a key industry in Europe – the results showed that current technology trends are intelligent driver assistance systems, light-weighted safety concepts, green engine technology, and mobile ICT systems. According to the experts, ICT-use in cars will rise by up to 50 % of value added (currently modern cars have a 20–30 % of ICT added value).

Cooperative systems, which are ICT systems able to exchange data with other systems, central servers, and the infrastructure, have a high potential in increasing traffic safety and efficiency. According to these experts, in the future the car will be a multi-functional and multi-modal node that will transmit hazard warnings and traffic related advice as well as personalised information and entertainment. But when will these future developments become real? When will 50 % of all new cars be able to communicate traffic and environment related content? Answering this question, 39 % of the experts predicted the period 2020–2024, 31 % the period 2025–2030, and 13 % the period 2015–2019. Although the experts did not doubt that these developments will take place, the time of their realisation was not clear.

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[5] Google Lat Long Blog: Arterial traffic available on Google Maps. http://google-latlong.blogspot.com/2009/08/arterial-traffic-available-on-google. html (2009).

Concerning ADAS, until now most of these technical systems were related to a single vehicle, e.g. automatic cruise control or lane departure warning. Currently and even more in the future, more and more cooperative ADAS are developed (e.g. hazard warning, automatic emergency call, intersection assistance) that are based on the communication between the vehicle and other vehicles (C2C) or vehicle and infrastructure (C2I; overall called C2X).

ITS will lead to vehicles that are not just information receivers but also information sensors and distributors. In this way, the driver will assist the infrastructure management, and hence other drivers, blurring the lines between ADAS and ITS, and between the drivers' levels of action they affect. These new feedback loops within both physical systems and driver levels of action have led to the term "cooperative systems" being frequently applied to new ITS technologies.

4.3 Challenges

According to experts [85], the most important barriers for implementation are the necessary investments into infrastructure (road side units), missing standards, high costs, issues of data privacy, and technical problems.

Concerning data privacy and ethical issues, innovative technical systems could feed the fear of a surveillance society that does not only monitor its citizens by CCTV cameras and credit or loyalty cards but also by mobile ICT systems that allow a comprehensive tracking of cars. Although this is done with the primary objective of giving important information related to current traffic, directions of appropriate parking, and warning of hazards – in short: enhancing traffic safety, efficiency, and eco friendliness – an abuse by criminals, companies, or the government is not impossible. Therefore, some ethical guidelines should be applied, if the tracking of persons/vehicles is a key requirement for future ICT systems Persons should be aware that they are being tracked, they must be able to withdraw at any time, data must be used for the agreed objectives and must be deleted as soon as possible [22].

Somewhat surprisingly, a study by the Deutsche Telekom in 2009 does not see the driver and the interaction between new systems and the driver as a major challenge for future research and development. As some systems carry out the driver's tasks (at least partially), the role of the driver begins to change from controlling to monitoring – the driver observes system performance and intervenes only if something is suboptimal. This could lead to new problems, e.g. reduced vigilance and situation awareness [9,24].

The next steps in technological development [11] – that will be driven by better sensor technology and faster data analysis – will lead to even more of the driving tasks being fulfilled partly or fully by assistance systems (e.g. lane keeping assistant, lane change assistance, stop & go ACC, collision warning, traffic sign detection, fatigue warning). The consequences for driving safety, (but also for the enjoyment of driving, [35]) must be analysed very carefully before such systems are brought to the market.

Clearly, the presence of ITS in traffic is serving to make the driver's decisions along the journey more dynamic and complex [23]. Much progress has been made in understanding system effects at the strategic level of action through the use of agent-based modelling to simulate complex evaluation decisions regarding routes [23], where the individual movements of vehicles are not of high concern. Leaving new systems aside, the global effects of systems already on the road are not fully understood. As an example, ACC ought to create platoons of drivers, theoretically reducing the likelihood of traffic flow breakdowns, yet there is debate about the actual in-vehicle uses and hence the global effects [50] of such a system. This is largely because the local interactions are relevant, but have not been closely examined and the results integrated into larger traffic models.

5 Validating Research Through Computer Simulation

One of the challenges that everyone involved in the deployment of AmI solutions for crowd evacuation faces is the difficulty of testing hypotheses, as regards both the unassisted behaviour of crowds and the influence of proposed technologies on this behaviour. Since it is difficult to test new devices during real emergencies, and to create large-scale, fake emergency situations (on the impossibility of trial studies, see e.g. [59]), most researchers turn to computer simulation to validate the solutions they propose. A sizeable part of the research on AmI and evacuation is devoted to the optimisation of such simulations; the present section reviews some discussions in this area.

It should be noted that, in comparison to research that refers to AmI specifically, the domain of computer-assisted crowd simulation is both older and much more extensive. [83] have produced a survey and summary of seven methodological approaches to the simulation of crowd evacuations: "cellular automata models, lattice gas models, social force models, fluid-dynamic models, agent-based models, game theoretic models, and approaches based on experiments with animals" [83, p. 437]. This variety of methods might be due to the complex nature of crowd behaviour. New propositions on the best methods to simulate evacuations are made regularly. For example, one very recent contribution developed a way of modelling crowd behaviour during evacuation which takes into account emotions such as fear and panic [53]; another focussed on the evacuation of very large spaces [44].

One of the methodologies that have been used in order to efficiently model crowd behaviour in AmI environments is to collect data on agents' behaviour at a microscopic level, in targeted environments. The collected data is then used to validate a series of hypotheses that can be used to parameterise wider-scale simulations. This strategy was used by Zia et al., who coin the end-goal of this process "Evidence based Simulation" [84, p. 104]. A further development of this modelling strategy includes predictions from macroscopic theories of crowd behaviour, emerging from the domains of e.g. sociology or psychology. The authors have dubbed this combination of micro- and macroscopic data "mixed-level simulation" [84, p. 104]. Using this type of simulation enables them to test the efficiency of AmI technologies such as the LifeBelt through computer simulation.

Sharpanskykh and Zia [66] ran a number of computer simulations in which they parameterised different levels of trust displayed by humans towards AmI technologies, using the specific example of the LifeBelt. They developed a 'cognitive agent model' based on an elaborate understanding of the influence of emotional states on decision making processes. This model allowed for the levels of trust an agent has in a source of information to increase and decrease depending on previous experience with that source. On the basis of this model, they showed how the introduction of AmI technologies can lead to the formation of groups and the spontaneous emergence of leaders during evacuations.

Researchers have started exploring the "Potential of Social Modelling in Socio-Technical Systems" [28]. This is innovative, as most prior research focused primarily on the technological side of such systems, a notable exception being [34]. The development of a socio-technical model that accounts for human sociality requires the development of a 'Cognitive Agent Model' [28, p. 236]. In such a model, agents have several attributes: intention (trust, belief), emotions (fear, hope), and individualism (expressiveness, openness and contagion). By implementing this model in NetLogo to simulate the evacuation of a railway station, it was found that the percentage of agents using the optimal exit strategy by following those who are AmI equipped, increases with the proportion of AmI equipped agents (device penetration rate, dpr). This demonstrates that "it is important to model a socio-technical system at representative social (human) level" [28, p. 237].

SOCIONICAL partners at the AGH University of Science and Technology, Krakow, developed an approach using symmetry analysis for the modelling of crowd evacuation [68]. They ran computer simulations of the evacuation of a "long, high building constructed with identical fractions repeated in three perpendicular directions" [68], in which the process of evacuation was described as a transition from a chaotic state to an ordered state, and in which symmetry played a role. They came to the conclusion that "using [symmetry analysis] to construction [sic] of good models of evacuation is possible," and that, in comparison to Voronoi models, it produces longer evacuation times for small numbers of evacuating people, but similar evacuation times for higher numbers of evacuating people.

The 'social force model' (SFM) for pedestrian dynamics was initially introduced by Helbing and Molnár [36]. It is a way of modelling pedestrians' behaviour in more or less crowded situations which takes into account both physical factors such as the proximity of e.g. walls and obstacles, and social norms such as the tendency of individuals to maintain a certain distance between each other (sometimes understood in terms of the respect for personal space). The SFM presents advantages over other forms of modelling, such as 'cellular automata' and 'lattice gas' techniques, which statically allocate an area to each pedestrian and consider a pedestrian's behaviour to be totally determined by the local environment [30, B–77].

Because the SFM produces good simulations of pedestrians' behaviour, it has been used by several researchers as a model to predict crowd behaviour during the process of evacuation. For example, using this model, SOCIONICAL partners have shown that, in cases where a large number of people ($N = 150$) try to leave an area through a small exit, the probability that an individual can separate him- or herself from the evacuating crowd is very low. [31]. The same researchers were part of a larger team that ran simulations in which a large number of pedestrians evacuate a room through an exit, and the crowd pushes towards that exit. They found that "the evacuation process simulated here is not stationary", in other words, that "the SFM successfully describes the effect of cumulation of the physical forces between agents at the exit [. . .], the pressure at the exit increases with the crowd size. If this pressure exceeds some critical value, pedestrians at the exit are not able to move, even if they are close to the exit" [30].

A rather different type of simulation was designed by SOCIONICAL partners at AGH, who note that the issue of collaboration between robots is critical when robots are used for SAR (Search and Rescue) purposes, since collaboration can mean more efficient penetration of disaster zones. A simulation was run in which a number of robot ants were used to explore a labyrinth. Ants could communicate when they met. Results were formulated regarding the gain in penetration time (i.e. the time it took for the ants to acquire knowledge of the labyrinth) and individual ant knowledge of the labyrinth was a function of the number of ants. The authors point out that this research "can be useful in practical applications, as localization of victims in complex environment, perhaps after some disasters. In less developed technological applications, the ants can represent personal devices, which are capable to register the map of a local environment along the owner's trajectory and transmit it to another device" [49].

Another utilisation of computer simulation is presented by Andrade and Fisher [7]. Their research is geared towards computer vision approaches for the automatic detection of crowd emergencies. Training and testing such automated systems requires considerable amounts of video footage in which crowd-related emergencies occur. Yet such footage is not easily available. Using the Social Force Model [36], they create simulations of emergency situations and evacuations, which are then translated, using computer generated imagery, into virtual footage which can be used to train and test computer vision algorithms for the detection of crowd-related emergencies.

Computer simulation of crowd behaviour is not necessarily geared exclusively towards the detection of crowd emergencies or towards testing new hypotheses on the possible influence of a new technology on evacuation processes. Sagun et al. [65] argue that it can be used to enhance building guidance and to design safer buildings: "Predictive crowd simulations can support the building design process by exploring the designs under certain conditions that occur in different buildings and circumstances by using scenario-based studies" [65, p. 1008].

Finally, SOCIONICAL partners at AGH have prepared a real–time simulation of a whole stadium area using a modified Social Distances Model of Pedestrian Dynamics. The application was presented under the title "Proxemics in Discrete Simulation of Evacuation" during the10th International Conference on Cellular Automata in Research and Industry – Crowds and Cellular Automata [73]. Figures 1 and 2 below, show the simulation of an evacuation of the Allianz Arena stadium, Munich, using the Social Distances Model.

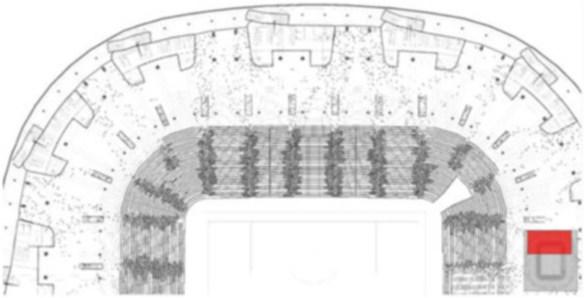

Fig. 1 Simulation of Munich Allianz Arena using Social Distances Model

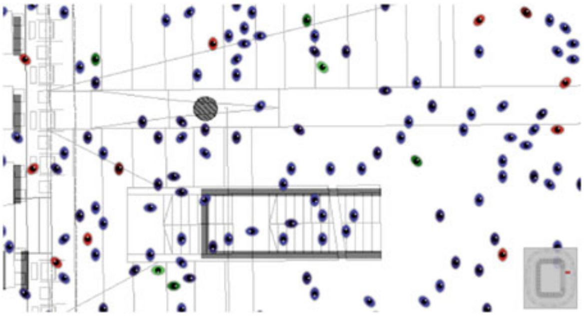

Fig. 2 Allianz Arena evacuation – different colours of agents represent different maximal velocities

The Social Distances Model was introduced by Was, Gudowski and Matuszyk [41]. It has been modified to enable the simulation of crowd behaviour in large facilities. The simulation is able to represent the **behaviour of 70,000 agents in real time**. The agents have abilities at strategic, tactical and operational levels.

Spatial relations between agents are represented using the Social Distances representation (Fig. 3). The relations are applicable in normal situations, when classical territoriality among pedestrians is observed.

In evacuation scenarios the crucial parameter is crowd density. Exemplary configurations in an agent neighbourhood for different values of probability are presented in Fig. 4, below:

6 Conclusions

This document reviewed recent research on two applications of AmI technologies: improving crowd evacuation during emergencies and improving traffic management. On the basis of the articles that were surveyed, we come to the following conclusions:

First, AmI is a relatively new field of research of technological and socio-technical development. It is multidisciplinary by design, bringing together a number of prior areas of research. Hence, the field is not rigid, and future research in AmI

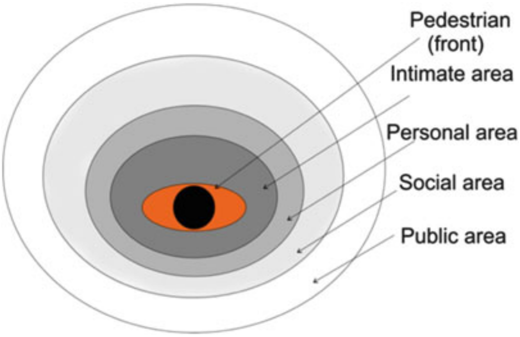

Fig. 3 Social areas representations using Social Distances Model – asymmetric social areas around a pedestrian

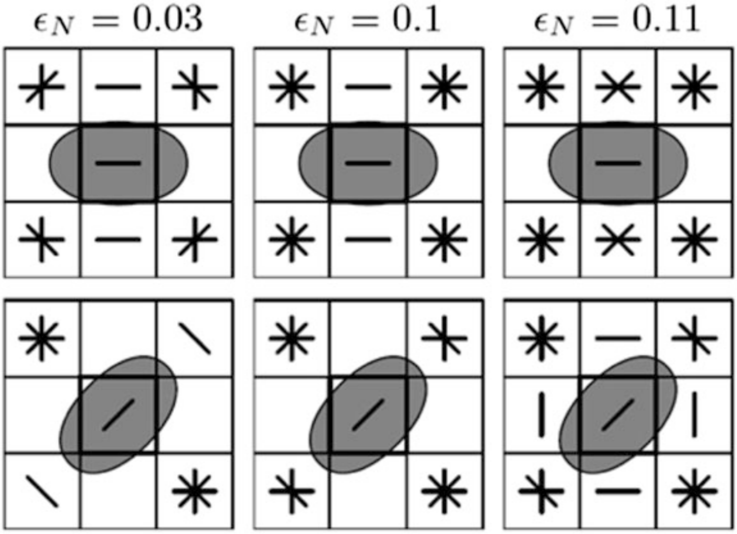

Fig. 4 Allowed configuration in an agent neighbourhood for different values of compressibility parameter

might evolve in several directions. New suggestions have been made recently concerning the scale of deployed AmI networks, the flexibility of their utilisation, and the way in which user-interaction is conceived.

Second, explicit mentions of emergency situations and evacuation in the AmI literature are more recent, but it appears that this area of research is burgeoning quite rapidly, in particular among a number of SOCIONICAL partners that are exploring its various aspects.

Third, research on the utilisation of AmI in emergency situations and for purposes of evacuation can be divided into two types. The first type comprises research that utilises AmI primarily for purposes of monitoring and early detection of crowd-related emergencies, the second encompasses research in which AmI is seen as a way of influencing and modifying the behaviour of individuals in crowds in the hope of improving the evacuation process. There is some overlap between these types.

Three AmI technologies for the improvement of crowd evacuation were discussed in this review. The first, predates the term 'AmI' but it can be included in the field since it is based on sensor networks and uses computer vision for crowd analysis. When approaches are concerned with the detection of anomalous crowd behaviour, they become relevant to the topic of emergency detection, since to a certain extent, crowd-related emergencies can be understood as a subset of anomalous crowd behaviour. The second technology uses location aware devices such as mobile phones and GPS devices to monitor crowds and detect emergencies. In the case where data is collected through smartphones, this potentially enables the modification of crowd behaviour through personalised, push-message feedback. The third technology is being developed by SOCIONICAL partners at Linz University; it uses a wearable computing device, namely a vibro-tactile belt, to provide guidance to its user in evacuation cases where other sensory channels might be impaired or overloaded.

As far as traffic is concerned, AmI technologies are used to assist traffic safety and efficiency as well as to improve environmental and comfort aspects of transport. Existing systems (ADAS and ITS) help drivers by providing information (e.g. weather condition or congestion) and assistance (e.g. navigation) or by controlling the vehicle (e.g. ACC). It is expected that traffic safety and efficiency will be improved by the developments in information and communication technologies (ICT). Increased communication and data exchange are expected to change the roles of vehicles and drivers in transportation systems. Vehicles will shift from receiver to sensor/distributor, while drivers will partly shift from controlling the driving to monitoring. There are also challenges, regarding AmI systems, which should be considered. Aside from obvious challenges such as costs, standards and technical complexities, data privacy is an important issue, which needs serious consideration. It is also highly important to understand global and local effects of new systems before widespread application in order to achieve the desired outcomes of a new system.

Furthermore, there is a problem, which most researchers involved in the development of AmI technologies to improve evacuation and prevent crowd-related disasters, face. This is the obvious impossibility of testing newly proposed technologies during real-world emergencies, and the impracticality of creating wide-scale 'fake' evacuations. Most researchers turn to computer simulation to validate their hypotheses. The literature on computer-assisted crowd simulation is extensive, and only selected contributions most relevant to AmI technology and crowd management were discussed here. One popular model is the Social Force Model [36], which is a relatively simple yet highly accurate way of modelling crowd behaviour, which takes into account both physical constraints and social norms in pedestrian behaviour. Using this model, several new findings on crowd dynamics were made.

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The Concept of 'Co-evolution' and Its Application in the Social Sciences: A Review of the Literature

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1 Defining Co-evolution

The Oxford Dictionary online describes co-evolution as a term originating in biology, meaning "the influence of closely associated species on each other in their evolution". Ehrlich and Raven [10] first used the term co-evolution in reference to biological evolution when looking at the relationship between the patterns of evolution of plants and butterflies, stating that it describes the simultaneous, reciprocal evolution of interacting populations. In biology, co-evolution refers to the change of a biological entity triggered by the change of a related entity [42]. Each entity exerts certain pressures and influences over the other, affecting the evolutionary trajectory of each.

Reciprocity is an element of co-evolutionary relationships stressed by all definitions in the literature. The influence of one species upon another's evolution is inherently important to the idea of co-evolution, but some definitions also stress an element of selection or competition in this dynamic. Co-evolution has been characterized as a reciprocal evolutionary process between interacting species, driven by a process of natural selection [14,40]. Raven and Johnson [35] define co-evolution as the simultaneous development of adaptations in two or more populations, species or other categories, that interact so closely each is a strong selective force on the other. However, within the social sciences emphasis is placed more often on the concepts of adaption and change rather than selection and competition.

Basic definitions of co-evolution are relatively homogeneous across both the natural and social science literature, converging in the sense that two systems or entities co-evolve when they have a causal influence on each other's evolution [17]. However, interpretations and applications of the concept of co-evolution vary.

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Interpretations range from the "specific, reciprocal, simultaneous evolution of traits between two closely related species" to "diffuse coevolution, meaning the adaptation of species to multiple features of their biotic and physical environment" [14, p. 708].

Co-evolution is a dynamic that has been most applied and explored in the field of evolutionary biology, however the concept has also been extended into diverse fields in the social sciences, applied as eithern an illustrative metaphor or as an interpretive frame that enables analysis of complex evolving phenomena. While the term was originally used only with reference to relations between biological species, it has now come to be used in reference to analogically similar dynamics between complex actors or systems that co-evolve [41]. This literature review focuses on the social sciences literature rather than natural sciences literature, and focuses on extended analyses of co-evolution as a dynamic of concurrent development and interaction, rather than its use in any metaphorical sense.

2 Co-evolution in the Social Sciences

Co-evolution now has a large range of applications in socio-economic contexts [31]. When applied within the social sciences, co-evolution usually refers to social co-evolution: the reciprocal evolution of two or more social systems or actors [18] and more specifically, as **reciprocal influence which changes the behaviour of the interacting entities within a social ecosystem** [26,29]. It has been used across a large range of disciplines such as computer science, economics, organizational theory, anthropology, archaeology, geography, history, sociology, and environmental sciences. It has also been used in more specific applications such as in IT legacy systems [25], and mergers and acquisitions [27,28]. Co-evolution can also refer to the reciprocal evolution of technologies and institutions, behaviours and institutions, populations of industries and universities, populations of producers and consumers (supply/demand co-evolution), organisations and their environments [18].

McKelvey [24] describes how various disciplines in the social sciences have been aware of the phenomenon of co-evolution without necessarily describing it using that term. For example, social psychologists have studied in detail the co-evolution of member attitudes and group norms, sociologists have observed the interaction and co-evolution of formal and informal systems in organizations, and economists have analysed the interaction between the behaviour of firms in creating industries and industry effects on firms [24]. Kauffman [19] argues that co-evolution is the central dynamic of all self-organizing behaviour. It allows dynamic system change to occur, and allows innovative structures to emerge.

Mitleton-Kelly was one of the first complexity theorists to apply the concept of co-evolution within the social sciences. She introduced the concept to the IT community in the UK in the late 1990s when it was the central concept of two EPSRC-funded (Engineering and Physical Sciences Research Council, UK) projects on IT legacy systems. The projects were part of the 'Systems Engineering for Business Process Change’ EPSRC Research Programme. The concept is used in most of her publications, and specifically in [25, 26, 27, 28] and [29], in a wide range of applications from IT legacy systems, to mergers & acquisitions and organisational transformation. In 2011 it was also applied to a study on disaster risk reduction in West African States.

McKelvey also applied this term to organisational management and he outlines five basic types of co-evolution, each involving a different relationship between the interacting and evolving entities, providing an example of how this type of co-evolution may operate in the social world [24, p. 3]:

- Co-evolution between the mutation or change rate of an entity and its environment: “The more the Internet develops the more people develop Internet skills; the more they develop their skills the faster the Internet develops, and so on”.
- Predator vs. prey co-evolution: “The faster large firms buy up start-up firms, the faster start-ups and IPOs materialize; the more start-ups and IPOs there are, the more large firms can buy them up, and so on”.
- Super-normal co-evolution: “The more that firms see MBAs as preferred, the more MBAs will be hired; the more MBAs are hired, the more they will tend to prefer hiring additional MBAs, and so on”.
- Co-evolution, restricted population size and inbreeding: “The more a small discipline uses its members as referees the more narrowly restricted are the ideas in their papers – the more intellectually inbred it is; the more restricted are the ideas (the more inbred), the more narrowly the membership allowed into the population, and so on”.
- Symbiotic co-evolution: “The more that a large firm hires surrounding suppliers, the more they survive and grow; the more that the suppliers survive and grow, the easier it is for the large firm to survive and grow in its competitive context, and so on”.
- Macro and micro co-evolution: A firm’s ability to effectively macro co-evolve with competitors depends on how its internal micro co-evolutionary processes are progressing.

Use of the concept of co-evolution in the social sciences can be organised into four main research clusters: (1) evolutionary economics, (2) socio-technical systems analysis, (3) human culture and cognition, and (4) socio-ecological evolution. These four fields comprise the bodies of literature that have applied co-evolutionary analysis in the most rigorous and extensive manner, and the remainder of this chapter will review this literature in turn.

3 Co-evolution in Economics

Research that approaches economic analysis from a co-evolutionary perspective examines the mutual interactions and adaptations that occur between the market, relevant social and economic institutions, and the operations and growth of companies or organisations. For example, within the established field of evolutionary economics, co-evolution is defined by one article as the dynamic interaction and developmental interplay between industrial sectors, institutional frameworks, networks and structures of agglomeration, “or, more simply, between firms and dimensions of their social and economic environments” [41, p. 282]. Similarly, co-evolution is now used in organisational science to describe both the behaviour of agents within organisations and the interaction of organisations with the wider environment they are embedded in [24].

Lewin and Volberda [21] propose that research into economic and organisational co-evolution should incorporate the following suggestions:

- To study organisational adaptations over a long period of time;
- To examine organisation adaptation within its historical context;
- To consider multi-directional causalities within and across organisations as well as between and across elements of the economic system;
- To incorporate mutual, simultaneous, lagged and nested effects of co-evolution, rather than just immediate or progressive adaptions;
- To incorporate analysis of the changes that occur at different levels of the organisation;
- To accommodate economic, social, and political macro-variables.

Prud’homme van Reine and Dankbaar [34] incorporate many of these research concerns, using the concept of co-evolution in reference to the interaction between corporate cultures and regional cultures. The paper investigates why some geographical and cultural regions in Europe are able to respond and adapt to change by evolving in line with new development paths while others remain locked in traditional patterns. The authors argue that under certain conditions, interaction between corporate cultures and regional cultures can become a virtuous circle, in which corporate performance and regional performance reinforce each other. Cultural change is a result of the interaction between companies and regions when tensions such as that between regional embeddedness and openness to outside influences are negotiated successfully: “Successful regions are regions that are handling the potential tensions in a balanced way. This requires mutual orientation in the actions of companies and regional actors and the development of change competencies on both sides” [34, p. 1865].

In the context of the economy, Arthur [3] argues that economic forms co-evolve with the behaviours of individual economic agents and group entities. Elsner [11] also describes the co-evolution of economic institutions and company/firm sizes, arguing that both have causal impact on the other. The economy emerges out of the interactions of individual agents whose behaviour constantly evolves, and whose strategies and actions are always adapting in turn to economic structures and rules [4].

A similar dynamic is reported by Song and Thakor [38], who look at the co-evolution of banks and markets, focusing on the way the structures and strategies used by banking finance systems influences development in the ‘real’ sector and vice versa. While the dominant view is that banks and markets compete, with development in one sector occurring at the expense of development of the other, Song and Thakor argue that they in fact mutually co-evolve. They posit that economic analysis needs to focus on the relationship between markets and banks, rather than just focusing on one entity's impact upon the other, as banks and markets evolve in tandem with each influencing the other. Developments in the credit screening strategies used by banks enhance the credit quality of borrowers going into the market, therefore increasing confidence and capital market investor participation. This allows the market to evolve, which in turn benefits banks by reducing the cost of bank equity capital and providing incentives for banks to hold more capital. "Bank evolution is thus stimulated as banks consequently serve previously unserved high-risk borrowers" [38, p. 1021].

Fatas-villafranca et al. [12] propose a co-evolutionary model to describe the simultaneous development of companies in science-based industries and their national university system. The success of technology companies on the international market often has impact on their domestic institutional environments, including the creation of research universities, the establishment of new disciplines of study, and the formation of publicly funded agencies with a technological or industrial focus. The authors suggest that the development of electricity, developments in organic chemistry and biotechnology, and the computer and IT revolution all have produced such impacts. The competence of universities and the resources available to them for research and innovation in these fields have a reciprocal impact on the development of the science-based companies, thus the institutional performance of both sectors – academic and industry – coevolves. The combination of scientific competence and institutional responsiveness is also central to Sæthera et al. [36] explanation of why Norway has benefited from its rich natural resources in comparison to other resource-based economies which have experienced a less positive path of development. The authors argue that Norway has formed a well-functioning national innovation system through the co-evolution of industry, knowledge organisations and national policy in the petroleum and aluminium sectors.

Mitleton-Kelly [27,28] developed the notion of *co-evolutionary integration*, when discussing mergers and acquisitions (M&A). She describes two cases with two different enabling environments, a successful and a dysfunctional environment; the former facilitated co-evolutionary integration post-M&A between the acquiring partner and the acquired, while the latter inhibited it. The paper analyses the factors that contribute to successful co-evolutionary integration, placing emphasis on the co-evolutionary dynamics.

Increased use of agent-based models in investigating co-evolution, (rather than the traditional biological examples) have uncovered some additional factors that must be taken into account when assessing the way that human organisational processes evolve [20]. For example, the knowledge and skills of older people can be passed down to younger people, or that of outgoing or long-term employees to newer employees, affecting the change and adaptation process. Human agents within a system may change their intentions, goals and strategies, in turn changing the way the system co-evolves in line with these goals and as a response to these strategies.

4 Co-evolution within Socio-technical Systems

The concept of co-evolution has also been used to inform analysis of information systems development. In fact, much of the research on co-evolution within socio-technical systems has focused on the development of effective information management systems within organisations and corporations. Literature in this area focuses on the "mutually constitutive role of Information Systems in shaping organisations and of organisations in shaping Information Systems" [20, p. 37]. This research emphasises that continual change is a fundamental factor in the co-evolution of socio-technical systems [7, 8, 29].

According to Kim and Kaplan [20], previous literature on information systems development has focused on implementation processes, technological resistance on the part of employees, and misalignment between the technological product or solution and the needs of the organisation. This focus, while generally useful, fails to take into account "the contextual and mutually constitutive nature of systems and organisations during Information Systems engagement, thereby ignoring the co-evolutionary phenomena that drive both in new, and largely unanticipated, directions" [20, p. 36]. On the contrary, implementing an information system is a co-evolutionary process in which the software system, the information technology provider or specialist, the organisation itself and its constitutive employees are all forced to continually adapt to a context that changes by the various actions of one another [20].

Other studies that approach information systems development from a co-evolutionary perspective agree with the central thrust of these findings. Benbya and McKelvey[7]) state that more effective information system design and operation can be achieved through a combination of top-down 'official' systems design and bottom-up 'emergent' co-evolutionary adaptations to user requirements. Information systems are emergent by nature, and need to respond to rapidly changing organisational demands and user requirements [8]. Traditional top-down, engineered approaches will be inadequately static, the authors argue. Managers should see information system design projects as 'complex adaptive systems' in order to deal with evolutionary complexity. To deal with unexpected contingencies, emergent goals and imperfect knowledge of current and future requirements, information system design should be seen as an ongoing, co-evolutionary process: "Information system alignment is not an event but a process of continuous adaptation and change" [7, p. 20].

An earlier paper [25] had anticipated these findings. The paper focuses on the enabling environment or infrastructure that facilitates co-evolution, and by so doing, helps to reduce the problem of IT legacy systems. The paper argues that 'legacy' is not solely a technical issue (p. 164) but a socio-technical one; legacy is a gap between the business needs and the organisation's technical capabilities (p. 168). It concludes that by "encouraging co-evolution (as opposed to the pursuit of separate evolutionary paths) between the domains [i.e. the information systems (IS) and business domains] requires an enabling infrastructure which provides the conditions for self-organisation, emergence and exploration of the space of possibilities". This insight highlights that co-evolutionary dynamics involve other principles of complex systems, such as self-organisation, emergence and the exploration of the space of possibilities. These dynamics have not been adequately explored in the literature.

The paper studies a specific case and looks at "reciprocal interactions among agents at all levels of analysis" both at "the micro level of interaction between individuals and between individuals and artefacts (IT systems) and the macro level of interaction between the business and IS domains as well as between the organisation and its environment" (p. 165).

Interactions are based on relationships between the interacting entities and the paper emphasises that these relationships are not simple. "In human systems, co-evolution in the sense of the evolution of interactions places emphasis on the relationship between the co-evolving entities. The study, therefore, focused on the relationship between the business and IS domains, and explored the assumption that the degree, intensity and density of interaction between the two entities affect the rate of co-evolution between the two domains." (p. 178) The conclusion is therefore that an enabling environment not only facilitates co-evolution but can also influence its rate.

Other research has taken a more birds-eye view of technological-social co-evolution. D'Hondt et al. [9] have applied the idea of co-evolution to their analysis of the relationship between computer hardware and software, web browsers and web applications, and computer operating systems and applications. Changes in the first entity in any of these three pairs creates new possibilities and features which are reflected in the second, often then creating new demand for further development. Evolution in one is accompanied necessarily by corresponding evolution in the other.

Other studies have looked at the influence of government policy on the evolution of socio-technical systems. Aarden et al. [1], for example, focus on the co-evolution between genetic diagnosis technologies and government policy that deals with its implementation. They show that co-evolution between pre-implantation genetic diagnoses (PGD) technologies and policy has led to specific technological arrangements in three countries: a very specific, technical version of PGD to deal with restrictive legislation in Germany, well-funded PGD with insecure indications in the Netherlands, and PGD with secure indications but uncertain funding in Britain.

Axtell [5] uses co-evolution as a framework to illustrate how increasing IT capabilities are reshaping the social sciences and vice versa. He proposes that one IT development in particular – multi-agent systems – could fundamentally alter the ways in which social science models are built, explored and evaluated. Ideas from fields of social science such as economics, sociology and game theory, particularly insights about strategic behaviour and networks, are also shaping the multi-agent systems models of computational science: "the rapid development of information technology has sparked concomitant developments in social science methodology, and obversely, computer science is being invigorated today by major research areas in the social sciences—e.g., market processes, auction design, social networks" [5, p. 3].

In another paper Axtell [6] describes a similar co-evolutionary dynamic between engineering systems and the social sciences. In the past the role of the social sciences in new engineering development and invention may have been limited to the design of user interfaces, bringing new products into the market, and enabling more sophisticated and large scale methodologies for investigation of the social world. However, increasingly engineering systems are designed and built using explicit social ideas and conceptions from the social sciences in a much needed 'science of interaction'. [6, p. 2] states: "Instead of having sharply demarcated domains of inquiry—technology on the one hand, its use by humans on the other—we are now confronted by the deep interconnectedness of the technological and the social, a phenomenon that is sure to become ever more important in the foreseeable future".

5 Co-evolution in Human Culture and Cognition

The interaction between the evolution of human cognition and cultural evolution has been long established in anthropological literature [30], however, not until recently using the specific terminology of co-evolution as an analytical frame. The human mind, cognition and perception have evolved influenced by the cultural context in which they are embedded within [18], and human culture has also been shaped by shifts in cognitive and perceptive capacity. A small number of researchers from the fields of cultural and cognitive anthropology, cognitive science and cultural psychology have all utilised the concept of co-evolution to analyse this complex dynamic to good effect.

Beat and Wettstein [39] use the concept of co-evolution in cultural psychology to analyse the relationship between the individual and culture, and the person and their environment. The authors identify three different types of human system – biotic, psychic and social – each of which are linked to particular operational processes. They suggest that culture should be conceptualized as the enduring social patterns of behaviour that are produced by a process of co-evolution of the individual psychic and social communicative systems.

Murray [30] describes how games have had an important role in shaping the human mind and in turn cultural forms, by preserving and expanding adaptive cultural patterns, and developing symbolic thinking. Games are intrinsically social, and are a foundational element of human culture, that allow individuals to engage in purposive, focused play, learn from others, and explore symbolic action and meaning. From a cognitive development perspective, games contribute to infants' development of language and recognition of others as agents with their own goals and purposes. Through a dual dynamic of presentation of the self and expression of social cohesion in games, games have contributed to human social organisation and developments in causal thinking, which in turn leads to more complicated games. Murray argues that digital games should be understood as extending these same roles and functions, using the new and developed technologies of the computer and

Internet. Games are instruments of cognitive evolution, which in turn evolve and become more complex and demanding as cognitive skills and technologies develop.

Jefarres [15] also discusses the co-evolutionary dynamic between the human mind and the tools and technologies that people create. He warns against interpreting archaeological evidence of cultural products such as tools as simply the product of human cognition: the human mind is as much a product of the tools used by humans as these tools are products of human intelligence. He states that "we should view archaeological evidence as one half of a feedback loop between the world and the cognition of our evolutionary ancestors. Tools and minds co-evolve..." [15, p. 504]. Tools can also be the cause or trigger of cognitive development, and furthermore, the use of tools and technology changes the environment which will trigger adaptive changes in human cognition – often to create new tools and technology.

Kallis and Norgaard [18] state that another major field in which co-evolutionary analysis has been applied is gene-culture co-evolution. They make reference to a number of examples of particular aspects of the mutual evolutionary impacts that human culture and genetic make-up have had on each other, including the co-evolution of lactose-tolerance with dairy farming, incest taboos with brother to sister mating and sickle-cell anaemia with forest clearing practices. "Cultural learning, imitation and experimentation shape human behaviors; they are conditioned by human biology, and in turn change it" [18, p. 691].

6 Human Ecology and Ecological Economics

As the term co-evolution was first coined within the scientific discipline of biology, it has been widely applied in studies of ecology. Social or human ecology and ecological economics are fields that necessarily straddle both the natural and social sciences, and there is a growing body of literature applying co-evolutionary analysis to the issues of ecological sustainability and the relationship between society and the natural environment [41]. The importance of co-evolution for these fields is summed up by Kallis and Norgaard: "At an epistemological level coevolution offers a powerful logic for transcending environmental and social determinisms and developing a cross-disciplinary approach in the study of socio-ecological systems" [18, p. 690]. Evolution in the human social system affects the natural bio-physical environment, which in turn affects evolution in the social system [18]. Examples include the development of fossil fuel resources, methods of generating power, and energy-intensive cultural practices.

Ecological economics is an interdisciplinary field of research that focuses on the co-evolution of human economies and natural ecosystems. A Springer Volume from 1994 titled *Coevolutionary Economics: The Economy, Society and the Environment* explored the human economy and its co-evolutionary relationship with the natural world and the impact of human actions on the biosphere. It states "The new fields of ecological economics and evolutionary economics can help us understand the relationship between the economy, society and the environment and may help us to formulate effective policies to manage these changes" [13].

A key theorist in this field, Norgaard has developed a co-evolutionary framework in a number of papers to explain the reciprocal evolution of sociosystems and ecosystems, driven by processes of mutual selection [32,33]. Gual and Norgaard [14, p. 710] state that ecological economists can use co-evolutionary thinking "to explore how the evolution of cultural systems affects and is affected by the overall biophysical system and, in particular, how it is literally modifying evolutionary processes (as conceived in the biosciences) guiding all living species". The evolutionary processes of the social and biotic systems are interdependent and interlinked, and require a common co-evolutionary framework of analysis to enable full understanding [14]. Evolving sociocultural systems are increasingly affecting their biophysical environment and evolving ecological environments increasingly also affect socio-cultural change. Biologists have traditionally focused on piecing together the process of evolution in environments undisturbed by human interaction, which "blinds evolutionary biology to the increasingly relevant processes of evolution in the context of human action" [14, p. 708].

Gual and Norgaard argue that a knowledge gap exists in how human action is affecting evolutionary processes and the links between cultural and ecological evolution that needs to be urgently addressed in order to incorporate greater understanding to human social and technological organisation. They identify three embedded systems: the biophysical, the biotic and the cultural, all of which evolve inter-connectedly and inter-dependently. The focus of co-evolutionary theory is the study of both what the basic units, characteristics and modes of this process of mutual evolution are, and how these processes relate to one another creating "the systemic coevolution that seems to be shaping life on our planet" [14, p. 711].

Specific examples of ecological co-evolution include: (1) co-evolution through systemic influence such as pollution of the biosphere; (2) co-evolution through consciously designed cultural products and processes, such as reciprocal changes in the genetic composition of pest populations and in agricultural practices and technologies, and the mutual adaptation of drug treatments and mutations of the HIV virus; and (3) forced co-evolution through genetic manipulation, such as the engineering of crops with higher production rates [14]. They make a distinction between more 'natural' forms of co-evolution and forms in which people have intentionally manipulated the biological evolution of other species, for example in the cases of domestication of animals or the genetic engineering of food crops. These cases still involve co-evolutionary dynamics, however must be analysed distinctively because of the element of intentional control.

The reciprocal influences between social evolution and biological evolution in the wider non-human environment are also highlighted by Kallis and Norgaard [18]. They cite co-evolution between pest populations and regulative strategies for the pesticide industry, fishing practices and fish populations, and viruses and medical practices as examples that have previously been explored in the literature. Their first example of pest populations is explored by Noailly [31], who looks at the co-evolutionary dynamic between agricultural pest management practices and changes in pest populations due to evolved pesticide resistance. As pesticide use has increased, an increasing number of pest species have developed resistance to these chemicals. The pesticide operates as a heightened form of natural selection, where genes that carry resistant traits are the ones that survive. The pest population eventually recovers as more individuals become resistant. The aim of Noailly's paper is to calculate, using a co-evolution model, the optimum level of pesticide to use when taking into account adaptive economic and agricultural practices as well as adaptive pest population genetic evolution.

Social or human ecology is another interdisciplinary field related to ecological economics, that examines the relationship between humans and their natural, social, and built environments. Research from this field tends to focus on the ways that humans have negatively influenced the natural environment by triggering unsustainable evolutionary pathways. Sustainability research from this field has used the concept of co-evolution as an analytical frame in order to study "the dynamic mutual interactions between human societies and their natural environment" [41, p. 281] and identify sustainable pathways for co-evolution in the future. For example, Schellnhuber's [37] 'theatre world' is a heuristic analytical model that represents possible pathways of sustainable development. It is presented as a diagram with a gradient of possible physical or ecological states of the globe on the one axis and a gradient of possible socio-economic conditions of human civilization on the other axis. Represented in the diagram between the two axes are all the nature/society co-evolutionary states possible. Global human society can be theoretically plotted at some point in this space, a point from which a certain number of co-evolutionary pathways are accessible. However, the space within which humans can subsist sustainably on this diagram is more limited than the possible pathways that are represented, as these include catastrophic possible worlds in which human socio-economic regimes have pushed global biosphere fertility rates to zero, an unsustainable situation for human society.

7 Additional Issues

McKelvey [24] stipulates a number of conditions which must be met for co-evolution to occur. Firstly, there must be **heterogeneous agents** within the system, as this provides the variation necessary for the adaptive selection crucial to evolution to occur. Agents in this sense can mean many entities, including people, groups, species, concepts, organisational processes, populations, companies, etc. Secondly, these agents must be capable of **learning** and adapting to circumstances in order to allow change, innovation, and therefore evolution to occur. Thirdly, these agents need to be **interacting and influencing each other** in order that mutual adaptation to one another's behaviour occurs, as this dynamic is central to co-evolution as opposed to just evolution. Additionally, there is usually some higher constraint in place that the agents must adapt to, as well as an initiating event or stimulus that triggers the co-evolutionary process [24].

The events or stimuli that initiate co-evolution may be random and insignificant [23], such as the butterfly effect example famous to chaos theory [22]. The butterfly effect is a theoretical example of a hurricane's formation being dependent and contingent upon a butterfly flapping its wings weeks before in another part of the atmosphere. The butterfly's wing flapping represents a small change in the initial conditions at one point in a non-linear system that causes a chain of subsequent events that can result in large differences at another point of the system. Co-evolutionary systems are dynamic, and highly sensitive to initial triggers and conditions. Small fluctuations in these initial conditions can cause widespread divergent outcomes that are often difficult or impossible to predict. In complexity theory, a distinction is often drawn between complex systems and complicated systems: "Complicated systems, although composed of many intricate parts, can be understood as the sum of these parts. Complex systems, on the other hand, are comprised of populations of interacting entities where the overall system behaviour is not predefined but rather emerges through the interactions of its entities" [20, p. 37]. The entities within a co-evolutionary relationship are constantly adapting to one another's adaptations in a manner that makes any form of accurate prediction highly speculative, as spontaneous events and stimuli will continue to occur and shape the nature of co-evolution. As McKelvey states, "small behavioral effects can lead to informal group formations of considerable significance" [24, p. 4].

As a result of the dynamism and unpredictability of co-evolution, McKelvey [24] states that one of the key challenges facing complexity theorists is the factor of knowledge limitation. Co-evolution is unpredictable and non-linear, because evolutionary dynamics are reactive rather than predictive. However, contextual constraints can narrow or expand the range of outcomes produced through self-organisation [16]. These constraints can be managed, in theory, to speed or slow down the process of co-evolution as required. McKelvey calls these 'damping mechanisms', methods of "controlling the rate of coevolution, or shutting it down altogether" [24, p. 7].

Loss of agent heterogeneity is an important factor that can work as a barrier to co-evolution. Biologically, it has been shown that as species lose variety in their gene pool they lose their adaptive capability and can go extinct [24]. Likewise, in an organisational context, it is important that there are a wide range of skills represented by employees to maintain an ability to adapt to the uncertainty of the market and other contextual constraints and shifts. According to Allen [2] managers should in fact ensure a level of 'excess' variety, because they cannot predict in advance what varieties of skills will be adaptively relevant. Diversity can however be difficult to maintain because of firstly, the tendency for individuals to form strong cliques that lead to groupthink rather than variety, and secondly, strong command and control systems in traditionally structured organisations or systems that reduce individual variations in behaviours [24].

Despite the increasing number of social theorists drawing on the concept of co-evolution in their research, its application in the social sciences has been both more ad hoc and more contested than in the natural sciences. As Gual and Norgaard state: "There is a well-developed, cohesive biological literature on the coevolution of species within ecological systems. . .The social science literature on the coevolution of components of social systems is noticeably less developed and far less cohesive than the biological literature. The social sciences have struggled with multiple, incompatible constructs" [14, p. 707].

In terms of generating policy recommendations, co-evolutionary theory is often ambiguous. Very little co-evolutionary theory has been used by social science researchers to make explicit policy recommendations, with the exception of sustainability researchers advocating that greater attention be paid to human impact on the biosphere and organisational management theorists providing recommendations to corporations. Yet many articles tend to assume that co-evolution is necessarily positive, and policies should support diversity and experimentation as these drive co-evolution forward [18]. For McKelvey, an ability to speed up co-evolutionary processes is a significant and sustained competitive advantage for groups, organisations and companies in the contemporary world. Changing environments themselves necessitate speedy evolution to keep up with dynamic contexts and demands. Co-evolution can be "the source of novelty, adaptation, and survival in a competitive, changing world" [24, p. 7]. However, as Cairns [43] states, co-evolutionary relationships can be either mutualistic or hostile to one or both parties. McKelvey [24] also warns that too much evolution can be disruptive or dysfunctional. Kallis and Norgaard state that, "coevolutionary outcomes are not necessarily beneficial in any particular sense and diversity or innovation may come at the expense of other social goals" [18, p. 697].

It may be more useful to see co-evolution as a neutral analytical frame that can determine what dynamics are at play in particular pathways of development. How to evaluate these pathways or future possibilities can then be explored depending on the goals of the particular piece of research at hand. Kallis and Norgaard [18]), for instance, specify that co-evolution is emphatically not a normative concept. Other authors [41] have pointed out that equating co-evolution with progress in social systems can imply dangerous forms of Social Darwinism. Co-evolution should be seen as a way of analysing a particular dynamic of pathways of development, rather than being associated with progress or a notion of 'survival of the fittest'. Co-evolution is "a value-free process of change" [18, p. 691].

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Part II
Emergency

Using Mobile Technology and a Participatory Sensing Approach for Crowd Monitoring and Management During Large-Scale Mass Gatherings

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1 Introduction

Understanding the behavior of pedestrian crowds in physical spaces is important in many areas ranging from urban planning, policy making at community and state level as well as design, and management of pedestrian facilities and transportation systems. Therefore, in the past few years, efforts have increased to study how human crowds form and how specific collective behavior patterns among the involved individuals emerge.

To do so, simulation tools have been used to study the self-organizing effects of large groups of pedestrians. Different models exist to simulate pedestrian dynamics. The most popular models include: Physical models that model pedestrians based on the analogy to gases or fluids; the social force model together with its extensions [1]; and cellular automata [2]. To perform a calibration of the model parameters, experiments under controlled conditions can be performed [3], [4] or video footage capturing pedestrian dynamics can be evaluated [5].

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Simulations can then be used to study the effect of architectural configurations on crowd dynamics, the emergence of collective behavior patterns in urban spaces, the influence of commuting patterns in a subway system, etc. and help to derive data-backed recommendations useful to advise policy makers and other stakeholders. One area where knowledge of crowd behaviour and pedestrian dynamics is of special importance is in the management and monitoring of large-scale mass events and city-wide festivals. Such mass events are popular gatherings and commonplace in human societies all over the world. They range from concerts with a few dozen attendees to events of massive scale like the Olympic Games with millions of spectators. It is a top priority for every organizer of such an event to be able to maintain a high standard of safety and to minimize the risk of incidents. Hence, establishing adequate safety measures is important. The knowledge of pedestrian and crowd dynamics together with simulation tools has enabled the identification of critical locations where dangerous crowd behaviors may emerge. This helps to design and proactively deploy crowd control mechanisms before an event to mitigate the risk of a fatal crowd incident. By generalizing the obtained findings, a set of safety regulations and procedures can be defined aiming to help optimally planning future events [6], [7].

However, deriving and deploying optimized emergency strategies based on simulations remains challenging due to many unpredictable factors inherent in the nature of such events. A key issue is that the actual number of attendees of such events may greatly deviate from estimations as it depends on factors like weather conditions, alternative events, and the program etc. Yet, the biggest challenge of all is that the behavior of the crowd during an event remains highly unpredictable. These challenges foster the need to detect critical crowd situations like overcrowding at an early stage in order to rapidly deploy adequate safety measures to mitigate the impact of a potentially dangerous situation. To do so, real-time information about the behavior of the crowd is required. At present, mostly video-based monitoring systems come into operation for this task. Recent research has focused on developing computer-based methods to automatically analyze the recorded scenes and to detect abnormal and potentially dangerous crowd situations [8], [9], [10], [11].

Vision-based approaches face several limitations: Cameras cannot capture elements outside their fields of view or occluded by other obstacles [10] and it is still difficult to fuse information from many cameras to obtain global situational awareness [12]. Another drawback is the need for good lighting conditions. Furthermore, as many events happen during the night, the application of a vision based approach is limited.

Some countries, such as the UK may also use helicopters to gain an overview either in daylight or at night with thermal imaging. The use of helicopters, however, is expensive and requires highly trained personnel; they are therefore usually only used for events, which are expected to be problematic.

As an alternative to traditional approaches, we see a big potential in monitoring crowd behaviors by tracking the locations of the attendees via their mobile phone. We believe that the high distribution of location-aware mobile phones in our society and the acceptance to share personal context information enables such an approach. A big advantage of tracking users via their mobile phone is that it allows these users to obtain notifications directly from the event organizers and security personnel. This is of particular relevance during emergency situations as the provided information can be timely, highly targeted and personalized.

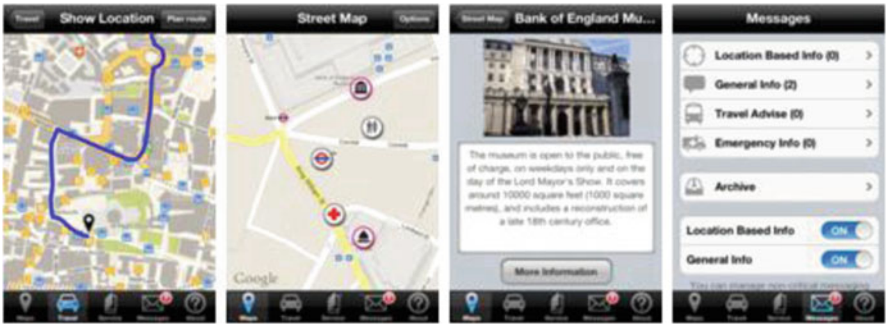
The aim of this Chapter is threefold: First, we discuss the technology for monitoring crowd behavior using mobile phones and present our framework, which allows us to collect real-time location data from event participants and to provide them with timely, targeted and personalized notifications in case of danger and emergency. Second, we identify crowd conditions hinting at critical situations and present a way to extract and visualize this information from the gathered data. In the third and final part, we present our findings obtained by deploying our system during two city-scale mass gatherings and by conducting interviews with the festival attendees using the app, the security personnel responsible for the safety of the event, as well as with policy makers responsible for contingency planning and implementation.

2 Monitoring Crowds with Mobile Phones

To infer crowd conditions, we require location information of festival attendees. We use attendees' mobile phones to obtain their location as most of today's mobile phones are situation and location aware.

Methods to obtain location information include GPS positioning and WiFi/GSM-fingerprinting [13]. With these approaches a location accuracy of up to 5 m can be obtained for GPS and around 20 m for WiFi-based positioning, respectively [14], [15]. However, on-device positioning methods require users to install and run a dedicated application on their mobile phones to collect the location updates. At first sight, such an approach may appear undesirable, as it can be assumed that people are not willing to install such an application. In the case of a mass gathering, this may mean that only a fraction of all attendees would run such an application and many would opt for not having their location tracked for various reasons, including privacy concerns and energy (battery life) considerations. Nevertheless, we believe this approach is still viable and promising by following a participatory sensing approach where users are motivated to deliberately share their location information by offering them a set of attractive incentives. In a preceding study, we have verified that people are willing to share privacy-sensitive location information if they receive some benefits or if they realize that sharing such information is for their own good and safety [16]. By following such an approach, we offer users full control of the recordings and allow them to disable it at anytime.

A further advantage of an approach following the on-device localization principle is that we can uniquely identify the location of a device and communicate with users directly, while maintaining the anonymity of the user. Thus providing every user with personalized information based on the location of the device.



The museum is open to the public, free of charge, on weekdays only and on the day of the Lord Mayor's Show. It covers around 10000 square feet (1000 square metres), and includes a reconstruction of a late 18th century office.

Fig. 1 Screenshots from the festival App

3 The S-App Framework

To collect location information of festival attendees, we developed a generic festival app for mobile devices which can be tailored to a specific event and provides the users with relevant, event-related information such as the festival program, a map indicating points of interest and background information (Fig. 1). These features are designed to be attractive and useful during the event to reach a large user base. Another incentive is provided through an intelligent notification system. Police forces and event organizers are able to send push notifications directly to the users' mobile phone and may inform them about critical crowd situations in certain areas and provide them with hints how any complications can be avoided e.g. by recommending alternative routes. Hereby, notifications can be targeted to people in a specific area so that only they receive the information, avoiding confusion among others, not affected users.

While a user is running the app, GPS location is regularly sampled with a frequency of 1Hz on the device and periodically sent to our servers running the CoenoSense[1] framework. CoenoSense acts as a centralized repository to store the location updates received from many mobile devices simultaneously and allows for real-time processing of the collected data. Figure 2 gives an overview of the platform's architecture. Our app offers users full control, at all times, over the sharing of data as data transmission can be disabled.

4 Crowd Conditions Hinting at Potentially Critical Situations

To improve pedestrians' safety, much research has been devoted to understanding crowd behaviors and to identify critical crowd conditions by conducting lab experiments and evaluating empirical data from real mass gatherings. An obvious,

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[1] www.conosense.com

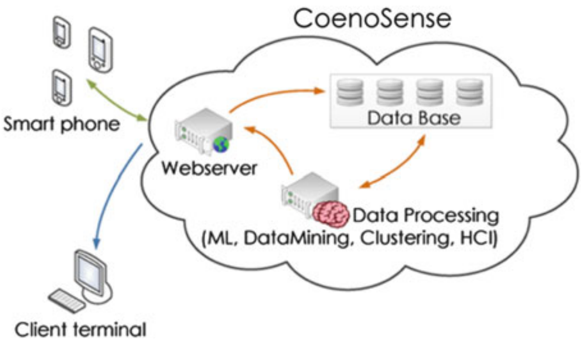

Fig. 2 Overview of the CoenoSense sensor data collection platform. Location updates are collected on mobile phones and periodically sent to a centralized server infrastructure where they are being stored in a data base. The collected data can be aggregated and processed in real-time to infer crowd characteristics. A terminal client can access this information via the web server

yet important crowd characteristic to assess the criticality of a situation is the density of a crowd. For example, most stampedes occurred in high-density crowds [3]. Different methods to measure crowd density and to identify dangerous overcrowding have been proposed [11]. The density, however, is not the only relevant characteristic. Also the movement velocity and the flow direction of a crowd have been identified as important indicators of critical situations [5], [17]. Methods for automatically measuring these conditions from location traces have been proposed in [4]. Johansson et al. identified a relation between flow and density of a crowd as they analyzed pedestrian dynamics of pilgrims visiting Makkah in Saudi-Arabia [5]. They measured a critical crowd density as soon as a breakdown of the flow occurred. They also identified crowd turbulence (irregular flows characterized by random displacement into all possible directions) occurring in high density crowds as especially dangerous, since the involved individuals are unable to self-control their motions and are pushed forwards and backwards by others [18]. In general, Helbing and Johansson [18], [5] suggest quantifying the hazard to the crowd (and with this the criticality of a situations in the crowd) by a measure they call *crowd pressure*, defined as the local pedestrian density multiplied by the variance of the local velocity of the crowd.

We have interviewed officers from the City of London Police Emergency Planning team to learn which crowd characteristics may be monitored during mass gatherings and which may give an early indication of crowd control issues. The City of London Police has a long history of policing and considerable experience in managing large scale events, often attended by thousands of people, within the City of London.

The interviewees reported that the main methods of gathering this information is through the monitoring of CCTV footage by Control Room staff and reports received from strategically deployed personnel on the ground. These methods cannot necessarily provide an overview of a large crowd that covers a widespread area as the section of the crowd that is monitored is limited to that which can be seen by the CCTV operator and/or the person(s) deployed and can be quite resource intensive. Crowd density information can be an important parameter when assessing the potential seriousness of an incident and can be relatively easily inferred by observation. Other information of use in a crowd control situation or emergency is the crowd's movement velocity and its direction which can assist in determining where resources could be deployed. Crowd turbulence can be useful as an early indicator of potential crowd control situations, but can be hard to infer from observation. In the case of an actual crowd control situation or emergency, information about jammed exits or passageways is crucial to the deployment of appropriate countermeasures. As stated by the interviewees, the ability to identify potential crowd management issues from CCTV footage requires that the CCTV operator is able to recognise the possible indicators of these issues and has a high level of concentration during the event.

5 Information Mining and Decision Making

In the previous section we discussed measurable crowd characteristics important to assess the criticality of a situation. We want to provide emergency response personnel means to instantaneously assess the current crowd situation during mass gatherings. Displaying information as an overlay over a map is a common approach to present spatial information and allows for a quick assessment of the situation. In this section we will briefly discuss methods to obtain these measures from the collected GPS location updates and the obtained information can be visualized in an intuitive way to easily and quickly grasp the important information.

We chose heat map visualizations to convey crowd condition information. A heat map is a graphical representation of spatial data where regions are colored according to measurement values found at the specific location. Heat map visualizations have been used in different applications to convey various types of spatial information.

For example Paulos et al. use heat maps to illustrate carbon monoxide concentration distributions in urban spaces [19]. Spakov and Miniotas perform eye gaze analysis and use heat maps to understand which part of a website is looked at for the longest period [20].

5.1 Crowd Density

To visualize density information, we calculate a density estimation by applying a Kernel Density Estimation (KDE) [21] from the active users' location updates at a given time. KDE is a non-parametric way of creating a smooth map of density values in which the density at each location reflects the concentration of sample points. Hereby, each sample point contributes to the density estimation based on the

Fig. 3 Heat map visualization of crowd conditions: Crowd density

distance from it. By using a Gaussian kernel K, the density estimation $\hat{d}$ at each location X_i at time t is given by

$$\hat{d}(X,t) = \frac{1}{h \cdot N} \sum_{i=1}^{N} K\left(\frac{X - X_{i,t}}{h}\right) \tag{1}$$

with h the Bandwidth (an application dependent smoothing parameter), and $X_{1,t} \ldots X_{N,t}$ the users' current location. The Gaussian kernel function K is given by

$$K(u) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}u^2\right). \tag{2}$$

By determining the density values $\hat{d}(X,t)$ for each location and mapping each density value to a color using a color gradient, a heat map representing the participant density estimation is obtained. Figure 3 shows an example of such a heat map. The visualization can be read in the following way: The warmer the color, the higher the crowd density at that location. The previously introduced approach is suitable to visualize the concentration of data samples as a density representation.

It is in the nature of our data that we have areas with many active app users and by contrast, areas with very few; also large parts with no users. We are only able to infer crowd conditions in areas where location updates have been recorded. By calculating crowd conditions in an area, the amount of active users (and hence available location updates) is relevant: Information from areas where many location updates were recorded might be more important as this region seems to be more popular than in regions with only a few individuals. To visualize the crowd conditions and to also include the importance, we adjust the heat map generation method in the following way: We use a color gradient to indicate the crowd conditions at a location with a varying opacity level that corresponds to density at the location.

The calculation of the density is identical to the approach presented previously by performing a KDE using Eq. 1. The obtained density estimation for a location is then directly mapped to the opacity value of the point. A very low density value will result in an almost transparent point, while a high density value will result in a fully opaque point. Hence, the more users are situated around a location, the more intense

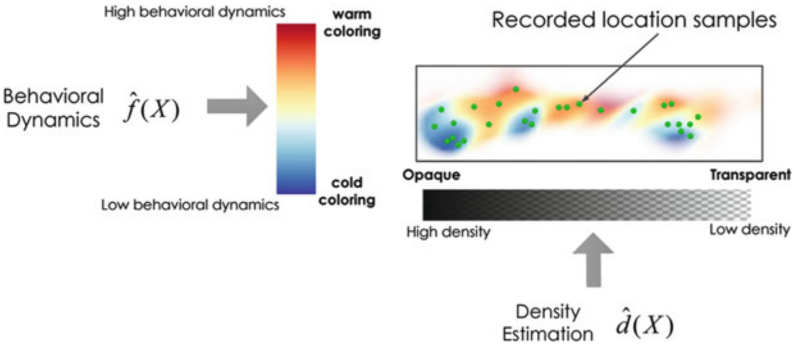

Fig. 4 Heat map of the crowd characteristics are generated by considering the density distribution of the recorded samples as an opacity value. The more users are situated around a location, the more intense the location color. Regions where no data is available remain transparent. The coloring is then determined by calculating the crowd conditions at the specific location and mapping this value to a color value using a color gradient

the location color. Regions where no data is available remain transparent. The coloring is then determined by calculating the crowd conditions at the specific location and mapping this value to a color value using a color gradient.

With this, for each point in space, we obtain an opacity value representing the density together with a color value for the crowd condition at that location. Figure 4 illustrates this process.

Next, we introduce the methodology to calculate the three remaining crowd conditions.

5.2 *Crowd Velocity*

The local crowd velocity can be seen as the weighted average velocity of each user at a given location by weighting the speed values of each user depending on the distance to that location with a Gaussian weighting scheme. With this, the formula to calculate the crowd movement velocity estimation $\hat{v}(X,t)$ at location X and time t is given by:

$$\hat{v}(X,t) = \frac{\sum_{i=1}^{N} v_{i,t}\, K\left(\frac{X-X_{i,t}}{h}\right)}{\sum_{i=1}^{N} K\left(\frac{X-X_{i,t}}{h}\right)} \tag{3}$$

where K is the Gaussian kernel according to Eq. 2 to determine the weight for each speed value $v_{i,t}$ and $X_{1,t} \dots X_{N,t}$ the locations of the active users.

For the heat map generation, the user density value is considered as the opacity and the crowd movement velocity estimation is mapped to a color gradient. Figure 5

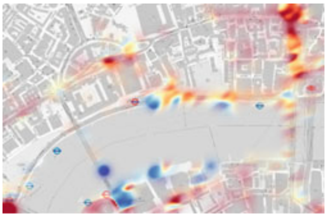

Fig. 5 Heat map visualization of crowd conditions: Crowd velocity

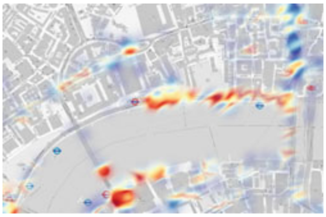

Fig. 6 Heat map visualization of crowd conditions: Crowd turbulence

shows an example of such a heat map. This heat map now conveys the following information: the warmer the color, the higher the movement dynamics and the more intense the color, the more users are to be found in this region.

5.3 Crowd Turbulence

To determine the crowd turbulence $\hat{c}(X,t)$ at location X and time t, we calculate the variance of the heading direction of the users at that location. We use the heading direction θ of each user to calculate the weighted circular variance introduced by Brundson et al. in [22] which is given as

$$\hat{c}(X,t) = 1 - \left| \frac{\sum_{i=1}^{N} K\left(\frac{X-X_{i,t}}{h}\right) z_{i,t}}{\sum_{i=1}^{N} K\left(\frac{X-X_{i,t}}{h}\right)} \right| \tag{4}$$

where $z_{i,t} = e^{i\theta_{i,t}}$, and $\theta_{i,t}$ is the heading angle of subject i at location X_i at time t. K is the Gaussian kernel according to Eq. 2 to determine the weight for each sample.

A heat map representation is now generated in the same way as previously by mapping the crowd turbulence values to colors using a color gradient and considering the user density values as opacity values. Figure 6 shows an example of such a heat map. The hotter the color, the larger the heading direction variance at this location, and thus the higher the turbulence. The more intense the color is, the higher the density of users in that spot.

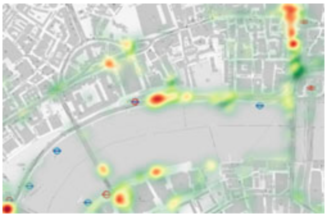

Fig. 7 Heat map visualization of crowd conditions: Crowd pressure

5.4 *Crowd Pressure*

According to [18], the crowd pressure is given as

$$p(X,t) = d(X,t) \cdot Var_{X,t}(v) \tag{5}$$

where $d(X,t)$ is the local pedestrian density and $Var_{X,t}(v)$ the local velocity variance. In our case, we can obtain a density measure using Eq. 1 and can calculate the velocity variance as

$$Var_{X,t}(v) = \frac{\sum_{i=1}^{N} \left| v_{X_i,t} - \hat{v}(X,t) \right|^2 \cdot K\left(\frac{X-X_{i,t}}{h}\right)}{\sum_{i=1}^{N} K\left(\frac{X-X_{i,t}}{h}\right)} \tag{6}$$

where K is the Gaussian kernel according to Eq. 2 to determine the weight $X_{1,t} \ldots X_{N,t}$ the locations of the active users. With this, the formula to calculate the crowd pressure estimation $\hat{p}(X,t)$ at the location X at time t is given by:

$$\hat{p}(X,t) = \hat{d}(X,t) \cdot Var_{X,t}(v) \tag{7}$$

The heat map is generated analogously to the other crowd conditions by mapping the crowd pressure to a color and combining it with the opacity obtained from the crowd density. Figure 7 shows an example of such a heat map.

6 System Trial and Interviews

To understand the usefulness of a real-time visualization of crowd conditions during mass gatherings, we deployed the system during various city-wide mass gatherings. Namely during the Notte Bianca Festival 2011 in Valletta, Malta, and the Lord Mayor's Show in London on 12th November 2011.

Fig. 8 A police officer in the control room is consulting the heat map visualization to assess the current crowd conditions

6.1 Lord Mayor's Show 2011 in London, UK

The Lord Mayor's Show is a street parade in the City of London, the historic core of London and the present financial centre. A new Lord Mayor of the City of London, is appointed every year and this public parade is organized to celebrate his inauguration. The day after being sworn in, the Lord Mayor and several others participate in a procession from the City of London to the Royal Courts of Justice in the City of Westminster, where the Lord Mayor swears his allegiance to the Crown. As in the Middle Ages, he is accompanied by military displays, marching bands, acrobats, dancers, displays of pomp and charity and symbols of London's ancient strength and resolve. The annual one-day event attracts about half a million spectators each year and is one of the City's longest established and best known annual events dating back to 1535.

The event starts at 11:00am and the processional route goes from the Mansion House via Bank, St. Paul's Cathedral and Fleet Street to the Aldwych; the tail of the procession will reach the Royal Courts at about 12.15pm. There is a short break during the ceremony, then the whole procession sets off again at 1pm to take the new Lord Mayor back to Mansion House. The procession finally ends at about 2.30pm when the last floats reach the City.

In collaboration with the event organizers, we tailored our festival app to the event and distributed it for free as the festival's official app. It was advertised on the Lord Mayor's Show website and available through Apple's iTunes app store.

Data collection was active between 00:01am and 11:59pm on November 12, but only if the user was in a specific geographical area around the festival venue. Over the whole day, we collected a total of 3'903'425 location updates from 827 different users. During the parade, location updates from a maximum of 244 users at any one time, were received simultaneously.

Security aspects of the Lord Mayor's Show 2011 were managed by the City of London Police. Together with the event organizers, they operated out of a Control Centre to monitor the event, from where they had access to the CCTV camera network and could communicate with strategically deployed personnel on the ground. Additionally, we provided access to a web interface displaying the heat map visualization of the density information. The photograph in Fig. 8 shows a police officer consulting the visualization to gain an overview of the current situation.

In the following we will report on feedback received from the City of London Police Emergency Planning team after the event, on the advantages and limitations of our system.

By asking the interviewees to compare our system to existing approaches, they reported that currently, mostly visually obtained information gathered from CCTV cameras and officers on the ground is used for crowd monitoring and management. Additionally, experience gained from policing the same event over several years, leads to a buildup of knowledge of where crowds gather, which routes are often jammed, etc. Such information is used to optimally distribute policing resources and event stewards over the event footprint. Additional crowd information could be obtained, if required, from the deployment of a police helicopter, which has equipment that can give an overview of the crowd from a higher vantage point during both day and night time. The use of a helicopter, however, is very expensive and resource intensive, and would not normally be used during events which are usually peaceful. All these methods can be used in conjunction to obtain an overall picture of the situation. A minimum of one person is required to monitor the CCTV footage in the Control Room and several people are needed on the ground especially in areas not covered by CCTV or at night when CCTV systems without infrared capability may be ineffective. The time required to detect a crowd problem (e.g. critical density, clogging of narrow pathways, etc.) is less when CCTV is available, but it is still difficult to build an overall picture of the whole situation.

Those viewing the heat map visualization during the Lord Mayor's Show 2011 found its interpretation was intuitive, with little explanation required. The heat map was seen as very helpful in obtaining an overview of the current crowd conditions at a glance. The police reported that the heat map provided an easier method of gaining an overview of crowds than from purely manual observation and/or CCTV system monitoring. The spatial resolution provided, was perceived to be sufficient for the nature of city streets. While more precise location information would be useful, it was stated that it was possible to get a sufficient overview of what was happening during the Show based on the visualization.

6.2 Lord Mayor's Show Survey and Telephone Interviews

The app users to the Lord Mayor's Show were asked to complete a short questionnaire and to participate in a short and anonymous telephone interview. The sample was small, and the findings are shown only as indicators, not as a statistically robust sample.

Seventy Percent of responders indicated that they would consult their iPhone app for advice during an emergency. They were then asked whether they would still consult their mobile phone if they were running for their lives; they answered that they would, but it depended on (a) the type of emergency and (b) whether official personnel were present and 30 % specified that they would prefer to follow instructions from figures of authority who were present, rather than from a mobile phone. If such a figure of authority was not present, then they would take the advice given through the smart phone if (c) it came from an authoritative source they could trust (e.g. the police or emergency services); (d) the information was reliable and consistent with what they were experiencing locally; and (e) the technology was robust.

Asked how they would communicate the information to others, without the app, they responded that they would talk face to face with those in the vicinity; and would also use twitter and other social media to communicate with others further afield.

Although the app showed overcrowding during exit periods, such as after the fireworks; the overcrowding combined with some physical barriers, which restricted exit, led to crowd frustration and a potentially risky situation. One insight from the interviews was that the visualisation was not enough to establish the position of barriers for future events, but that additional information in terms of context and understanding of crowd behaviour, was also needed.

The experiment showed that the app was found to be very useful during the event, both for users and organisers, but for a deeper understanding of crowd behaviour during such events and for future planning, short surveys and interviews provide a deeper context, not available through the technology on its own.

6.3 Notte Bianca 2011 in Valletta, Malta

The Notte Bianca is an annual event held in Valletta, Capital City of Malta, aiming to promote culture through arts. The event runs from around 7.30pm until the early hours of the morning with an estimated 40,000–70,000 people flocking into the city, visiting the numerous shows, activities, and exhibitions running throughout the night at various locations across the city. Although, the city is closed to traffic during the event, there are still problems related to traffic and parking as a considerable number of people, park their cars in the car parks available or in the surrounding nearby towns. During the evening, various museums, and other historical places, including the Parliament and the Prime Minister's offices are open to the general public with free access, thus generating a relatively large crowd and queues waiting at the doors.

The Civil Protection Department of Malta (CPD) is one of the officially appointed teams of emergency first responders that are on location throughout the night, in the event of any emergency. Other agencies, including the Malta Red Cross, are also on location, ready to help in the case of any emergency.

Although there is direct communication amongst the various emergency services throughout the event, it is not always easy to reach the responders spread across the city by radio contact. Communication between the Notte Bianca organisers and the CPD is also difficult to control and manage, and is subject to a number of challenges that are often difficult to overcome. In addition, the Notte Bianca organisers have very limited information and feedback from the people attending the event, in terms of the venues and activity which attract the largest number of people, or those which generate the greatest amount of congestion in the crowd movement.

Although the city is closed to the traffic for the evening and throughout the night, there are areas, in which there is a considerable increase in crowd density, thus causing some turbulence in the flow of people as they move towards different venues and activities. During these periods, an emergency is quite likely to occur, as people may be subject to medically-related failures and would thus be in need of immediate medical attention. When the CPD and the Ministry of Home Affairs officials were first contacted, with a description of the possible services that might be offered by the SOCIONICAL app, the potential which such an app holds for the protection of the individual, was immediately recognised and all the possible support was thus given to be able to pilot this app for the event. The most important features, which this app holds for an emergency rescue team, include amongst others the real time crowd density information, which would be important to identify areas in which an emergency would be most likely to occur. The more information which is gathered from the people attending the event, through their movement, direction and speed of travel – all gathered from the app running on their smart phone, the easier it would be for any emergency service to provide in-time rescue and first-response service. Moreover the possibility of relaying back important information to users and providing them with alternative route directions, especially in areas of heavy congestion in crowd movement, would also help in easing inconvenience as well as possibly preventing any incidents which might occur. The Notte Bianca organisers, as well as the Mayor of the city of Valletta, were also very helpful and supportive in setting up the pilot for the app. Since this was a pilot to test the technology, statistical information was not available for analysis. The potential, however, is recognized; as such information might lead to the improvement of this annual event for the people who attend both in terms of the individual's safety and protection, as well as in the entertainment value, that such an event promises for attendees.

7 Conclusion

Understanding the behavior of pedestrian crowds in physical spaces in real-time is important for many fields of application. In this work, we introduce a framework to infer real-time crowd conditions by tracking people's movement traces via their mobile phone. By aggregating and visualizing this information as heat maps, we can offer an intuitive way to obtain a global view of the crowd situation and to assess different crowd conditions instantaneously. Our framework also allows direct interaction with each user individually. This can be used to directly communicate with the users and provide them with targeted and highly personalized information e.g. in the case of a critical situation. That each person can be notified individually has the advantage that different users may receive different information e.g. on how to behave and where to go during an evacuation. This can be used to streamline the evacuation process by sending users not only to the nearest available exit but to also perform a load balancing by distributing them across all suitable exits. This is a great advantage over traditional systems like loudspeakers or information screens.

There are, however, some challenges inherent in this approach. Mainly, due to the participatory nature of our sensing approach, the system can only collect data from the users of the mobile phone app, which form only a subset of all attendees. Keeping this in mind, two aspects are crucial:

- **Ensuring a large user base:** Providing attractive incentives is important to reach a large user base. We reach this by offering festival attendees an enhanced experience by using our festival app. Hereby, a user study has revealed a set of attractive features and helped us to design the app accordingly [16]. Advertising the app in an appropriate way is key. Recently, big events started to offer their own app. Our tools can easily be integrated into their existing solution.
- **Seeing users as probes:** By designing robust crowd condition measures that are robust with respect to the ratio of the app users, it is possible to extract accurate crowd condition measures, even when not all attendees are being tracked. To do so, we have to consider the users as probes and conclude from their behavior the overall crowd situation. This can be achieved e.g. through calibration of the data. While the ratio of app users to festival attendees remains unknown, we assume that the spatio-temporal distribution of users reflects the distribution of attendees at any one time during the event. With this assumption in mind, an actual crowd density estimation can still be obtained by determining the ratio of mobile app users to festival users in a given area e.g. by inspecting CCTV recordings. This ratio has to be updated periodically throughout the event.

The framework can provide the following features of value to policy makers: (a) an overview, not available by the usual means of crowd monitoring including CCTV, as it can cover a larger area at any one time, for longer; (b) it is cheaper than a helicopter. Helicopters do have thermal imagery technology, but they are expensive and need highly trained personnel to fly them and on the ground; (c) especially valuable at night, (e.g. during the Fireworks display at the LMS), when CCTV cameras are not effective; (d) can be used to plan future events and to position barriers, ambulance stations, etc. more accurately; (e) using the heat map is intuitive and does not require any training, although it does need a trained officer to identify potential critical issues and take appropriate action. Overall the framework was found by the organisers and emergency services to be a valuable tool in taking appropriate action quickly to avoid a potential incident, thus increasing safety.

From a complexity theory perspective it shows evolving emergent crowd dynamics; it can be used to illustrate self-organising behavior of groups; and the messaging feature would contribute to active co-evolution between users and emergency personnel.

During the Lord Mayor's Show 2011, only the emergency response personnel and security personnel had access to the real-time visualization of the crowd conditions. It will be of further interest from a complexity science point of view to investigate the dynamics evolving when festival attendees themselves are given access to such crowd information. It would then be of interest to study how the available information is considered in their decision making process and what kind of co-evolutionary dynamics will emerge. Ultimately, we would like to understand if such information can help to lower the number of overcrowded situations, while decreasing turbulence and crowd pressure.

So far, we used the location updates from the users to assess the current crowd state and visualized this information. The relevance has been evaluated in this work. However, we believe there is much that can be done with this data for mitigating the risk of crowd incidents. Of great interest would then be to evaluate if this data can be used to predict upcoming crowd situations. So to speak, the available locations information from the users can be used to predict the future behavior of the crowd and identify potentially dangerous situations that may happen in the near future. With this, counter measures can be employed at a very early stage in order to prevent any potentially fatal incident.

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Agent-Based Modelling of Social Emotional Decision Making in Emergency Situations

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1 Introduction

Decision making under stressful circumstances is a challenging type of human process. For example, in emergency evacuations of a group of persons, the quality of such decision making processes may make a difference between surviving or not. Decision making under stress involves a number of aspects that have to be dealt with, such as high levels of emotions, adequate predictive capabilities, and social impact from other group members.

Mental states of individuals making a decision in a social context are not static. They often show high extents of dynamics due to social interaction. In Social Neuroscience neural mechanisms have been discovered that indeed – often in unconscious manners – account for mutual mirroring effects between mental states of different persons; e.g., [25], [34], [36]. For example, an emotion expresses itself in a smile which, when observed by another person, automatically triggers certain preparation neurons (also called mirror neurons) for smiling within this other person, and consequently generates the same emotion. Similarly, mirroring of intentions and beliefs can be considered.

In this paper group decision making in stressful circumstances is addressed. In these circumstances, emotions have an important interaction with the beliefs and intentions involved in a decision making process. The aim was to design a human-like computational model which is biological plausible by exploiting knowledge from Social Neuroscience about the relevant underlying mechanisms. Such a model

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may be useful not only for purposes of prediction, but also to obtain more insight in the dynamics of the social mechanisms and their emergent properties as described in a noncomputational manner in Social Neuroscience.

Based on modelling principles from neuroscience (Sect. 2), the computational model ASCRIBE (for Agent-based Social Contagion Regarding Intentions, Beliefs and Emotions) is introduced that not only incorporates mechanisms for mirroring emotions, intentions and beliefs between different persons (Sect. 3), but also addresses how within a person beliefs and emotions affect each other, and how they both affect the person's intentions. To illustrate the model, a number of example simulations in the context of a fictional emergency case study have been performed (Sect. 4). In the simulation scenario's agents are equipped with personal assistant devices with a tool for sharing emergency information over a short distance.

For agent-based modelling of collective phenomena individual agent behaviours can be modelled either from an agent-internal perspective, in the form of relations involving internal states of the agent, as in the ASCRIBE model, or from an agent-external, behavioural perspective, in the form of input-output relations for the agent, abstracting from internal states. Illustrated by a case study on collective decision making, this paper addresses how the two types of agent models can be related to each other by a behavioural abstraction mechanism described in Sect. 5. These relationships imply that, for example, collective behaviour patterns shown in multi-agent systems based on a behavioural agent model are shared for multi-agent systems based on corresponding cognitive agent models.

As a case study the model was evaluated based on empirical data for crowd behaviour. Behavioural patterns emerging in large crowds are often difficult to regulate. Various examples have shown how things can easily get out of control when many people come together during big events. Especially within crowds, the consequences can be devastating when emotion spirals (e.g., for aggression or fear) develop to high levels. In Sect. 6 a computational analysis is presented of the incident that happened at the Dam square in Amsterdam on the 4th of May in 2010. It is shown how the model is able to simulate an outburst of panic and its consequences. Finally, Sect. 7 concludes the paper.

2 Modelling Principles

This section briefly introduces the neurological/cognitive principles on which the models described in this chapter are based, and discusses the dynamical systems modelling approach used.

2.1 Generating Emotional Responses and Feelings

The question on the direction of causality between feeling and emotional response has a long history. A classical view on emotions is that based on some sensory input, due to internal processing emotions are felt, and based on this they are expressed in some emotional response (e.g., a body state such as a face expression):

stimulus → sensory representation → felt emotion → preparation for bodily changes → expressed emotion

James [26] claimed a different direction of causality (see also Damasio [12], pp. 114–116):

stimulus → sensory representation → preparation for bodily changes → expressed emotion → felt emotion

The perspective of James assumes that a *body loop* via the expressed emotion is used to generate a felt emotion by sensing the own body state. Damasio made a further step by introducing the possibility of an *as-if body loop* bypassing actually expressed bodily changes (cf. Damasio [8], pp. 155–158; see also Damasio [10], pp. 79–80; Damasio [12]):

stimulus → sensory representation → preparation for bodily changes → felt emotion

An as-if body loop describes an *internal simulation* of the bodily processes, without actually affecting the body, comparable to simulation in order to perform, for example, prediction, mindreading or imagination; e.g., [3], [17], [10]. Damasio [10] distinguishes an emotion (or emotional response) from a feeling (or felt emotion). The emotion and feeling in principle mutually affect each other in a bidirectional manner: an as-if body loop usually occurs in a cyclic form by assuming that the emotion felt in turn affects the prepared bodily changes; see, for example, in (Damasio [12], pp. 119–122):

emotion felt → preparation for bodily changes

A brief up-to-date survey of Damasio's ideas about emotion and feeling, and the 'tightly bound cycle' between them can be found in (Damasio [11], pp. 91–92) and (Damasio [12], pp. 108–129); for example (here the internal 'object' refers to the body state): 'The object at the origin on the one hand, and the brain map of that object on the other, can influence each other in a sort of reverberative process that is not to be found, for example, in the perception of an external object.' (Damasio [11], pp. 91–92). This essentially shows a cyclic process that (for a constant environment) can lead to equilibrium states for both emotional response (preparation) and feeling; see Fig. 1. Note that what is called stimulus s here can be taken as the sensor state sensing s. Given the cyclic nature of this process, a dynamical systems approach is a suitable modelling choice.

2.2 Mirroring

It has been found that certain preparation states for actions or for expressing body states (at the neural level called *mirror neurons*) have multiple functions, not only the function of preparing, but also the function of *mirroring* a similar state of another person; e.g., [25], [36], [15], [27], [29].

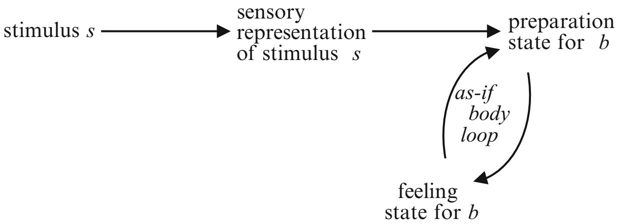


Fig. 1 Generating emotions and feelings based on an as-if body loop

Activation of mirror neurons is important not by itself, but because it plays a crucial role in an important mental function: *mirroring* mental processes of other persons by *internal simulation* using as-if body loops. From a more general viewpoint, as-if body loops as introduced above contribute:

(1) Sensory input directly affects preparation states, after which further internal processing takes place
(2) The notion of internal simulation involving body representations

Here (1) breaks with the tradition that there is a standard order of processing sensing – internal processing – preparation for action, and (2) allows for involving changing body representations in internal processes without actually having to change any body state. As mirror neurons make that some specific sensory input (an observed person) directly links to related preparation states, just like (1) above, it fits quite well in the perspective based on as-if body loops. In this way mirroring is a process that fully integrates mirror neuron activation states in the ongoing internal simulation processes based on as-if loops; see also (Damasio [12], pp. 102–104). This mirroring process is schematically shown in Fig. 2.

Here the preparation for body state *b* (e.g., some emotional response) can either be triggered by sensing an external stimulus *s* associating to *b*, or by observing somebody else performing *b* (upper part of Fig. 2). In both cases, as a first step the sensory representation affects the preparation state, after which further internal processing takes place based on the as-if body loop (lower part in Fig. 2) which in turn affects both the related feeling and the preparation state. Note that, as this mirroring process happens mostly in an unconscious manner, in a social context mirroring imposes limitations on the freedom for individuals to have their own personal emotions, beliefs, intentions, and actions.

2.3 Feelings and Valuing in the Emergence of Collective Action

Usually in the individual process of action selection, before a prepared action comes in focus to be executed, an internal simulation to predict the effects of the action takes place: the action is simulated based on prediction links, and in

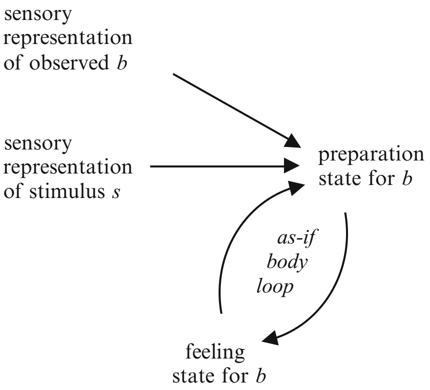


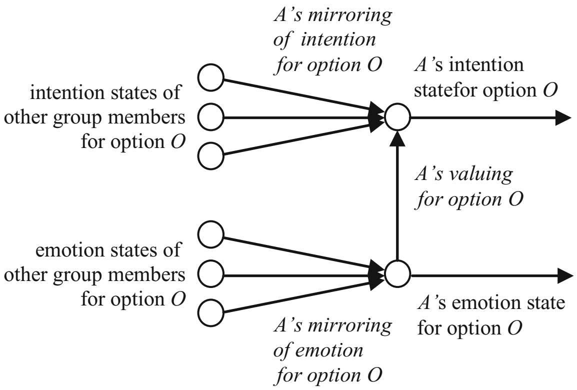
Fig. 2 Mirroring process based on mirror neuron activation and internal simulation

particular for the associated affective effects, based on as-if body loops that predict the body state which is the basis of the related feeling. Based on these predicted effects a valuation of the action takes place, which may involve or even be mainly based on the associated affective state, as, for example, described in [2], [8–12], [28], [30]. The idea here is that by an as-if body loop each option (prepared action) induces a simulated effect including a feeling which is used to value the option. For example, when a negative feeling and value is induced by a particular option, it provides a negative assessment of that option, whereas a positive feeling and value provides a positive assessment. The decision for executing a prepared action is based on the most positive assessment for it.

This simulation process for prepared actions does not only take place for preparations of self-generated actions, but also for intentions or actions from other persons that are observed. In this way by the mirroring process not only a form of action or intention recognition takes place in the form of activation of corresponding own preparation states by mirror neurons, but in addition also the (predicted) effects are simulated, including the affective effects. This provides an emotionally grounded form of understanding of the observed intention or action, including its valuing, which is shared with the observed agent; see also [12].

Given the important role of the feeling states associated to preparations of actions, it may be unrealistic to expect that a common action can be strong when the individual feelings and valuations about such an action have much variation over a group. When only the preparations for options are tuned to each other while in the meantime still the individual internal processes underlying the decision making remain a strong drive in a different direction, the overall process may result in no collectiveness at all. To achieve emergence of strong collective action, also a shared feeling and valuation for this action has to develop: also mirroring of the associated emotions has to play an important role. When this is achieved, the collective action has a solid shared emotional grounding: the group members do not only intend to perform that action collectively, but they also share a good feeling about it. In this process social media can play an important facilitating role in that (1) they dramatically strengthen the connections between large numbers of

Fig. 3 Mirroring processes for both emotions and intentions and their internal interaction



individuals, and (2) they do not only support transfer of, for example, beliefs and intentions as such, but also associated emotions reinforcing them. Thus emergence of collectiveness of action is achieved by not only tuning the preparations or intentions for options to each other, but by also tuning the individual internal processes underlying the decision making for these options; see Fig. 3. This double-effective form of contagion enables both the emergence of a collective action and of a solid emotional grounding for this collective action.

2.4 Modelling Perspective

To model the types of dynamic and cyclic processes as discussed here in a neurologically inspired computational manner, a dynamical modelling perspective is needed, such as the dynamical systems perspective advocated, for example in [1], [35]. Modeling causal relations as discussed in neurological literature does not need to take specific neurons into consideration but can use more abstract mental states, relating, for example, to groups of neurons. In this way within the cognitive/affective modelling area results from the large and more and more growing amount of neurological literature can be exploited. This can be considered as lifting neurological knowledge to a mental (cognitive/affective) level considering temporal-causal relations between mental states. Nevertheless, the type of computational model that is designed can benefit by using some technical elements from the neural modelling level. In particular the approach based on small continuous-time recurrent neural networks is adopted; this approach is advocated by Beer (1995), and was inspired, for example, by earlier work in [18], [23], [24], [16]. This approach takes states as having a certain activation level (a number in the interval [0, 1]), and makes reciprocal loops and gradual adaptation possible. In [4] it is claimed that they are an obvious choice for this type of work because (1) they are the simplest nonlinear, continuous dynamical neural network model,(2) they are universal dynamics approximators in the sense that, for any finite interval of time, they can approximate the trajectories of any smooth dynamical system on a compact subset of IR^n arbitrarily well [16], and (3) they have a plausible neurobiological interpretation. This type of computational model is formulated as follows. For a state depending on multiple other states, to update its activation level, input values for incoming activation levels have to be combined to some aggregated input value. This update takes place according to the differential equation

$$\boldsymbol{d}y_i/\boldsymbol{dt} = \gamma_i[agginput_i - y_i]$$

where γ_i is the update speed of state i, $agginput_i$ is the aggregated input for i, and y_i is the activation value of i. The aggregation is created from the individual inputs $\omega_{j,i}$ y_j for all states j connected to i, where $\omega_{j,i}$ is the strength of the connection from j to i. For this aggregation a combination function $f(V_1, \ldots, V_k)$ is needed, applied to the different incoming values $V_j = \omega_{j,i}\ y_j$. It will be assumed that such a combination function satisfies:

(1) $0 \leq f(V_1, \ldots, V_k) \leq 1$ whenever $V_1, \ldots, V_k \leq 1$
(2) f is monotonous: $f(V_1, \ldots, V_k) \leq f(W_1, \ldots, W_k)$ whenever $V_i \leq W_i$ for all i

A simple example of a combination function is the sum function:

$$f(V_1, \ldots, V_k) = \sum\nolimits_i V_i$$

For this function to satisfy (1), this puts strong constraints on the values $V_1, \ldots, V_k$: the sum of the inputs has to be at most 1, i.e., $\sum_{j \in s(i)} \omega_{j,i} \leq 1$, where $s(j)$ is the set of states connected as a source to state i. This dependency between connections is often not considered practical, nor biologically plausible. An often used combination function (e.g., in [4]) is based on a continuous logistic threshold function:

$$f(V_1, \ldots, V_k) = th(V_1 + \ldots + V_k)$$

with

$$th(X) = \frac{1}{1 + e^{-\sigma(X-\tau)}} \text{ or } th(X) = \left(\frac{1}{1 + e^{-\sigma(X-\tau)}} - \frac{1}{1 + e^{\sigma\tau}}\right)(1 + e^{-\sigma\tau})$$

Note that in the former variant $th(0) = \frac{1}{1+e^{\sigma\tau}}$ and this is nonzero; this is compensated in the latter variant. The former variant can be used as a suitable approximation when $\sigma\tau$ is large enough, e.g. $\sigma\tau \geq 20$. Given this, the type of computational model considered here uses $agginput_i = th(\sum_{j \in s(i)} \omega_{j,i}\ y_j)$ and provides a dynamical system of the form:

$$dy_i/dt = \gamma_i[th(\sum\nolimits_{j \in s(i)} \omega_{j,i}\ y_j) - y_i]$$

Note that the type of model can be described in difference equation format as follows:

$$y_i(t+\Delta t) = y_i(t) + \gamma_\mathrm{i}[th(\textstyle\sum_{j\in s(i)} \omega_{j,i}\, y_j) - y_i]\Delta \mathrm{t}$$

This difference equation can be directly used for simulation, or more dedicated numerical approximation methods can be used.

3 ASCRIBE Model

In this section the computational model for group decision-making is introduced, which is based on the neurological principles of somatic marking and mirroring discussed in the previous section. More details on the model and its origins are addressed in. An elaborate description of the interplay of the different states can be found in [22]. In Sect. 3.1 the general model for the mirroring of mental states is introduced. Section 3.2 provides more details on the interplay between the different states of emotions, intentions and beliefs.

3.1 *The General Model*

The most important parameters and states within this general model will be described in this section. An overview of these parameters and states can be found in Table 1.

The model describes at an abstract level the mirroring of a mental state S (which can be, for example, an emotion, belief or intention) between agents. An important factor in determining the value of state S, is the contagion strength γ_{SBA} from agent B to agent A in a group. This denotes how much the state S of A is influenced by the state S of B. It is defined by

$$\gamma_{SBA} = \varepsilon_{SB}\alpha_{SBA}\delta_{SA} \tag{1}$$

Here, ε_{SB} is the personal characteristic *expressiveness* of the sender B for S, δ_{SA} the personal characteristic *openness* of the receiver A for S, and α_{SBA} the interaction characteristic *channel strength* for S from sender B to receiver A. In order to determine the level q_{SA} of state S in an agent A, first, the overall contagion strength γ_{SA} from the group towards agent A is calculated:

$$\gamma_{SA} = \textstyle\sum_{B\neq A}\gamma_{SBA} \tag{2}$$

This contagion strength is used to determine the weighed impact $q_{SA}{}^*$ of all the other agents upon state S of agent A:

Table 1 Parameters and states

q_{SA}	Level for state *S* for person *A*
ε_{SA}	Extent to which person *A* expresses state *S*
δ_{SA}	Extent to which person *A* is open to state *S*
η_{SA}	Tendency of person *A* to absorb or amplify state *S*
β_{SA}	Positive or negative bias of person *A* on state *S*
α_{SBA}	Channel strength for state *S* from sender *B* to receiver *A*
γ_{SBA}	Contagion strength for *S* from sender *B* to receiver *A*

$$q_{SA}{}^{*}(t) = \sum\nolimits_{B \neq A} \gamma_{SBA}\ \ q_{SB}(t)/\gamma_{SA} \tag{3}$$

The dynamics of the different mechanisms involved are modelled by dynamical relationships using the following general pattern:

$$Y_A(t + \Delta t) = Y_A(t) + \gamma < change\_expression > \Delta t$$

The change of Y is specified for a time interval between t and $t + \Delta t$; the γ represents the speed of the adjustment processes. Applied to the variable $q_{SA}(t)$ for $Y_A(t)$ the following is taken:

$$< change\_expression >= f(q_{SA}{}^{*}(t), q_{SA}(t)) - q_{SA}(t)$$

where $f(q_{SA}{}^{*}(t), q_{SA}(t))$ is a combination function. Thus the resulting update-rule for the considered states is:

$$q_{SA}(t + \Delta t) = q_{SA}(t) + \gamma_{SA}[f(q_{SA}{}^{*}(t), q_{SA}(t)) - q_{SA}(t)]\Delta t \tag{4}$$

Two additional personal characteristics determine how much this external influence actually changes state S of agent A, namely the tendency η_{SA} to absorb or to amplify the level of a state and the bias β_{SA} towards increasing (upward) or reducing (downward) impact for the value of the state. Based on this the combination function $f(q_{SA}{}^{*}(t), q_{SA}(t))$ used was taken as:

$$\begin{aligned} f(q_{SA}{}^{*}(t), q_{SA}(t)) = {} & \eta_{SA}[\beta_{SA}(1 - (1 - q_{SA}{}^{*}(t))(1 - q_{SA}(t))) \\ & + (1 - \beta_{SA})\ q_{SA}{}^{*}(t)\ q_{SA}(t)] + (1 - \eta_{SA})\ q_{SA}{}^{*}(t) \end{aligned}$$

By Eq. 4 the new value for the state S at time $t + \Delta t$ is calculated from the old value at t, plus the change of the value based upon the transfer by mirroring. This change is defined as the multiplication of the overall contagion strength γ_{SA} times the difference of a combination function of $q_{SA}{}^{*}$ and q_{SA} with q_{SA}. The combination function used has a component for amplification (after $\eta_{SA}(t)$) and one for absorption. The amplification component depends on the tendency of the person towards more positive (part multiplied by $\beta_{SA}(t)$ or negative part of equation multiplied by $1 - \beta_{SA}(t)$ side).

3.2 Dynamics Between Emotions, Beliefs and Intentions

When considering a computational model for group decision making, it is evident that beliefs, intentions and emotions make up a large part of this process. However, these aspects also influence each other. This section describes a computational model for the interplay of emotions, beliefs and intentions in a group of persons in the context of collective decision making. The model is extended by forming specializations of the generic model from Sect. 3.1, so as to incorporate internal interactions between the different types of states. Three different types of mental states S (as used in Eq. 4) are considered: beliefs, emotions, and intentions, indicated by *belief(X)*, *fear*, *emotion(O)*, *intention(O)* for information X and options O. In addition, interactions between these different states are modeled at the individual level; see also Table 2 for a brief explanation of all interactions in the model. In the following subsections, the specific interactions as shown in Table 2 will be addressed.

3.2.1 The Effect of Emotions on Beliefs

To model the effect of emotions on information diffusion, the personal characteristics δ_{SA}, η_{SA} and β_{SA} for a belief state S = belief(X) are not assumed constant, but are instead modeled in a dynamic manner, depending on emotions. Personal characteristics $\varepsilon_{belief(X)A}$, $\delta_{belief(X)A}$, $\eta_{belief(X)A}$, $\beta_{belief(X)A}$ and interaction characteristic $\alpha_{belief(X)BA}$ are parameters in the model as described in Sect. 3.1. One additional category is introduced here, namely informational state characteristics r_{XA} denoting how relevant, and p_{XA} denoting how positive information X is for person A. An assumption made for the model is that the intensity of the fear state of a person will affect his ability to receive information, by affecting the value of the individual person characteristics; in particular, a high level of fear affects $\beta_{belief(X)A}$, $\eta_{belief(X)A}$ and $\delta_{belief(X)A}$. First the effect of fear upon the openness for a belief belief (X) (characterized by a relevance r_{XA} of information X for A) is expressed:

$$\begin{aligned}\delta_{belief(X)A}(t+\Delta t) = {} & \delta_{belief(X)A}(t) + \mu \cdot (1/1 + e^{-\sigma(q_{fear,A}(t)-\tau)}) \cdot \\ & [(1 - \cdot (1 - r_{XA}) \cdot q_{fear,A}(t)\, \delta_{belief(X)A}(t)] \cdot \Delta t \qquad (5)\end{aligned}$$

If $q_{fear,A}$ is lower than threshold τ (on the interval [0,1]), it will not contribute to the value of $\delta_{belief(X)A}$. If $q_{fear,A}$ has a value above τ, the openness will depend on the relevance of the information: when the relevance is high, openness will increase, while if the relevance is low, openness will decrease. In all formulae, μ is an

Table 2 The different types of processes in the model

From S	To S'	Type	Description
Belief(X)	*Fear*	Internal	Affective response on information; for example, on threats and possibilities to escape
Emotion(O)	*Emotion(O)*	Interaction	Emotion mirroring by nonverbal and verbal interaction; for example, fear contagion
Fear	*Belief(X)*	Internal	Affective biasing; for example, adapting openness, amplification extent and orientation
Belief(X)	*Belief(X)*	Interaction	Belief mirroring by nonverbal and verbal interaction; for example, of information on threats and options to escape
Belief(X)	*Intention(O)*	Internal	Cognitive response on information; for example, aiming for an exit that is believed to be reachable
Emotion(O)	*Intention(O)*	Internal	Somatic marking of intention options; for example, giving options that feel bad a low valuation
Intention(O)	*Intention(O)*	Interaction	Intention mirroring by nonverbal and verbal interaction; for example, of tendency to go in a certain direction

adaptation parameter. This proposed model corresponds to theories of emotions as frames for selective processing, as described in [14], [32]. A distinction between amplification values for different types of information is also made, depending on the emotional state fear. The dynamics for the characteristic $\eta_{belief(X)A}(t)$ modeling the amplification or absorption of *belief(X)* are described as follows:

$$\begin{aligned}\eta_{belief(X)A}(t+\Delta t) = \eta_{belief(X)A}(t) + \mu \cdot (1/1 + e^{-\sigma(q_{fear,A}(t)-\tau)}) \cdot \\ [r_{XA} \cdot (1-p_{XA}) \cdot (q_{fear,A}(t)\,\eta_{belief(X)A}(t))] \cdot \Delta t \qquad (6)\end{aligned}$$

The emotion of fear only has an influence when it is above the threshold. In that case the parameter only changes for relevant, non-positive information for which the parameter starts to move towards the value for the emotion of fear (meaning this type of information will be amplified). This property represents an interpretation of [7] on how emotion can result in selective processing of emotion-relevant information.

The bias of a person is also influenced by its emotion, but in addition depends on the content of the information, which can be either positive or negative:

$$\begin{aligned}\beta_{belief(X)A}(t+\Delta t) = \beta_{belief(X)A}(t) + \mu \cdot (1/(1+e^{\sigma(q_{fear},\, A^{(t)^{-\tau}}})) \cdot (1-q_{belief(X)A}(t)) \cdot \\ [(\zeta_A \cdot p_{XA} + (1-\zeta_A) \cdot (1-p_{XA})) - \beta_{belief(X)A}(t)] \cdot \Delta t \qquad (7)\end{aligned}$$

Parameter τ is a number between 0 and 1 and represents a threshold for q_{fear}: when $q_{\text{fear}} > \tau$, then $q_{fear,A}$ has an influence on the bias $\beta_{belief(X)A}(t)$. Parameter ζ_A is a personality characteristic; if $\zeta_A = 1$, represents a person who is optimistic when he/she experiences a lot of fear: positive information will be strengthened more and negative information will be weakened more. The opposite happens when $\zeta_A = 0$, this represents a person who is more ‘pessimistic’ when experiencing fear: negative information will be strengthened and positive information will be weakened. Both personality characteristics seem to exist in people: a bias towards the negative side of information in case of experiencing a high level of fear corresponds with the narrowing hypothesis from Frederickson’s broaden-and-build theory in [14]. Others have a bias towards more positive information and emotions. Leaders could use this ability motivate their followers in times of crisis, as positive information and emotions broaden people’s mindset [14], and focusing on positive information and emotions can contribute positively to individual’s mental states (including attention and cognitive capacity) and resources [14]. The dynamically changing ‘parameters’ $\delta_{belief(X)A}(t)$, $\eta_{belief(X)A}(t)$, $\beta_{belief(X)A}(t)$ are used in the equation describing the dynamics of the belief state *belief(X)*:

$$q_{belief(X)A}(t+\Delta t) = q_{belief(X)A}(t) + \gamma_{belief(X)A}(t) \cdot \left[f\left(q_{belief(X)A}{}^{*}(t), q_{belief(X)A}(t)\right) - q_{belief(X)A}(t)\right] \Delta t \tag{8}$$

Here the combination function $f(q_{SA}{}^{*}(t), q_{SA}(t))$ used is taken in a dynamic manner as:

$$\begin{aligned} f\left(q_{belief(X)A}{}^{*}(t), q_{belief(X)A}(t)\right) = {} & \eta_{belief(X)A}(t) \ \ [\beta_{belief(X)A}(t) \\ & (1-(1-q_{belief(X)A}{}^{*}(t))(1-q_{belief(X)A}(t))) \\ & + (1-\beta_{belief(X)A}(t)) \ q_{belief(X)A}{}^{*}(t) \ q_{belief(X)A}(t)] \\ & + (1-\eta_{belief(X)A}(t)) \ q_{belief(X)A}{}^{*}(t) \end{aligned}$$

Note that since it depends on $\delta_{belief(X)A}(t)$, also $\gamma_{belief(X)A}(t)$ becomes dynamic.

3.2.2 The Effect of Beliefs on Emotions with Respect to the Dynamics of Fear

In this subsection it is addressed how emotions are being influenced by information. This influence is modelled by altering the overall weighed impact of the contagion of the emotional state for fear:

$$q_{fear,A}{}^{*}(t) = \nu_A \cdot (\Sigma_{B \neq A} \gamma_{fearBA} \cdot q_{fearB} / \gamma_{fearA}) + (1-\nu_A) \cdot (\Sigma_X \ \omega_{X,fear,A} \cdot (1-p_{XA}) \cdot r_{XA} \cdot q_{belief(X)A}) \tag{9}$$

Here the influence depends on the impact from the emotion fear by others (the first factor, with weight ν_A) in combination with the influence of the belief present within the person. In this case, information has an increasing effect on fear if it is relevant and non-positive. This $q_{fear,A}{}^{*}(t)$ is used in the equation describing the dynamics of fear:

$$q_{fearA}(t+\Delta t) = q_{fearA}(t) + \gamma_{fearA}\left[f\left(q_{fearA}{}^{*}(t), q_{fearA}(t)\right) - q_{fearA}(t)\right]\Delta t \tag{10}$$

with

$$\begin{aligned} f(q_{fearA}{}^{*}(t),\ q_{fearA}(t)) = \eta_{fearA}[\beta_{fearA}(1-(1-q_{fearA}{}^{*}(t))(1-q_{fearA}(t))) \\ +(1-\beta_{fearA})\ q_{SA}{}^{*}(t)\ q_{SA}(t)]\ +(1-\eta_{fearA})\ q_{fearA}{}^{*}(t) \end{aligned}$$

3.2.3 The Effect of Beliefs and Emotions on Intentions

The abstract model for mirroring described above applies to emotion, belief and intention states *S* for an option *O* or the situation in general, but does not describe any interplay for intentions yet. Taking the Somatic Marker Hypothesis on decision making as a point of departure, not only intentions of others, but also own emotions affect the own intentions. To incorporate such an interaction, the basic model is extended as follows: to update $q_{intention(O)A}$ for an intention state *S* relating to an option *O*, both the intention states of others for *O* and the $q_{emotion(O)A}(t)$ values for the emotion state *S′* for *O* are taken into account. These intention and emotion states *S* and *S′* for option *O* are denoted by *OI* and *OE*, respectively:

Level of fear of person *A*: $q_{fearA}(t)$
Level of emotion for option *O* of person *A*: $q_{emotion(O)A}(t)$
Level of intention indication for option *O* of person *A*: $q_{intention(O)A}(t)$
Level of belief supporting option *O* of person *A*: $q_{beliefsfor(O)A}(t)$

Here $q_{beliefsfor(O)A}(t)$ denotes to aggregated support for option *O* by beliefs of *A*; it is defined as

$$q_{beliefsfor(O)}(t) = \Sigma_X \omega_{XOA}\ q_{belief(X)A} / \Sigma_X \omega_{XOA} \tag{11}$$

Here ω_{XOA} indicates how supportive information *X* is concerning option *O*. The combination of the own (positive) emotion level and the rest of the group's aggregated intention is made by a weighted average of the two:

$$\begin{aligned} q_{intention(O)A}{}^{**}(t) = (\omega_{OIA1}/\omega_{OIEBA})q_{intention(O)A}{}^{*}(t) \\ + (\omega_{OEA2}/\omega_{OIEBA})q_{emotion(O)A}(t) \\ + (\omega_{OBA2}/\omega_{OIEBA})q_{beliefsfor(O)A}(t) \end{aligned} \tag{12}$$

$$\gamma_{intention(O)A}{}^{*} = \omega_{OIEBA}\gamma_{intention(O)A} \tag{13}$$

$\omega_{OIA1}, \omega_{OBA2}$ and ω_{OEA2} are the weights for the contributions of the group intention impact (by mirroring), the own emotion impact (by somatic marking), and the own belief impact on the intention of A for O, respectively, and

$$\omega_{OIEBA} = \omega_{OIA1} + \omega_{OEA2} + \omega_{OBA2}$$

The combination of the own belief level and the rest of the group's aggregated emotion for a certain option O is made by a weighted average of the two:

$$\begin{aligned} q_{emotion(O)A}{}^{**}(t) = {} & (\omega_{OEA1}/\omega_{OEBA})\ q_{emotion(O)A}{}^{*}(t) \\ & + (\omega_{OBA1}/\omega_{OEBA}) q_{beliefsfor(O)A}(t) \end{aligned} \tag{14}$$

$$\gamma_{emotion(O)A}{}^{*} = \omega_{OEBA}\ \gamma_{emotion(O)A} \tag{15}$$

ω_{OEA1} *and* ω_{OBA1} are the weights for the contributions of the group emotion impact (by mirroring), the own belief impact on the emotion of A for O, respectively, and $\omega_{OEBA} = \omega_{OEA1} + \omega_{OBA1}$. Then the overall model for the dynamics of emotions and intentions for options becomes:

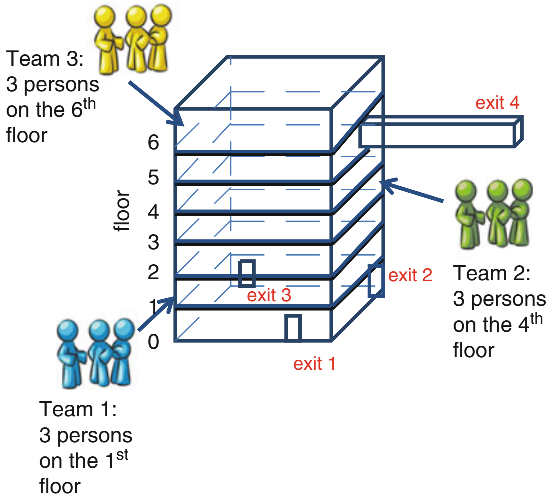
$$\begin{aligned} q_{emotion(O)A}(t+\Delta t) = {} & q_{emotion(O)A}(t) + \gamma_{intention(O)A}{}^{*} \cdot [\eta_{emotion(O)A}(\beta_{emotion(O)A} \\ & (1-(1-q_{emotion(O)A}{}^{**}(t))(1-q_{emotion(O)A}(t))) \\ & + (1-\beta_{emotion(O)A})\ q_{emotion(O)A}{}^{**}(t)\ q_{emotion(O)A}(t)) \\ & + (1-\eta_{emotion(O)A})\ q_{emotion(O)A}{}^{**}(t) - q_{emotion(O)A}(t)] \cdot \Delta t \end{aligned} \tag{16}$$

$$\begin{aligned} q_{intention(O)A}(t+\Delta t) = {} & q_{intention(O)A}(t) + \gamma_{intention(O)A}{}^{*} \cdot [\eta_{intention(O)A}(\beta_{intention(O)A} \\ & (1-(1-q_{intention(O)A}{}^{**}(t))(1-q_{intention(O)A}(t))) \\ & + (1-\beta_{intention(O)A})\ q_{intention(O)A}{}^{**}(t)\ q_{intention(O)A}(t)) \\ & + (1-\eta_{intention(O)A})\ q_{intention(O)A}{}^{**}(t) - q_{intention(O)A}(t)] \cdot \Delta t \end{aligned} \tag{17}$$

4 Simulation Studies

In this section, some example results of a small fictional case study will be presented. The goal of the case study was to investigate if the computational model can simulate the interplay of emotions, intentions and beliefs, as described in neuroscientific, social and psychological literature. The computational model was implemented in Matlab in the context of an evacuation scenario.

Fig. 4 The location of three teams in a building of six floors with four exits



The example scenario is expressed as follows: at the end of a working day in an office, the fire alarm goes off and all the persons that are in the building need to evacuate immediately. At the time of the alarm, three teams of each three people are present on different floors, as can be seen in Fig. 4. Persons can communicate with each other when they are on the same floor, or they can communicate to each other through their personal device, which is equipped with a tool for sharing emergency information over a short distance. Communication through such personal devices can only occur in case the distance is three floors or less. The building has four emergency exits, three at the ground floor and one at the 5th floor via a skyway to another building. If an exit is accessible, the information is rated as 'positive' information in the model, if not accessible then the information is rated 'not positive'. In the formalization, this leads to the following information state characteristics: $p_{ExitX} = 1$ for accessible exits and $p_{ExitX} = 0$ for blocked exists. The relevance of this information for survival is always 1, i.e. $r_{ExitX} = 1$.

4.1 An Example Scenario

In the example scenario, the three persons located at the top floor know that exit 4 is available (i.e. they have a belief of *1* in information $p_{Exit4} = 1$), whereas the three persons on the middle floor do not have any strong beliefs about any of the emergency exits. The three at the first floor know the situation of the exits 1 and 2 at the first floor, thus they have beliefs of strength *1* concerning those exists. In this case, the first exit is blocked and the second is accessible, therefore $p_{Exit1} = 0$ and $p_{Exit2} = 1$. They do not know anything about exit 3, therefore a belief of strength *0* is present concerning exit 3. Besides these values, all other values are

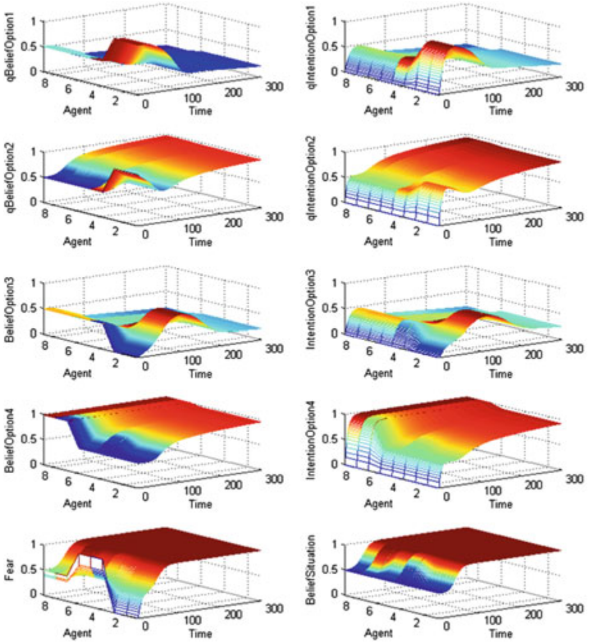


Fig. 5 Simulation results for an example scenario

set to 0.5 with respect to the beliefs to indicate that they know the exits are there but do not know specifically whether the exit is accessible or not. Moreover, the intentions of all agents are initially set to 0 (i.e. they start with not specific intention to leave the building via any of the exits) and the emotions to $0, 1, 0$, and 1 for exit 1, 2, 3, and 4 respectively (since exit 1 and exit 3 represent negative information, the emotion for that option is not positive). Finally, for the emotion of fear the agents at the first floor have no fear, at the middle floor they have maximum fear, and at the top floor medium fear is present. Furthermore, the initial belief about the situation itself is 0.5. Furthermore, each agent has the same initial set of parameters.

Figure 5 shows the change of the values of the beliefs, intentions, and emotions. The top four rows represent the values related to the four exits. Here, the values for all agents during the simulation runs are shown. The y-axis of the graphs represents all nine persons, who have values for certain variables, stated on the z-axis. The values develop over time, which is represented by the x-axis. At the bottom row of the figure, diagrams with the amount of fear and the judgment of the entire situation are shown. It can be seen that fear spreads quickly, resulting in a very negative judgment of the situation by all agents. For exit 1 the belief about the exit being an option for evacuation eventually stabilizes at a relatively low value due to the fact that no human has a good feeling for that option (although in the beginning the emotions are slightly pulled upwards as well as the intention, due to the very strong belief of the three agents at the first floor). For exits 2 and 4 a very strong belief occurs rapidly for all agents as well as a very strong intention and the positive emotions also remain high. Finally, for exit 3 the agents at the first floor get a slightly stronger belief, intention, and emotion due to the fact that the other agents have a belief with value 0.5 about the exit. Eventually however, the values return to a rather low value again due to the fact that the others have lowered their value again. Without the ability to communicate with each other using personal devices, the beliefs, intentions, and emotions would not have been influenced by those on the other floors.

4.2 More Systematic Variations

The context of this case study was used to explore whether under a variety of parameter settings patterns emerge as expected.

4.2.1 The Effect of Information on Fear

A first prediction about the interplay of emotions, intentions and beliefs, according to the computational model is that from formula (8), it is expected that if a person experiences a situation as dangerous, then this person's fear level should increase. Simulations where the persons believed that the situation is dangerous were compared with simulations where they believed that that situation was not dangerous. The result of these simulations were that if persons believe that the situation is not dangerous ($p_{belief(s)A} = 1$), then $q_{fearA}(t)$ goes to 0, meaning that the persons will experience no fear. If the persons believe that the situation is dangerous ($p_{belief(s)A} = 0$), then $q_{fearA}(t)$ increases to 1, meaning that the persons will increase their experience of fear, when they consider the situation as dangerous. This result corresponds with our expectation.

4.2.2 The Effect of Emotion on Beliefs

According to formulas (5), (6), and (7) the level of fear that a person is experiencing, can have an effect on the way a person processes information. More precisely: it is expected that when $q_{fearA}(t)$ is above threshold τ, then the emotion fear should have an effect on the way persons process information. Multiple simulations were run to test this. In the simulations, the threshold τ was set to 0.5 and the initial value of $q_{fearA}(t)$ is below or above threshold τ, for example, 0.1 or 0.7. Whenever $q_{fearA}(t)$ is above the threshold τ (either from the start, or at a later time point), $\delta_{belief(X)A}(t)$, $\eta_{belief(X)A}(t)$ and $\beta_{belief(X)A}(t)$ start to change indeed. Here results will be briefly presented where ζ was 1.

The openness $\delta_{belief(X)A}(t)$ becomes 1 or stays 1, this is according to the model, because when $\zeta = 1$ and $r_{belief(s)A} = 1$ (the information is relevant for survival), $\delta_{belief(X)A}(t)$ should increase.

The bias factor $\beta_{belief(X)A}(t)$ increases for the situation, exit 1 and 3 (which are not accessible), but decreases for exit 2 and 4 (which are accessible). This is what was expected, because the higher $p_{belief(s)A}$ is (meaning the more 'positive' information is), the lower $\beta_{belief(X)A}(t)$ should become (meaning information will be spread weaker by this person), the lower $p_{belief(s)A}$ is, the higher $\beta_{belief(X)A}(t)$ should become (meaning strengthening the spread of negative information).

The amplification extent $\eta_{belief(X)A}(t)$ increases differently for the situation, where exit 1 and 3 are not accessible. For this situation it goes towards 1 and it increases more, the further the agents are away from the exit. This is according to expectation, because $\eta_{belief(X)A}(t)$ should only increase if $p_{belief(s)A} =$ low and $r_{belief(s)A} =$ high, in these instances, $p_{belief(s)A} = 0$ and $r_{belief(s)A} = 1$. For exit 2 and 4, $p_{belief(s)A} = 1$ and $r_{belief(s)A} = 1$. In that case $\eta_{belief(X)A}(t)$ should not increase, and that is what is happening correctly in this evacuation scenario.

4.2.3 The Effects of a Combination of Beliefs and Emotions

In the simulations it was found that the combination of emotions and beliefs decreases the level of $q_{emotion(X)A}(t)$ more than they do separately. This effect was expected from formula (1) for $q_{emotion(X)A}(t)$**. For example, here one can see that in this situation the combination of emotions and beliefs makes $q_{emotion(X)A}(t)$ increase more, than when beliefs are not combined with emotions.

5 Model Abstraction

To obtain an agent-based social level model for group decision making, the general internal agent-based model for contagion described in Sect. 3.1 for any decision option O has been applied to both the emotion states S for O and intention or choice tendency states S' for O. In addition, an interplay between the two types of states has been modelled. To incorporate such an interaction, the general model from Sect. 3.1 was extended as follows: to update $q_{SA}(t)$ for an intention state S relating to an option O, both the intention states of others for O and the $q_{S'A}(t)$ values for the emotion state S' for O are taken into account. Note that in this model a fixed set of options was assumed that all are considered. The emotion and choice tendency states S and S' for option O are denoted by $b(O)$ and $c(O)$, respectively. Then the expressed level of emotion for option O of person A is $e_{b(O)A}(t)$, and of choice tendency or intention for O is $e_{c(O)A}(t)$. The combination of the own (positive) emotion level and the rest of the group's aggregated choice tendency for option O is made by a weighted average of the two:

$$\begin{aligned} s_{g(c(O))A}{}^{*}(t) &= (\omega_{c(O)A}/\omega_{OA})\ s_{g(c(O))A}(t) + (\omega_{b(O)A}/\omega_{OA}) e_{b(O)A}(t)/\varepsilon_{SA} \\ \gamma_{c(O)_A}{}^{*} &= \omega_{OA}\gamma_{c(O)_A} \end{aligned}$$

where $\omega_{c(O)A}$ and $\omega_{b(O)A}$ are the weights for the contributions of the group choice tendency impact and the own emotion impact on the choice tendency of A for O, respectively, and $\omega_{OA} = \omega_{c(O)A} + \omega_{b(O)A}$.

Then the behavioural agent-based model for interacting emotion and intention (choice tendency) contagion expressed in numerical format becomes:

$$s_{g(b(O))A}(t) = \Sigma_{B \neq A}\alpha_{b(O)BA} \cdot e_{b(O)B}(t)/(\Sigma_{B \neq A}\varepsilon_{b(O)B} \cdot \alpha_{b(O)BA})$$

$$\begin{aligned} e_{b(O)A}(t + \Delta t) = e_{b(O)A}(t) + \varepsilon_{b(O)A}\gamma_{b(O)A}c(&s_{g(b((O))A}(t), \\ &e_{b(O)A}(t)/e_{b(O)A})\,\Delta t \end{aligned}$$

with as an example

$$\begin{aligned} c(X,\ Y) = \eta_{b(O)A} \cdot [&\beta_{b(O)_A} \cdot (1 - (1 - X) \cdot (1 - Y)) + (1 - \beta_{b(O)_A}) \cdot XY] \\ &+ (1 - \eta_{b(O)A}) \cdot X - Y \end{aligned}$$

$$s_{g(c(O))A}(t) = \Sigma_{B \neq A}\alpha_{c(O)BA} \cdot e_{c(O)B}(t)/(\Sigma_{B \neq A}\varepsilon_{c(O)B} \times \alpha_{c(O)BA})$$

$$\begin{aligned} e_{c(O)A}(t + \Delta t) = e_{c(O)A}(t) + \varepsilon_{c(O)A}\omega_{OA}\gamma_{c(O)A}d(&(\omega_{c(O)A}/\omega_{OA})s_{g(c(O))A}(t) \\ &+ (\omega_{b(O)A}/\omega_{OA})e_{b(O)A}(t)/\varepsilon_{b(O)A}, e_{c(O)A}(t)/\varepsilon_{c(O)A})\Delta t \end{aligned}$$

with as an example

$$\begin{aligned} d(X,\ Y) = \eta_{c(O)A} \cdot [&\beta_{c(O)_A} \cdot (1 - (1 - X) \cdot (1 - Y)) + (1 - \beta_{c(O)_A}) \cdot XY] \\ &+ (1 - \eta_{c(O)A}) \cdot X - Y \end{aligned}$$

For the behavioural abstraction, the internal agent model (**IAM**) is expressed in a hybrid logical/numerical format in a straightforward manner (a graphical representation of the model, based on the principles from Sect. 2 is provided in Fig. 6):

IP1 From sensor states (SS) to sensory representations (SRS)

$$\mathrm{SS(A,\ S,\ V)} \twoheadrightarrow \mathrm{SRS(A,\ S,} \upsilon_{\mathrm{SA}}\mathrm{V)}$$

where S has instances c, g(c(O)) and g(b(O)) for options O.

IP2 Preparing for an emotion expressed in a body state (preparation state PS)

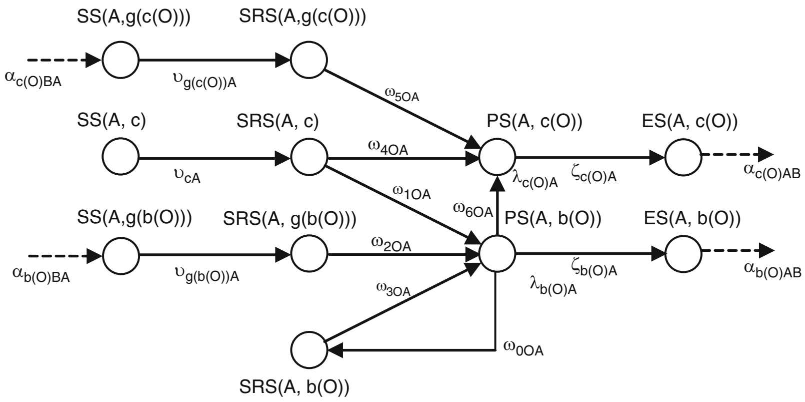


Fig. 6 Overview of the internal agent model **IAM**

$$\begin{aligned}&\mathrm{SRS(A,\ c,\ V_1)\ \&\ SRS(A,\ g(b(O)),\ V_2)}\\&\mathrm{\&\ SRS(A,\ b(O),\ V_3)\ \&\ PS(A,\ b(O),\ V)}\\&\twoheadrightarrow \mathrm{PS\big(A,\ b(O),\ V + \lambda_{b(O)A}g(\omega_{1OA}V_1, \omega_{2OA}V_2, \omega_{3OA}V_3,\ V)\Delta t\big)}\end{aligned}$$

IP3 Preparing for an option choice (preparation state PS)

$$\begin{aligned}&\mathrm{SRS(A,\ c,\ V_1)\ \&\ SRS(A,\ g(c(O)),\ V_2))}\\&\mathrm{\&\ PS(A,\ b(O),\ V_3)\ \&\ PS(A,\ c(O),\ V)}\\&\twoheadrightarrow \mathrm{PS\big(A,\ c(O),\ V + \lambda_{c(O)A}h(\omega_{4OA}V_1, \omega_{5OA}V_2, \omega_{6OA}V_3,\ V)\Delta t\big)}\end{aligned}$$

IP4 From preparation to effector state (ES)

$$\mathrm{PS(A,\ S,\ V)} \twoheadrightarrow \mathrm{ES(A,\ S, \zeta_{SA}V)}$$

where S has instances b(O) and c(O) for options O.

IP5 From preparation to sensory representation of body state (SRS)

$$\mathrm{PS(S,\ V)} \twoheadrightarrow \mathrm{SRS(S, \omega_{0OA}V)}$$

where S has instances b(O) for options O.

ITP Sensing aggregated group members' bodily responses and intentions

$$\wedge_{\mathrm{B}\neq \mathrm{A}}\ \mathrm{ES(B,\ S,\ V_B)} \twoheadrightarrow \mathrm{SS\big(A,\ g(S), \Sigma_{B\neq A}\alpha_{SBA}V_B / \Sigma_{B\neq A}\alpha_{SBA}\zeta_{SB}\big)}$$

where S has instances b(O), c(O) for options O.

Also, the behavioural agent model **BAM** is translated in a hybrid logical/numerical format, using atoms has_value(x, V) with x a variable name and V a value. Here s(g(b((O)), A), s(g(c((O)), A), e(b(O), A) and e(c(O), A) for options O are names of the specific variables involved :

BP1 Generating a body state

$$\begin{aligned}&\text{has\_value}(s(g(b(O)), A),\ V_1)\ \&\ \text{has\_value}(e(b(O), A),\ V)\\&\twoheadrightarrow \text{has\_value}(e(b(O), A,\ V + \varepsilon_{b(O)A}\gamma_{b(O)A}\mathbf{c}(V_1, V/\varepsilon_{b(O)A})\Delta t)\end{aligned}$$

BP2 Generating an option choice intention

$$\begin{aligned}&\text{has\_value}(s(g(c(O)), A),\ V_1)\ \&\ \text{has\_value}(e(b(O), A),\ V_2)\\&\&\ \text{has\_value}(e(c(O), A),\ V) \twoheadrightarrow \text{has\_value}(e(c(O), A),\ V\\&+ \varepsilon_{c(O)_A}\omega_{OA}\gamma_{c(O)_A}\mathbf{d}((\omega_{c(O)_A}/\omega_{OA})V_1\\&+ (\omega_{b(O)_A}/\omega_{OA})V_2/\varepsilon_{b(O)A}, V/\varepsilon_{c(O)_A})\Delta t)\end{aligned}$$

BTP Sensing aggregated group members' bodily responses and intentions

$$\wedge_{B\neq A}\ \text{has value}(e(S,B),\ V_B) \twoheadrightarrow \text{has value}\big(s(g(S), A), \Sigma_{B\neq A}\alpha_{SBA}V_B/\Sigma_{B\neq A}\alpha_{SBA}\varepsilon_{SB}\big)$$

In the following it is described how the behavioural agent model **BAM** is related to the internal agent model **IAM,** via the abstracted (from **IAM**) behavioural agent model **ABAM**. First, from the model **IAM** by a systematic transformation, an abstracted behavioural agent model **ABAM** is obtained. Then, the two behavioural agent models **ABAM** and **BAM** will be related. In [38] an automated abstraction transformation is described from a non-cyclic, stratified internal agent model to a behavioural agent model. As in the current situation the internal agent model is not assumed to be noncyclic, this existing transformation cannot be applied. The two main steps in this transformation are: elimination of sensory representation atoms, and elimination of preparation atoms.

1. Elimination of sensory representation atoms
   It is assumed that sensory representation atoms may be affected by sensor atoms, or by preparation atoms. These two cases are addressed as follows
   (a) *Replacing sensory representation atoms by sensor atoms*
      - Based on a property $SS(A,\ S,\ V) \twoheadrightarrow SRS(A,\ S, \upsilon V)$ (such as IP1), replace atoms SRS(A, S, V) in an antecedent (for example, in IP2 and IP3) by SS(A, S, V/υ).

   (b) *Replacing sensory representation atoms by preparation atoms*
      - Based on a property $PS(A,\ S,\ V) \twoheadrightarrow SRS(A,\ S, \omega V)$ (such as IP5), replace atoms SRS(A, S, V) in an antecedent (for example, in IP2) by $PS(A,\ b(O),\ V/\omega)$.

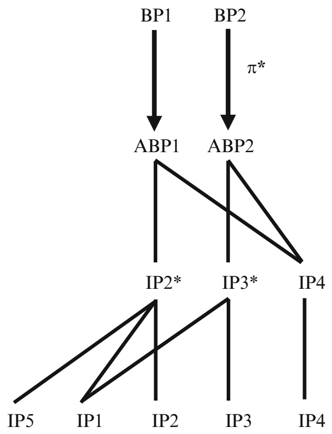


Fig. 7 Logical relations from network specification via internal agent model and abstracted behavioural model to behavioural agent model: **IAM**$\vdash$ **ABAM** = **π**(**BAM**)

Note that this transformation step is similar to the principle exploited in [38]. It may introduce new occurrences of preparation atoms; therefore it should preceed the step to eliminate preparation atoms. In the case study this transformation step provides the following transformed properties (replacing IP1, IP2, IP3, and IP5; see also Fig. 7):

IP2* Preparing for a body state

$$\begin{aligned}&\mathrm{SS}(\mathrm{A},\ \mathrm{c},\ \mathrm{V}_1/\upsilon_{\mathrm{cA}})\ \&\ \ \mathrm{SS}\big(\mathrm{A},\ \mathrm{g}(\mathrm{b}(\mathrm{O})),\ \mathrm{V}_2/\upsilon_{\mathrm{g(b(O))A}}\big)\\ &\&\ \ \mathrm{PS}(\mathrm{A},\mathrm{b}(\mathrm{O}),\mathrm{V}_3/\omega_{0\mathrm{OA}})\ \&\ \ \mathrm{PS}(\mathrm{A},\ \mathrm{b}(\mathrm{O}),\ \mathrm{V})\\ &\twoheadrightarrow \mathrm{PS}\big(\mathrm{A},\ \mathrm{b}(\mathrm{O}),\mathrm{V}+\lambda_{\mathrm{b(O)A}}\mathbf{g}(\omega_{1\mathrm{OA}}\mathrm{V}_1,\omega_{2\mathrm{OA}}\mathrm{V}_2,\omega_{3\mathrm{OA}}\mathrm{V}_3,\ \mathrm{V})\Delta \mathrm{t}\big)\end{aligned}$$

IP3* Preparing for an option choice

$$\begin{aligned}&\mathrm{SS}(\mathrm{A},\ \mathrm{c},\ \mathrm{V}_1/\upsilon_{\mathrm{cA}})\ \&\ \ \mathrm{SS}\big(\mathrm{A},\ \mathrm{g}\big(\mathrm{c}(\mathrm{O})\big),\ \mathrm{V}_2/\upsilon_{\mathrm{g(c(O))A}}\big)\big)\\ &\&\ \mathrm{PS}(\mathrm{A},\ \mathrm{b}(\mathrm{O}),\ \mathrm{V}_3)\ \&\ \mathrm{PS}(\mathrm{A},\ \mathrm{c}(\mathrm{O}),\ \mathrm{V})\twoheadrightarrow \mathrm{PS}(\mathrm{A},\ \mathrm{c}(\mathrm{O}),\\ &\mathrm{V}+\lambda_{\mathrm{c(O)A}}\mathbf{h}(\omega_{4\mathrm{OA}}\mathrm{V}_1,\omega_{5\mathrm{OA}}\mathrm{V}_2,\omega_{6\mathrm{OA}}\mathrm{V}_3,\ \mathrm{V})\Delta \mathrm{t})\end{aligned}$$

2. Elimination of preparation atoms
   Preparation atoms in principle occur both in antecedents and consequents. This makes it impossible to apply the principle exploited in [38]. However, it is exploited that preparation states often have a direct relationship to effector states:

   - Based on a property $\mathrm{PS}(\mathrm{A},\ \mathrm{S},\ \mathrm{V})\twoheadrightarrow \mathrm{ES}(\mathrm{A},\ \mathrm{S},\zeta \mathrm{V})$ (such as in IP4), replace each atom PS(A, S, V) in an antecedent or consequent by $\mathrm{ES}(\mathrm{A},\ \mathrm{S},\zeta \mathrm{V})$.

In the case study this transformation step provides the following transformed properties (replacing IP2*, IP3*, and IP4; see also Fig. 7):

IP2* Preparing for a body state

$$\begin{aligned}&\mathrm{SS}(A,\ c,\ V_1/\upsilon_{cA})\ \&\ \mathrm{SS}\big(A,\ g(b(O)),\ V_2/\upsilon_{g(b(O))A}\big)\\ &\&\ \mathrm{ES}(A,\ b(O), \zeta_{b(O)A}V_3/\omega_{0OA})\ \&\ \mathrm{ES}(A,\ b(O), \zeta_{b(O)A}V)\\ &\twoheadrightarrow \mathrm{ES}\Big(A, b(O), \zeta_{b(O)A}V + \zeta_{b(O)A}\lambda_{b(O)A}\mathbf{g}(\omega_{1OA}V_1, \omega_{2OA}V_2, \omega_{3OA}V_3,\ V)\Delta t\Big)\end{aligned}$$

IP3* Preparing for an option choice

$$\begin{aligned}&\mathrm{SS}(A,\ c,\ V_1/\upsilon_{cA})\ \&\ \mathrm{SS}(A,\ g(c(O)),\ V_2/\upsilon_{g(c(O))A}))\\ &\&\ \mathrm{ES}(A, b(O), \zeta_{b(O)A}V_3)\ \&\ \mathrm{ES}(A,\ c(O), \zeta_{c(O)A}V) \twoheadrightarrow \mathrm{ES}(A,\ c(O),\\ &\zeta_{c(O)A}V + \zeta_{c(O)A}\lambda_{c(O)A}\mathbf{h}(\omega_{4OA}V_1, \omega_{5OA}V_2, \omega_{6OA}V_3, V)\Delta t)\end{aligned}$$

By renaming V_1/υ_{cA} to V_1, $V_2/\upsilon_{g(b(O)A}$ to V_2, $\zeta_{b(O)A}\ V_3/\omega_{0OA}$ to V_3, $\zeta_{b(O)A}V$ to V (in IP2∗), resp. $V_2/\upsilon_{g(c(O))A}$ to V_2, $\zeta_{b(O)A}V_3$ to V_3, and $\zeta_{c(O)A}V$ to V (in IP3∗), the following is obtained:

IP2 Preparing for a body state**

$$\begin{aligned}&\mathrm{SS}(A,\ c,\ V_1)\ \&\ \mathrm{SS}(A,\ g(b(O)),\ V_2)\ \&\ \mathrm{ES}\ (A,\ b(O),\ V_3)\ \&\ \mathrm{ES}(A,\ b(O),\ V)\\ &\twoheadrightarrow \mathrm{ES}(A,\ b(O), V + \zeta_{b(O)A}\lambda_{b(O)A}\mathbf{g}(\omega_{1OA}\upsilon_{cA}V_1, \omega_{2OA}\upsilon_{g(b(O))A}V_2,\\ &\quad \omega_{3OA}\omega_{0OA}V_3/\zeta_{b(O)A},\ V/\zeta_{b(O)A})\Delta t)\end{aligned}$$

IP3 Preparing for an option choice**

$$\begin{aligned}&\mathrm{SS}(A,\ c,\ V_1)\ \&\ \mathrm{SS}(A,\ g(c(O)),\ V_2)\ \&\ \mathrm{ES}(A,\ b(O),\ V_3)\ \&\ \mathrm{ES}(A,\ c(O),\ V)\\ &\twoheadrightarrow \mathrm{ES}(A,\ c(O),\ V + \zeta_{c(O)A}\lambda_{c(O)A}\mathbf{h}(\omega_{4OA}\upsilon_{cA}V_1, \omega_{5OA}\upsilon_{g(c(O))A}V_2,\\ &\quad \omega_{6OA}V_3/\zeta_{b(O)A},\ V/\zeta_{c(O)A})\Delta t)\end{aligned}$$

Based on these properties derived from the internal model **IAM** the specification of the abstracted behavioural model **ABAM** can be defined; see also Fig. 7, lower part.

5.1 Hybrid Specification of the Abstracted Behavioural Agent Model ABAM

Note that in IP2** V_2 and V have the same value, so a slight further simplification can be made by replacing V_3 by V. After renaming of the variables according to

ABP1
$V_1 \rightarrow W_0$
$V_2 \rightarrow W_1$
$V_3 \rightarrow W$
$V \rightarrow W$

ABP2
$V_1 \rightarrow W_0$
$V_2 \rightarrow W_1$
$V_3 \rightarrow W_2$
$V \rightarrow W$

the following abstracted behavioural model **ABAM** for agent A is obtained:

ABP1 Generating a body state

$$\begin{aligned}&\mathrm{SS(A,\ c,\ W_0)\ \&\ SS(A,\ g(b(O)),\ W_1)\ \&\ ES(A,\ b(O),\ W)}\\&\twoheadrightarrow \mathrm{ES(A,\ b(O),\ W} + \zeta_{\mathrm{b(O)A}}\lambda_{\mathrm{b(O)A}}\mathbf{g}(\omega_{\mathrm{1OA}}\upsilon_{\mathrm{cA}}\mathrm{W}_0, \omega_{\mathrm{2OA}}\upsilon_{\mathrm{g(b(O))A}}\mathrm{W}_1,\\&\quad \omega_{\mathrm{3OA}}\omega_{\mathrm{0OA}}\mathrm{W}/\zeta_{\mathrm{b(O)A}},\ \mathrm{W}/\zeta_{\mathrm{b(O)A}})\Delta \mathrm{t})\end{aligned}$$

ABP2 Generating an option choice intention

$$\begin{aligned}&\mathrm{SS(A,\ c,\ W_0)\ \&\ SS(A,\ g(c(O)),\ W_1)\ \&\ ES(A,\ b(O),\ W_2)\ \&\ ES(A,\ c(O),\ W)}\\&\twoheadrightarrow \mathrm{ES(A,\ c(O),\ W} + \zeta_{\mathrm{c(O)A}}\lambda_{\mathrm{c(O)A}}\mathbf{h}(\omega_{\mathrm{4OA}}\upsilon_{\mathrm{cA}}\mathrm{W}_0, \omega_{\mathrm{5OA}}\upsilon_{\mathrm{g(c(O))A}}\mathrm{W}_1,\\&\quad \omega_{\mathrm{6OA}}\mathrm{W}_2/\zeta_{\mathrm{b(O)A}},\ \mathrm{W}/\zeta_{\mathrm{c(O)A}})\Delta \mathrm{t})\end{aligned}$$

ITP Sensing aggregated group members' bodily responses and intentions

$$\wedge_{\mathrm{B}\neq\mathrm{A}}\ \mathrm{ES(B,\ S,\ V_B)} \twoheadrightarrow \mathrm{SS(A,\ g(S)}, \Sigma_{\mathrm{B}\neq\mathrm{A}}\alpha_{\mathrm{SBA}}\mathrm{V_B}/\Sigma_{\mathrm{B}\neq\mathrm{A}}\alpha_{\mathrm{SBA}}\zeta_{\mathrm{SB}})$$

where S has instances b(O), c(O) for options O.

Note that as all steps made are logical derivations, it holds **IAM $\vdash$ ABAM**. In particular the following logical implications are valid (shown hierarchically in Fig. 7):

$$\text{IP1 \& IP5 \& IP2} \Rightarrow \text{IP2*} \qquad \text{IP4 \& IP2*} \Rightarrow \text{ABP1}$$
$$\text{IP1 \& IP3} \Rightarrow \text{IP3*} \qquad \text{IP4 \& IP3*} \Rightarrow \text{ABP2}$$

The transformation as described is based on the following of assumptions:

- Sensory representation states are affected (only) by sensor states and/or preparation states
- Preparation atoms have a direct relationship with effector atoms; there are no other ways to generate effector states than via preparation states
- The time delays for the interaction from the effector state of one agent to the sensor state of the same or another agent are small so that they can be neglected compared to the internal time delays
- The internal time delays from sensor state to sensory representation state and from preparation state to effector state within an agent are small so that they can be neglected compared to the internal time delays from sensory representation to preparation states

Now the model **BAM** is related to the behavioural agent model **ABAM**. First the notion of interpretation mapping induced by an ontology mapping is briefly introduced (e.g., [21], pp. 201–263; [40]). By a basic ontology mapping $\boldsymbol{\pi}$ atomic state properties (e.g., a_2 and b_2) in one ontology can be related to state properties (e.g., a_1 and b_1) in another (e.g., $\boldsymbol{\pi}(a_2) = a_1$ and $\boldsymbol{\pi}(b_2) = b_1$). Using compositionality a basic ontology mapping used above can be extended to an interpretation mapping for temporal expressions. As an example, when $\boldsymbol{\pi}(a_2) = a_1$, $\boldsymbol{\pi}(b_2) = b_1$, then this induces a mapping $\boldsymbol{\pi}^*$ from dynamic property $a_2 \twoheadrightarrow b_2$ to $a_1 \twoheadrightarrow b_1$ as follows: $\boldsymbol{\pi}^*(a_2 \twoheadrightarrow b_2) = \boldsymbol{\pi}^*(a_2) \twoheadrightarrow \boldsymbol{\pi}^*(b_2) = \boldsymbol{\pi}(a_2) \twoheadrightarrow \boldsymbol{\pi}(b_2) = a_1 \twoheadrightarrow b_1$. In a similar manner by compositionality a mapping for more complex temporal predicate logical relationships A and B can be defined, using

$$\boldsymbol{\pi}^*(A\&B) = \boldsymbol{\pi}^*(A)\&\boldsymbol{\pi}^*(B) \qquad \boldsymbol{\pi}^*(A \vee B) = \boldsymbol{\pi}^*(A) \vee \boldsymbol{\pi}^*(B)$$
$$\boldsymbol{\pi}^*(A \Rightarrow B) = \boldsymbol{\pi}^*(A) \Rightarrow \boldsymbol{\pi}^*(B) \qquad \boldsymbol{\pi}^*(\neg A) = \neg\boldsymbol{\pi}^*(A)$$
$$\boldsymbol{\pi}^*(\forall T\ A) = \forall T \boldsymbol{\pi}^*(A) \qquad \boldsymbol{\pi}^*(\exists T\ A) = \exists T\ \boldsymbol{\pi}^*(A)$$

o obtain a mapping the given behavioural model **BAM** onto the abstracted **ABAM**, first, consider the basic ontology mapping $\boldsymbol{\pi}$ defined by:

$$\boldsymbol{\pi}(\text{has value}(e(S, A),\ V)) = ES(A,\ S,\ V) \quad \text{(instances for S are } b(O),\ c(O) \text{ for options O)}$$
$$\boldsymbol{\pi}(\text{has value}(s(S, A),\ V)) = SS(A,\ S,\ V) \quad \text{(instances for S are } g(b((O)),\ g(c((O)) \text{ for options O)}$$

Next by compositionality the interpretation mapping $\boldsymbol{\pi}^*$ is defined for the specification of the behavioural model **BAM** as follows:

Mapping BP1 Generating a body state

$$
\begin{aligned}
\boldsymbol{\pi}^*(\mathrm{BP1}) = {} & \boldsymbol{\pi}^*(\mathrm{has\_value}(\mathrm{s}(\mathrm{g}(\mathrm{b}(\mathrm{O})), \mathrm{A}),\ \mathrm{V}_1)\ \&\ \mathrm{has\_value}(\mathrm{e}(\mathrm{b}(\mathrm{O}), \mathrm{A}),\ \mathrm{V}) \\
& \twoheadrightarrow \mathrm{has\_value}(\mathrm{e}(\mathrm{b}(\mathrm{O}), \mathrm{A}),\ \mathrm{V} + \varepsilon_{\mathrm{b(O)A}} \gamma_{\mathrm{b(O)A}} \mathbf{c}(\mathrm{V}_1, \mathrm{V}/\varepsilon_{\mathrm{b(O)A}})\, \Delta \mathrm{t})) \\
= {} & \boldsymbol{\pi}(\mathrm{has\_value}(\mathrm{s}(\mathrm{g}(\mathrm{b}(\mathrm{O})), \mathrm{A}),\ \mathrm{V}_1))\ \&\ \boldsymbol{\pi}(\mathrm{has\_value}(\mathrm{e}(\mathrm{b}(\mathrm{O}), \mathrm{A}),\ \mathrm{V})) \\
& \twoheadrightarrow \boldsymbol{\pi}(\mathrm{has\_value}(\mathrm{e}(\mathrm{b}(\mathrm{O}), \mathrm{A}),\ \mathrm{V} + \varepsilon_{\mathrm{b(O)A}} \gamma_{\mathrm{b(O)A}} \mathbf{c}(\mathrm{V}_1, \mathrm{V}/\varepsilon_{\mathrm{b(O)A}})\, \Delta \mathrm{t})) \\
= {} & \mathrm{SS}(\mathrm{A}, \mathrm{g}(\mathrm{b}(\mathrm{O})),\ \mathrm{V}_1)\ \&\ \mathrm{ES}(\mathrm{A}, \mathrm{b}(\mathrm{O}), \mathrm{V}) \\
& \twoheadrightarrow \mathrm{ES}(\mathrm{A}, \mathrm{b}(\mathrm{O}), \mathrm{V} + \varepsilon_{\mathrm{b(O)A}} \gamma_{\mathrm{b(O)A}} \mathbf{c}(\mathrm{V}_1, \mathrm{V}/\varepsilon_{\mathrm{b(O)A}})\, \Delta \mathrm{t})
\end{aligned}
$$

Mapping BP2 Generating an option choice intention

$$
\begin{aligned}
\boldsymbol{\pi}^*(\mathrm{BP2}) = {} & \boldsymbol{\pi}^*(\mathrm{has\_value}(\mathrm{s}(\mathrm{g}(\mathrm{c}(\mathrm{O})), \mathrm{A}),\ \mathrm{V}_1)\ \&\ \mathrm{has\_value}(\mathrm{e}(\mathrm{b}(\mathrm{O}), \mathrm{A}),\ \mathrm{V}_2) \\
& \&\ \mathrm{has\_value}(\mathrm{e}(\mathrm{c}(\mathrm{O}), \mathrm{A}),\ \mathrm{V}) \twoheadrightarrow \mathrm{has\_value}(\mathrm{e}(\mathrm{c}(\mathrm{O}), \mathrm{A}),\ \mathrm{V} \\
& + \varepsilon_{\mathrm{c(O)A}} \omega_{\mathrm{OA}} \gamma_{\mathrm{c(O)A}}\ \mathbf{d}((\omega_{\mathrm{c(O)A}}/\omega_{\mathrm{OA}})\mathrm{V}_1 \\
& + (\omega_{\mathrm{b(O)A}}/\omega_{\mathrm{OA}})\mathrm{V}_2/\varepsilon_{\mathrm{b(O)A}}, \mathrm{V}/\varepsilon_{\mathrm{c(O)A}})\, \Delta \mathrm{t})) \\
= {} & \boldsymbol{\pi}(\mathrm{has\_value}(\mathrm{s}(\mathrm{g}(\mathrm{c}(\mathrm{O})), \mathrm{A}),\ \mathrm{V}_1))\ \&\ \boldsymbol{\pi}(\mathrm{has\_value}(\mathrm{e}(\mathrm{b}(\mathrm{O}), \mathrm{A}),\ \mathrm{V}_2)) \\
& \&\ \boldsymbol{\pi}(\mathrm{has\_value}(\mathrm{e}(\mathrm{c}(\mathrm{O}), \mathrm{A}),\ \mathrm{V})) \twoheadrightarrow \boldsymbol{\pi}(\mathrm{has\_value}(\mathrm{e}(\mathrm{c}(\mathrm{O}), \mathrm{A}),\ \mathrm{V} \\
& + \varepsilon_{\mathrm{c(O)A}} \omega_{\mathrm{OA}} \gamma_{\mathrm{c(O)A}}\ \mathbf{d}((\omega_{\mathrm{c(O)A}}/\omega_{\mathrm{OA}})\mathrm{V}_1 + (\omega_{\mathrm{b(O)A}}/\omega_{\mathrm{OA}}) \\
& \mathrm{V}_2/\varepsilon_{\mathrm{b(O)A}}, \mathrm{V}/\varepsilon_{\mathrm{c(O)A}})\, \Delta \mathrm{t})) \\
= {} & \mathrm{SS}(\mathrm{A}, \mathrm{g}(\mathrm{c}(\mathrm{O})),\ \mathrm{V}_1)\ \&\ \mathrm{ES}(\mathrm{A}, \mathrm{b}(\mathrm{O}), \mathrm{V}_2)\ \&\ \mathrm{ES}(\mathrm{A}, \mathrm{c}(\mathrm{O}), \mathrm{V}) \\
& \twoheadrightarrow \mathrm{ES}(\mathrm{A}, \mathrm{c}(\mathrm{O}), \mathrm{V} + \varepsilon_{\mathrm{c(O)A}} \omega_{\mathrm{OA}} \gamma_{\mathrm{c(O)A}}\ \mathbf{d}((\omega_{\mathrm{c(O)A}}/\omega_{\mathrm{OA}})\mathrm{V}_1 \\
& + (\omega_{\mathrm{b(O)A}}/\omega_{\mathrm{OA}})\mathrm{V}_2/\varepsilon_{\mathrm{b(O)A}}, \mathrm{V}/\varepsilon_{\mathrm{c(O)A}})\, \Delta \mathrm{t})
\end{aligned}
$$

Mapping BTP Sensing aggregated group members' bodily responses and intentions

$$
\begin{aligned}
\boldsymbol{\pi}^*(\mathrm{BTP}) = {} & \boldsymbol{\pi}^*(\wedge_{\mathrm{B} \neq \mathrm{A}}\ \mathrm{has\_value}(\mathrm{e}(\mathrm{S}, \mathrm{B}),\ \mathrm{V}_{\mathrm{B}}) \\
& \twoheadrightarrow \mathrm{has\_value}(\mathrm{s}(\mathrm{g}(\mathrm{S}), \mathrm{A}), \Sigma_{\mathrm{B} \neq \mathrm{A}}\ \alpha_{\mathrm{SBA}} \mathrm{V}_{\mathrm{B}} / \Sigma_{\mathrm{B} \neq \mathrm{A}}\ \alpha_{\mathrm{SBA}} \varepsilon_{\mathrm{SB}})) \\
= {} & \wedge_{\mathrm{B} \neq \mathrm{A}}\ \boldsymbol{\pi}(\mathrm{has\_value}(\mathrm{e}(\mathrm{S}, \mathrm{B}),\ \mathrm{V}_{\mathrm{B}})) \twoheadrightarrow \boldsymbol{\pi}(\mathrm{has\_value}(\mathrm{s}(\mathrm{g}(\mathrm{S}), \mathrm{A}), \\
& \Sigma_{\mathrm{B} \neq \mathrm{A}}\ \alpha_{\mathrm{SBA}} \mathrm{V}_{\mathrm{B}} / \Sigma_{\mathrm{B} \neq \mathrm{A}}\ \alpha_{\mathrm{SBA}} \varepsilon_{\mathrm{SB}})) \\
= {} & \wedge_{\mathrm{B} \neq \mathrm{A}}\ \mathrm{ES}(\mathrm{B}, \mathrm{S},\ \mathrm{V}_{\mathrm{B}})) \twoheadrightarrow \mathrm{SS}(\mathrm{A}, \mathrm{g}(\mathrm{S}), \Sigma_{\mathrm{B} \neq \mathrm{A}}\ \alpha_{\mathrm{SBA}} \mathrm{V}_{\mathrm{B}} / \Sigma_{\mathrm{B} \neq \mathrm{A}}\ \alpha_{\mathrm{SBA}} \varepsilon_{\mathrm{SB}})
\end{aligned}
$$

So to explore under which conditions the mapped behavioural model **BAM** is the abstracted model **ABAM**, it can be found out when the following identities (after unifying the variables V_i, V and W_i, W for values) hold.

$$\boldsymbol{\pi}^*(\mathrm{BP1}) = \mathrm{ABP1} \qquad \boldsymbol{\pi}^*(\mathrm{BP2}) = \mathrm{ABP2} \qquad \boldsymbol{\pi}^*(\mathrm{BTP}) = \mathrm{ITP}$$

However, the modelling scope of **ABAM** is wider than the one of **BAM**. In particular, in **ABAM** an as-if body loop is incorporated that has been left out of consideration for **BAM**. Moreover, in the behavioural model **BAM** the options O are taken from a fixed set, given at forhand and automatically considered, whereas in **ABAM** they are generated on the basis of the context c. Therefore, the modelling scope of **ABAM** is first tuned to the one of **BAM**, to get a comparable modelling scope for both models **IAM** and **ABAM**. The latter condition is achieved by taking the activation level W_0 of the sensor state for the context c and the strengths of the connections between the sensor state for context c and preparations relating to option O can be set at *1* (so $\upsilon_{cA} = \omega_{1OA} = \omega_{4OA} = 1$); thus the first argument of g and h becomes 1. The former condition is achieved by leaving out of **ABAM** the dependency on the sensed body state, i.e., by making the third argument of g zero (so $\omega_{0OA} = 0$).

Given these extra assumptions and the mapped specifications found above, when the antecedents where unified according to $V_i \leftrightarrow W_i$, $V \leftrightarrow W$ the identities are equivalent to the following identities in V, V_i

$$\varepsilon_{b(O)A}\,\gamma_{b(O)A}\,\mathbf{c}(V_1, V/\varepsilon_{b(O)A}) = \zeta_{b(O)A}\lambda_{b(O)A}\,\mathbf{g}(1, \omega_{2OA}\upsilon_{g(b(O))A}\,V_1,\ 0,\ V/\zeta_{b(O)A})$$

$$\begin{aligned}&\varepsilon_{c(O)A}\,\omega_{OA}\,\gamma_{c(O)A}\,\mathbf{d}((\omega_{c(O)A}/\omega_{OA})\,V_1\ + (\omega_{b(O)A}/\omega_{OA})\,V_2/\varepsilon_{b(O)A}, V/\varepsilon_{c(O)A})\\ &= \zeta_{c(O)A}\,\lambda_{c(O)A}\,\mathbf{h}(1, \omega_{5OA}\upsilon_{g(c(O))A}V_1, \omega_{6OA}\upsilon_{b(O)A}V_2/\zeta_{b(O)A},\ V/\zeta_{c(O)A})\end{aligned}$$

$$\Sigma_{B\neq A}\ \alpha_{SBA}V_B/\Sigma_{B\neq A}\ \alpha_{SBA}\varepsilon_{SB} = \Sigma_{B\neq A}\ \alpha_{SBA}V_B/\Sigma_{B\neq A}\ \alpha_{SBA}\zeta_{SB}$$

The last identity is equivalent to $\varepsilon_{SB} = \zeta_{SB}$ for all S and B with $\alpha_{SBA} > 0$ for some A. Moreover, it can be assumed that $\varepsilon_{SB} = \zeta_{SB}$ for all S and B. There may be multiple ways in which this can be satisfied for all values of V_1, U_2, U. At least one possibility is the following. Assume for all agents A

$$\lambda_{b(O)A} = \gamma_{b(O)_A} \qquad \upsilon_{b(O)A} = 1$$

$$\lambda_{c(O)A} = \omega_{OA}\gamma_{c(O)A} \qquad \upsilon_{g(S)A} = 1$$

for S is b(O) or c(O). Then the identities simplify to

$$\mathbf{c}(V_1, U) = \mathbf{g}(1, \omega_{2OA}V_1,\ 0,\ V)$$

$$\mathbf{d}((\omega_{c(O)A}/\omega_{OA})\,V_1\ + (\omega_{b(O)A}/\omega_{OA})\,V_2,\ V) = \mathbf{h}(1, \omega_{5OA}V_1, \omega_{6OA}V_2,\ V)$$

Furthermore, taking $\omega_{2OA} = 1, \omega_{5OA} = \omega_{c(O)A}/\omega_{OA}, \omega_{6OA} = \omega_{b(O)A}/\omega_{OA}$, the following identities result (replacing $\omega_{5OA}V_1$ by V_1 and $\omega_{6OA}V_2$ by V_2)

$$\mathbf{c}(V_1, V) = \mathbf{g}(1,\ V_1,\ 0,\ V) \qquad \mathbf{d}(V_1 + V_2, V) = \mathbf{h}(1,\ V_1,\ V_2,\ V)$$

There are many possibilities to fulfill these identities. For any given functions $\mathbf{c}(X, Y)$, $\mathbf{d}(X, Y)$ in the model **BAM** the functions **g**, **h** in the model **IAM** defined by

$$\mathbf{g}(W,\ X,\ Y,\ Z) = \mathbf{c}(W - 1 + X + Y, Z)$$
$$\mathbf{h}(W,\ X,\ Y,\ Z) = \mathbf{d}(W - 1 + X + Y, Z)$$

fulfill the identities $\mathbf{g}(1, X, 0, Z) = \mathbf{c}(X, Z)$ and $\mathbf{h}(1, X, Y, Z) = \mathbf{d}(X + Y, Z)$. It turns out that for given functions $\mathbf{c}(X, Y)$, $\mathbf{d}(X, Y)$ in the model **BAM** functions **g**, **h** in the model **IAM** exist so that the interpretation mapping $\boldsymbol{\pi}$ maps the behavioural model **BAM** onto the model **ABAM**, which is a behavioural abstraction of the internal agent model **IAM** (see also Fig. 7): $\boldsymbol{\pi}^*(\text{BP1}) = \text{ABP1}$, $\boldsymbol{\pi}^*(\text{BP2}) = \text{ABP2}$, $\boldsymbol{\pi}^*(\text{BTP}) = \text{ITP}$. As an example direction, when for $\mathbf{c}(X, Y)$ a threshold function th is used, for example, defined as $\mathbf{c}(X, Y) = \text{th}(\sigma, \tau, X + Y) - Y$ with $\text{th}(\sigma, t, V) = 1/\left(1 + e^{-\sigma(V-\tau)}\right)$, then for $\tau' = \tau + 1$ the function $\mathbf{g}(W, X, Y, Z) = \text{th}(\sigma, \tau', W + X + Y + Z) - Z$ fulfils $\mathbf{g}(1, X, 0, Z) = \mathbf{c}(X, Z)$. Another example of a function $\mathbf{g}(V, W, X, Y)$ that fulfills the identity when $\mathbf{c}(X, Z) = 1 - (1 - X)(1 - Z) - Z$ is $\mathbf{g}(W, X, Y, Z) = W\ [1 - (1 - W)(1 - X)(1 - Z)] - Z$. As the properties specifying **ABAM** were derived from the properties specifying **IAM**, it holds **IAM** ⊢ **ABAM**, and as a compositional interpretation mapping $\boldsymbol{\pi}$ preserves derivation relations, the following relationships holds for any temporal pattern expressed as a hybrid logical/numerical property A in the ontology of **BAM**:

$$\mathbf{BAM} \mid\!- A \ \Rightarrow\ \boldsymbol{\pi}(\mathbf{BAM}) \mid\!- \boldsymbol{\pi}(A) \ \Rightarrow\ \mathbf{ABAM} \mid\!- \boldsymbol{\pi}(A) \ \Rightarrow\ \mathbf{IAM} \mid\!- \boldsymbol{\pi}(A)$$

Such a property A may specify certain (common) patterns in behaviour; the above relationships show that the internal agent model **IAM** shares the common behavioural patterns of the behavioural model **BAM**. An example of such a property A expresses a pattern that under certain conditions after some point in time there is one option O for which both b(O) and c(O) have the highest value for each of the agents (joint decision).

The precision of the abstracted model **ABAM** is evaluated by calculating the root mean squared error:

$$err = \sqrt{\frac{\sum_{i=1}^{N} (f_i - y_i)^2}{N}}$$

where N is the number of time points, f_i is the value of an output of an abstracted model at time point t_i, and y_i is the value of the corresponding output of the model **IAM**.

The root mean squared errors for the model outputs ES(b(O)) and ES(c(O)) are 0.017 and 0.026 correspondingly.

6 Model Analysis: A Real World Case Study

The computational model introduced in Sect. 3 has been tested by applying it to a real world case study. A description of this case study is provided in Sect. 6.1. Next, Sect. 6.2 describes how the model was extended and instantiated for the case study. Section 6.3 explains how the parameters of the model were tuned to reproduce the real world scenario, and Sect. 6.4 presents the results. More details of this case study can be found in.

6.1 Case Study: The May 4 Incident

The case study addressed is the May 4 incident in Amsterdam (The Netherlands). The incident took place in the evening of May 4th 2010, when approximately 20.000 people gathered on Dam Square in Amsterdam for the National Remembrance of the dead. What follows is a short description of the events.

At 20:00 h everyone in the Netherlands, including the crowd on Dam Square, was silent for 2 min to remember the dead. Fences and officials compartmented the 20,000 people on Dam Square. At 20:01 a man in the crowd on Dam Square disturbed the silence by screaming loudly. People standing directly near him could see that this man looked a bit 'crazy' or 'lost', and they did not move. Those not within a few meters of the screaming source, started to panic and ran away from the man that screamed. The panic spread through the people that were running away who infected each other with their emotions and intentions to flee. This panic was fuelled by a loud 'BANG' that was heard about 3 s after the man started screaming. Queen Beatrix and other royal members present were escorted to a safe location nearby. In total, 64 persons got injured: they got broken bones and scrapes by being pushed, or got run over by the crowd. The police exported the screaming man and got control over the situation within 2 min. After 2½ min, the master of ceremony announced to the crowd that a person had become ill and had received care. He asked everybody to take his or her initial place again, and to continue the ceremony. After this, the ceremony continued.[1]

---

[1] A short movie with images from the live broadcast on Dutch National Television, can be found at: http://www.youtube.com/watch?v=0cEQp8OQj2Y. This shows how, within two minutes, the crowd starts to panic and move.

Fig. 8 Still image of the people on Dam Square starting to flee. The circle on the *right* bottom indicates the location of the yelling person

The live broadcast of the National Remembrance on Dutch National Television has been acquired in HD-quality.[2] In this video, one can see the crowd on Dam Square flee from the perspective shown in Fig. 8. The video includes the cuts and editing that were done during the live broadcast, because the un-edited video material of all cameras that were filming that day was not saved.

From the total broadcast, a shorter 3-min movie was made, starting the moment when the crowd was silent and the person started to scream loudly. In this 3-min movie there are two time slots that were further processed (11–17 s and 20–27 s), because (i) they showed the clear camera angle like the one that can be seen in Fig. 8, and (ii) the direction and speed of the movements of people could be clearly analysed. They were analysed as follows. The movie was cut into still images, to detect the location of people by hand. Ten still images per second were chosen in order to be able to detect the movements of running people frame by frame. By keeping track of the coordinates of mouse-clicks on the locations of people in the crowd while they were moving, their trace of movement could be detected.

A total of 130 frames were analysed by hand. Not all people could be analysed, both because of the quantity, and the impossibility to trace every ‘dot’ (person) over multiple still images. Persons in different positions of the crowd with simultaneous movements to the people around them were chosen, such that these target subjects were able to represent multiple people around them. In total 35 persons were traced.

The next step was to correct for the angle the camera makes with the floor by recalculating the coordinates into coordinates that would fit into a bird’s-eye view on the Dam Square, perpendicular to the floor. People’s distance in meters from

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[2] Permission granted for educational and research purposes by The Netherlands Institute for Sound and Vision.

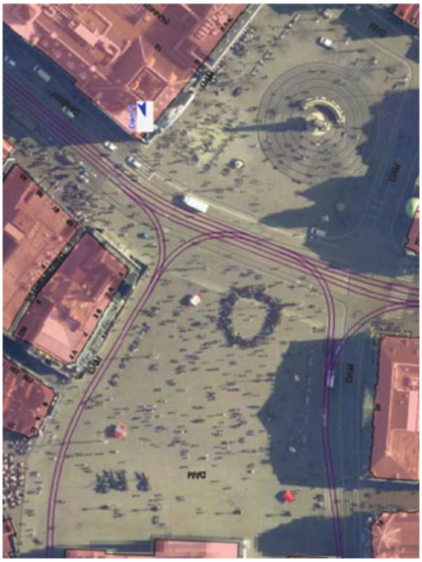

Fig. 9 600 x 800 pixel image of Dam Square

corners of the buildings were translated to the position in pixels on a 600 × 800 map of the area, using offsets and scaling. Specifically, the following formulae are used to translate movements in pixels to movements in meters:

$$x_{meter} = x_{pixel}/\ 22$$

$$y_{meter} = y_{pixel}/\ 8$$

This was then transformed to the map using the following formulae:

$$x_{map} = (x_{meter}{}^{*}\ 5.15) + 136$$

$$y_{map} = (y_{meter}{}^{*}\ 5.15) - 167$$

The bird's eye view perspective used in the computational model can be seen in Fig. 9. The resulting figure was represented in the simulation in Matlab. Locations of certain obstacles, like buildings and fences, were also transformed into the bird's-eye view.

6.2 Instantiating the Model for the Case Study

To tailor the ASCRIBE model towards the case study, a number of steps were taken.

First of all, the relevant states for the agents have been distinguished. In this case, the emotion, belief and intention states relate to the options for each agent. A total of nine options are available including ‘remain standing’, and moving in any wind direction (N, NE, E, SE, S, SW, W, NW). Besides these, there is an additional belief about the current situation. This expresses how positive a person judges the current situation (*0* a negative judgment, and *1* a positive judgment). Finally, the emotions for each option and the emotion *fear* are represented.

In the case study, the channel strengths between the various agents are dependent on the physical location of the agents. If other agents are close, the channel strength is high, whereas it is low or *0* in case agents are far apart. Therefore, a threshold function was used expressing within which reach agents still influence each other in a significant manner:

$$\alpha_{SBA}(t) = 1 - \left(1/1 + e^{-\sigma(distance_{BA}(t) - {}^{\tau}distance)}\right)$$

Here σ and $\tau_{distance}$ are global parameters and $distance_{BA}$ is the Euclidean distance between the positions $(x_A(t),\ y_A(t))$ and $(x_B(t),\ y_B(t))$ of A and B at t.

The movement of the agents directly depends upon their intentions. Recall that the strength of the intention is determined by the intentions of others (see Sect. 3), and the agent’s own personality characteristics and mental states, such as beliefs and emotions (see Sect. 4). The highest feasible intention is selected (in cases where certain movements are obstructed, the next highest intention is selected). For each of the selected options O, the movement $x_{movement(O)}$ on the x-axis and $y_{movement(O)}$ on the y-axis is specified; e.g., the option for going south means -1 step on the y-axis and none on the x-axis: $x_{movement(O)} = 0$ and $y_{movement(O)} = -1$. The actual point to which the agent will move is then calculated by taking the previous point and adding the movement of the agent during a certain period to that. The movement of the agent depends upon the strength of the intention for the selected option and the maximum speed with which the agent can move. If the intention is maximal (i.e., *1*) the agent will move with the maximum speed. In case the intention is minimal (i.e., *0*) the agent will not move. The dependency between mental states and speed of movement has been described, e.g., in [19]. The model that establishes this relationship is expressed as follows:

$$x_A(t + \Delta t) = x_A(t) + max\_speed_A \cdot q_{intention(O)A}(t) \cdot x_{movement(O)} \cdot \Delta t$$

$$y_A(t + \Delta t) = y_A(t) + max\_speed_A \cdot q_{intention(O)A}(t) \cdot y_{movement(O)} \cdot \Delta t$$

Here the maximum speeds max_speed_A are agent-specific parameters.

6.3 Parameter Tuning

As explained above, the ASCRIBE model contains a large number of parameters; these parameters address various aspects of the agents involved, including their personality characteristics (e.g., expressiveness, openness, and tendency to absorb or amplify mental states), physical properties (e.g., minimum and maximum speed, and limit of their sight), and characteristics of their mutual interactions (e.g., channel strength between sender and receiver). The accuracy of the model (i.e., its ability to reproduce the real world data as closely as possible) heavily depends on the settings of these parameters. Therefore, parameter estimation techniques [39] have been applied to learn the optimal values for the parameters involved.

In order to determine what is 'optimal', first an error measure needs to be defined. The main goal is to reproduce the movements of the people involved in the scenario; thus it was decided to take the average (Euclidean) distance (over all agents and time points) between the actual and simulated location:

$$\varepsilon = \sum_{agents\ a}\ \sum_{timepoints\ t} \frac{\sqrt{(x(a,t,sim) - x(a,t,data))^2 + (y(a,t,sim) - y(a,t,data))^2}}{\#agents \cdot \#timepoints}$$

Here, *x(a, t, sim)* is the x-coordinate of agent *a* at time point *t* in the simulation, and *x(a, t, data)* the same in the real data (similarly the y-coordinates). Both are in meters.

Next, the relevant parameters were tuned to reduce this error. To this end, the approach described in detail in Sects. 3 and 4 of [5] was used. This approach makes use of the notion of *sensitivity* of variables for certain parameter changes. Roughly spoken, for a given set of parameter settings, the idea is to make small changes in one of the parameters involved, and to observe how such a change influences the change of the variable of interest (in this case the error). Here, 'observing' means running the simulation twice, i.e., once with the original parameter settings, and once with the same settings were one parameter has slightly changed. Formally, the sensitivity $S_{X,P}$ of changes ΔX in a variable X to changes ΔP in a parameter P is defined as follows (note that this sensitivity is in fact the partial derivative $\partial X/\partial P$): $S_{X,P} = \Delta X/\Delta P$. Based on this notion of sensitivity, the adaptation process as a whole, is an iterative process, which roughly consists of: (1) calculating sensitivities for all parameters under consideration, and (2) using these sensitivities to calculate new values for all parameters. This second step is done by changing each parameter with a certain amount ΔP, which is determined as follows: $\Delta P = -\lambda * \Delta X/S_{X,P}$. Here, ΔX is the deviation found between actual and simulated value of variable X, and λ is a speed factor. Note that, since in the current case X represents the error, the 'actual value' of X is of course *0*, so ΔX simply equals ε in the simulation.

6.4 Results

This section presents the results of specialising and tuning the ASCRIBE model with 35 agents, to the real world data of the May 4 incident. The results are presented for the first part of the data (i.e., seconds 11–17 of the 3-min movie). To assess the performance of the ASCRIBE model, it was compared to three other models. First, one baseline model was developed in which the agents do not move at all. Second, the model was compared to an implementation of the model by Helbing and colleagues [20], which is currently one of the most influential models in the area of crowd simulation. Third, a variant of ASCRIBE was developed in which all agents also make individual decisions, but do not influence each other (i.e., no contagion takes place). This was done to assess whether the idea and implementation of contagion of mental states is useful at all. This resulted in three different models (in addition to our own ASCRIBE model with contagion of mental states), to which we refer below as *baseline*, *Helbing*, and *without contagion*, respectively. To enable a fair comparison, parameter tuning was applied for all models (except for the baseline model, since it did not contain any parameters to tune) in order to find optimal settings; see for details.

Figure 10 shows for each of the four variants how the average error (over all agents) increases during the simulation. Note that the error is expressed in meters. At the first time point, the error is *0* (all agents start at their actual position), but over time the error increases very quickly in the baseline case, so that the error at the last time step of the simulation becomes quite large (2.35 m). For this model, the average error per time step is 0.87 m. The average error found for the tuned model without contagion is much lower (*0.66*, i.e., an improvement of *24 %*), and is even lower for the tuned model with contagion (*0.54*, i.e., an improvement of *38 %*). This finding provides evidence for the conclusion that incorporating the contagion makes the model more accurate, even when it is based on default settings for the parameters. Note that in the current scenario, the agents' movements involve relatively small steps, compared to the size of the grid; the total distance that the agents travel during the 7 s of analysis is only 2.35 m. Therefore, the relative errors found (i.e., the percentages of improvement mentioned above) are more insightful that the absolute errors. In case the total distance travelled would have been larger, the absolute difference in performance between the four models would be expected to have been bigger as well.

As for the Helbing model, the average error of this model per time step was found to be *0.59* (i.e., an improvement of *32 %* w.r.t. the baseline model). As can be observed from Fig. 10, this model performs better than the model without contagion, but worse than the model with contagion (at least, in this particular scenario). One of the main reasons for this is that the model with contagion seems to be better able to deal with the fact that some agents only start moving half way the scenario. This phenomenon, which is also well visible in the video of the event, is caused by the fact that the crowd is separated by fences (see also Fig. 8), and especially the people that are located on the left hand side of the area wait a couple of seconds

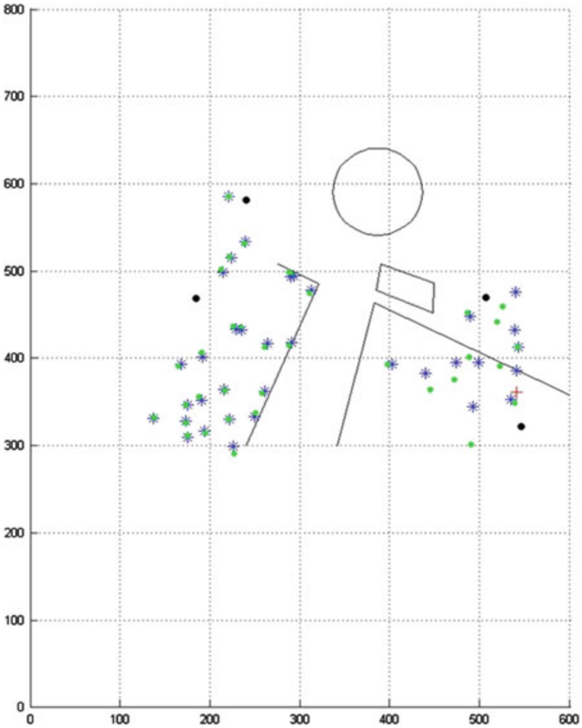

Fig. 10 Screenshot of the simulation. Units displayed on the axes are in pixels, where 5.15 pixels equals 1 m

before they start moving, whereas other people start moving right after the scream. In the model with contagion, this phenomenon can be reproduced quite accurately by means of the contagion mechanism: the agents at the left hand side of the area initially have a low level of fear (since they are not directly affected by the screaming man), but only when they observe other agents panicking and trying to escape, they are influenced by them and attempt to get away as well. Since the Helbing model does not include an explicit mechanism for contagion of mental states, it has more difficulties in reproducing this particular effect (because in this model, the speed by which the agents move is more stable – although not completely constant – over time). Therefore, for the Helbing model, the parameter tuning resulted in an optimal situation where some agents on the left hand side hardly move at all. This is reflected by the fact that the error for this model (compared to the model with contagion) only increases in the last eight time steps.

When comparing the Helbing model with the model without emotion, one can observe that, although the errors of both models at time point 45 are comparable, the Helbing model performs slightly better when taking the overall average error over all time points. This can in part be explained by the fact that the Helbing model has more freedom when it comes to selecting the direction in which the agents move. In our model (both with and without contagion), selection of actions has been implemented in such a way that the agents can only pick one out of eight wind directions (see Sect. 6.2), whereas the Helbing model uses a continuous scale for this. We speculate that the performance of our model (both with and without contagion) may be further improved by changing this discrete mechanism for action selection into a continuous mechanism.

After the tuning process was finished, the optimal settings found for all parameters were used as input for the four simulation models, to generate simulation traces which closely resemble the real world scenario. Using visualisation software (written in Matlab), these simulation traces have been visualised in the form of a 2D animation.[3] A screenshot of the animation of the ASCRIBE model with contagion is shown in Fig. 10.

Here, the lines represent fences that were used to control the crowd, the large circle represents the monument on the square (see Fig. 8 for the actual situation), and the big dots represent corners of other buildings. The plus sign on the right indicates the location of the screaming man. The small dots represent the actual locations of the 35 people in the crowd that were tracked, and the stars represent the locations of the corresponding agents in the simulation. Even at the end of the simulation (see Fig. 10), the distances between the real and simulated positions are fairly small for this model.

7 Conclusions and Discussion

In this paper a computational model for collective decision making based on neural mechanisms revealed by recent developments in Social Neuroscience is proposed; e.g., [5], [6], [9], [12], [14], [34].

These mechanisms explain how mutual adaptation of individual mental states can be realised by social interaction. They not only enable intentions to converge to an emerging common decision, but at the same time enable to achieve shared underlying individual beliefs and emotions. Therefore a situation can be achieved in which a common decision is made that for each individual is considered in agreement with the own beliefs and feelings. More specifically, this model for collective design making involves on the one hand individual beliefs, emotions and intentions, and on the other hand interaction with others involving mirroring of such mental states; e.g., [20], [32], [33]. The model involves seven types of interactions: three types of mirroring interactions between different persons, and within each person four types of interactions between the individual mental states.

The ASCRIBE model has been adapted to construct a model for behaviour in a crowd when a panic spiral occurs. Experiments have been performed in which the model was compared to three other models, namely (1) a baseline model where the

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[3] See http://www.few.vu.nl/~tbosse/may4/. This URL contains two animations: one in which only the result of the model with contagion is shown, and one in which the results of all four models are shown together.

agents do not move at all, (2) a model by Helbing and colleagues [20], and (3) a variant of the model where parameters related to contagion were set in such a way that there was no contagion at all; in this case the movement of individuals is only determined by their individual state. In the full ASCRIBE model, mutual influencing took place because emotions, beliefs and intentions were spreading to persons nearby. When comparing the simulations of the four models with the most optimal settings for certain parameters, the variant with contagion had the lowest average error rate per time step. Thus, it is shown that the contagion of mental states is an essential element to model the behaviour of crowds in panic situations.

The paper addressed also how internal agent models and behavioural agent models for collective decision making can be related to each other. The relationships presented were expressed for specifications of the agent models in a hybrid logical/numerical format. It was shown how the internal agent model IAM can be systematically transformed into an abstracted behavioural model ABAM, where the internal states were abstracted away, and such that IAM $\vdash$ ABAM. Moreover, it was shown that under certain conditions the obtained agent model ABAM can be related to the behavioural agent model BAM by an interpretation mapping π, i.e., such that π(BAM) = ABAM. In this way hybrid logical/numerical relations where obtained between the different agent models according to:

$$\mathbf{IAM} \;|\!-\; \mathbf{ABAM} \text{ and } \mathbf{ABAM} = \boldsymbol{\pi}(\mathbf{BAM})$$

These relationships imply that, for example, collective behaviour patterns shown in multi-agent systems based on the behavioural agent model BAM are shared (in the form of patterns corresponding via $\boldsymbol{\pi}$) for multi-agent systems based on the models ABAM and IAM.

Previous works have presented several models for crowd behaviour. As mentioned above, an influential paper has been written by Helbing and colleagues [20], in which a mathematical model for crowd behaviour in a panic situation is presented, based on physics theories and socio-psychological literature. This model is based on the principle of particle systems, in which forces and collision preventions between particles are important. This approach is often used for simulating crowd behaviour in virtual environments [37], [41]. In [6] the model of [20] is extended by adding individual characteristics to agents, such as the need for help and family membership. In both models, there are no individual emotion, belief and intention states that play a role. In contrast, in [31] an agent has an ‘emotional status’, which determines whether agents walk together (i.e. it influences group formation). The emotional status of an agent can change when to agents meet. An even further elaborated role of emotional and psychological aspects in a crowd behaviour model can be found in [33]. In this model, several psychological aspects influence the decision making of individual agents, for example, motivation, stress, coping, personality and culture. In none of the models presented above, there is contagion of emotional or other mental states between people. Also, in contrast to the analysis results presented in this paper, no evaluation with real qualitative data has been performed in these previous studies.

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Designing Complex Socio-Technical Systems: Empirically Grounded Simulations as Tools for Experience-Based Design Space Explorations

Markus Valle-Klann

1 Introduction

In 1999, a fire in an abandoned cold storage warehouse in Worcester, Massachusetts claimed the lives of six firefighters [1]. While in recent years over 100 firefighters have been killed annually in the United States and the death toll among the general public is significantly higher [2], the relatively high number of firefighters that died under unfortunate circumstances in this single important fire created a particularly strong interest within the general public and among politicians alike.

The funeral for the Worcester firefighters was attended by then president Bill Clinton and other high-ranking politicians. And afterwards public pressure was mounting for politicians to pass legislation that would improve the safety for firefighters.

One of the stated deficits was that there was no support for locating firefighters within building structures and therefore no efficient way of rescuing them in case of need:

> Systems that would enable fire departments to quickly locate downed firefighters are also desperately needed. Why is it America has the technology to track whales across oceans around the world and pinpoint rocks to the centimeter on the surface of Mars, but no devices to accurately pinpoint the location of downed firefighters inside a simple two-story building? [3]

What is embedded in this demand is the assumption that available technological capabilities should be sufficient to create better support and that therefore the death of firefighters should no longer be accepted as a sad but unavoidable fate. Instead, politicians should promote the creation of such supportive systems for firefighters. While in hindsight hope for the rapid availability of localization support proved to

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be premature, the need for this kind of support certainly coincided with the emergence of technologies and systems that suggested that better support was in fact possible [4].

Another important element in understanding the strong reactions to this event, beyond the already unusually high loss of human life itself, is the disheartening realization that those in charge of fighting fires professionally may not always be able to do so successfully and may indeed fall victim to fires themselves. Beyond the tragedy of the individual incident, the general implication of this is that the prevalent feeling of safety within the general public, established partially through the objective capabilities of the emergency services and partially through the subjectively perceived image of powerful protectors, suffers a blow. If the people in charge of protecting us cannot protect themselves, our protection is very clearly limited.

As frequently happens, the public pressure tied to widely perceived incidents, as well as relevant emerging technologies promoted political actions in the form of funding programs for research and development of related systems. Some of many examples for projects in the US under these programs with the objective of increasing firefighter safety through localization are the Wireless Firefighters Lifeline [5], the FIRE [6] and the SIREN [7] projects. Related research programs in the EU followed a few years later and the author of this chapter has been involved in projects on supporting firefighters as well, namely the wearIT@work and the PROFITEX projects.

Another response to the 1999 Worcester fire was the creation of a workshop at the Worcester Polytechnic Institute (WPI) dedicated to the topic of indoor localization [8]. Over the years this workshop has featured presentations and demonstrations of a significant number of systems developed for localization. The author of this chapter was invited to the 2012 WPI workshop to present on the work of the PROFITEX project and had the opportunity to make a few observations during the workshop worth sharing here.

The official highlight of the workshop was the presentation of the GLANSER system, developed by an industry consortium on a grant from the Department of Homeland Security as “their response” to the localization needs of firefighters, according to the DHS project manager. The presentation included in particular the report on a non-public testing of the system with Worcester firefighters in parallel to the workshop.

Essentially, the GLANSER devices track the location for the firefighters wearing them and transmit them to an outside computer where the paths of the firefighters can be visualized three-dimensionally on a map. GLANSER is not the first system to show this functionality and in fact there have been quite a number of approaches and prototypes with comparable functionality and various differences in terms of technology, performance and maturity.

But for the purpose of the present discussion the specific differences are of little interest. What is of interest is that GLANSER was presented maybe not downright as the solution to the localization needs of firefighters that had been so shockingly demonstrated by the Worcester fire but pretty much as a decisive step in the development of this type of systems. As one can imagine, this was not expressed in a perfectly direct fashion and in fact some moderation was used but the historical connection between the deficits exemplified in the 1999 Worcester fire and the support now provided by the GLANSER system was clearly drawn.

The question was then brought up how to move ahead, specifically how to continue towards marketable systems that could eventually be actually bought by fire services. The instructive part was the way the search for an answer to this question was organized at the workshop.

In the plenary the question was asked, whether DHS should still fund further research on localization support or whether GLANSER essentially settles the matter. There was no real count of votes but the author's subjective judgment would be that after a moment of silence, the dominant reaction was that continuing work in this area would probably be a good idea.

Then the participants were split up into two groups to discuss matters, with the technology people in the one group and the end-users in the other. One central question the two groups were asked to answer was what level of accuracy should be the target for the eventual system. Specifically, participants were asked whether 3 m 95 % of the time would be sufficient.

I had the opportunity to participate in the discussion of the end-users, attended by maybe two dozen people, mostly senior officers from fire services and few people from technology companies. A number of points are worth mentioning from the discussion:

- There was a shared feeling that if fire services do not specify their requirements now, the opportunity of getting a system might be lost.
- There was a controversial discussion about how much accuracy was really required. The discussion essentially considered whether 6, 5 or 3 m would be sufficient.
- A participant reported on an incident where a firefighter was found dead right next to the backside door of a fast food restaurant. This illustrated the general fact that under zero-visibility firefighting conditions even the otherwise most obvious navigational tasks may become impossible to carry out. This showed that under such conditions the considered accuracy may prove insufficient.

The purpose of this introduction is to show a case of a complex socio-technical system and some of the factors and challenges relevant for design processes within it. This case will be expanded on in Sect. 3 and will serve as a reference for the following discussion.

2 Challenges of Designing Complex Socio-Technical Systems

Designing complex socio-technical systems poses challenges on several different levels.

First, currently emerging technologies that enable the creation of complex socio-technical systems are considered to also create a larger design space which is to say a larger space of possible design options [9]. These technologies enable adding sensing, computation and communication capabilities to an increasing percentage of elements in our environment, including to ourselves. Different from traditional desktop or mobile computing, this makes these capabilities more or less ubiquitous and enables the delivery of services that adapt to the personal, environmental and social context of users, possibly without their explicit interaction. Different from the more localized and contained services delivered by traditional devices, this new form of distributed technology can be used to embed context-sensitive services into the environment which justifies to some degree that they have also been called ambient intelligence technologies.

The increased design space for these technologies comes about through the increased number of relations they entertain with their environment and the increased depth of these relations in terms of exchanged information. In particular, the relations of systems to human beings may go beyond input and output through explicit interaction to include all aspects of a person that can be sensed or retrieved through communication, either through an explicit interaction or implicitly. Finally, different kinds of communication services may create networks of human beings in which information can flow, again either through explicit messaging or implicitly.

As a consequence, human-technology relations can become much more intricate than they used to be and correspondingly the impact of these technologies becomes more difficult to understand and assess. Acceptance of new technologies and undesirable effects become harder to predict.

An essential factor in this equation is that the use of technology is always embedded in an existing practice. Changes in technology, especially radical ones as considered here require or at least promote changes of these practices which in turn have an influence on what is seen as usable and satisfactory technology. As a result, a well-fitting combination of technologies and practice of use is typically the result of a process of co-evolution between these two parts. Typically the creation of a satisfactory practice of use requires using the technology. This is a key reason for developing technologies iteratively and by way of prototyping and human-driven simulations [10].

The increase in size of the design space in conjunction with increased development costs for this type of technology reduces the possibility to explore the design space with traditional design and development approaches [9].

When designing complex socio-technical systems an additional challenge is scale. Traditional approaches help in designing systems for small groups of users where interactions are typically confined in space and time. For cases where hundreds or thousands of users are involved, these approaches become impractical.

Yet another challenge is related to the kind of scenarios considered for the socio-technical systems. Many scenarios can be recreated satisfactorily to study the use of the system. Other scenarios, such as specific medical conditions of individual users or incidents or disasters involving damage and injuries can only be recreated with certain more or less relevant limitations.

Finally, considering design and innovation processes from a wider societal perspective another challenge can be identified. Ideally, people with expertise in the area under consideration should participate in design processes to contribute their expertise and to practically assess prototypes. But this requires considerable effort and often does not yield an immediate result that is meaningful for the participants. It is therefore a challenge to recruit sufficient numbers of participants and to keep them motivated.

3 Example of a Complex Socio-Technical System

The LifeNet tactical navigation support system for firefighters is an example for a complex socio-technical system [10–12] in the sense discussed in the previous section. It involves a network of distributed sensor nodes called beacons for navigation support and environmental sensing, a wearable system to provide navigational guidance to firefighters and to enable them to enter certain tactical information, as well as further systems for firefighters up the command hierarchy to monitor firefighting squads and assign missions to them.

The technical details of this system are not of relevance for the present discussion. What is of relevance are certain design challenges that it exemplifies:

- The involved technological fields of wearable computing and distributed sensor networks as a case of ubiquitous computing were first introduced decades ago now. But they can still be considered emerging in the sense that their use, particularly in challenging domains such as firefighting, remains difficult and insufficiently understood. Still it is already clear that they enable new and desirable kinds of implicit and social interaction, such as interaction through body movement and notification based on proximity or group membership.
- Several dimensions have been identified for the LifeNet design space. Examples are the density and strategy with which beacons are deployed, their weight, size, autonomy, sensing capabilities in terms of range and quality, their communication range and bandwidth, and finally the interfaces through which the LifeNet is used. There are significant trade-offs between most of these dimensions that heavily influence the performance of the system. This complexity of the design-space makes it difficult to anticipate the influence of any given factor as well as to identify a combination of design options for optimal performance.
- The attitude of the prospective users is often characterized by trust and appreciation for physical robustness. Firefighters tend to trust the physical lifeline that many firefighting squads use to secure their retreat path. This is at odds with the concept of reliability underlying the LifeNet which favors networking, network health monitoring, self-healing, redundancy and graceful degradation over physical robustness. The challenge here is that users cannot relate concepts like these to their experience and therefore have trouble trusting them, even if they perform objectively better.

- Assessment of risks and benefits: the LifeNet system holds the potential to increase efficiency and safety of search and rescue operations, but it also has a potential to introduce new and perhaps deeper dependencies. As it is much easier to show cases in which benefits can be realized than it is to show that benefits outweigh risks over all possible cases, a comparative assessment between the two is hard to make.
- Anticipation of future work practice: the LifeNet system affords opportunities to organize communication and workflows differently than today. But how exactly they should be organized is difficult to anticipate given the novelty of the technology and the lack of analogous experiences.
- Disruptive innovation: a system may be radically different from current ones. The LifeNet system can be radically different from the lifelines used today but can also be integrated with them in order to not be disruptive.
- Extensive resources required for development: many different specialized competencies may be required and development cycles may be very time-consuming and costly. For LifeNet, this is particularly true for the hardware development.

These challenges show the complexity of designing this class of systems and illustrate why the reduction to accuracy is inappropriate as well as why end-users find it hard to specify such an accuracy.

4 The FireSim Approach to Simulation-Based Innovation of Socio-Technical Systems

For the creation of technical systems, computer-aided simulations have been used for several decades now. A well-known example is the use of virtual simulations by car manufacturers. Another example is the use of virtual reality flight simulators used by airline companies to train their pilots but also to study new functionalities during development. More recently, simulations have been adopted as tools for learning, innovation and design in various business and engineering contexts, often referred to as serious games [13].

The intentions and interests in using simulations are very diverse. For instance, a car manufacturer may use a virtual driver model to test whether all controls are comfortably reachable. And a municipality may use interactive virtual simulations of a building under planning to enable citizens to explore the building and provide feedback as input to the design process.

For the challenges involved in designing complex socio-technical systems, discussed in Sects. 2 and 3, two aspects are of particular interest.

The first aspect is the experience that human beings make in these socio-technical systems. When designing novel socio-technical systems, it is essential to provide experiences of them to the prospective actors of these systems because their ability to assess them and provide feedback is at least partially embedded in their ability to act in the context under consideration [14]. This is to say that an analytical pre-experience examination of a prospective novel socio-technical system is typically insufficient to properly assess its evolution because part of the ability of the actors to act in a meaningful way in the considered context exists in the form of tacit knowledge [15, 16].

This is a general consideration that is valid for even the simplest use of tools [cp. 17]. But one of the most significant differences of the emerging technologies of ubiquitous computing and ambient intelligence compared to tools in general and traditional computing in particular is that they can integrate more closely and more intimately into the relation of human beings with their respective context. As a consequence, using them can take on more thoroughly a quality of implicit interaction [18] and designing them depends more deeply on experiencing their use in action.

Obviously, the need for experiencing novel designs in order to properly assess them is a key motivation for iterative design in which successive prototypes are created the use of which informs the creation of the next ones [19]. From a systematic standpoint this approach tries to integrate into the design process the improvements that users have always made to their tools in the course of using them. Depending on the tool under consideration it is easier or more difficult to recreate a sufficiently authentic context of use during the design process.

The second relevant aspect for designing complex socio-technical systems comes about through the other new and emerging characteristic of ubiquitous computing and ambient intelligence, namely that they exist in the form of numerous interconnected devices that are embedded in the environment and provide services collectively and transparently. This makes recreating the context of use particularly challenging. To some extend this has been addressed in the last years by initiatives that try to integrate innovation processes into large-scale real-world contexts such as cities in the form of living labs [cp. 20].

But as has been discussed in Sects. 2 and 3, there are important limitations to these kinds of approaches. It is in this sense, namely as tools for experience-based innovation processes that this article speaks of simulation-based innovation. And it is to address the above limitations to a certain extend that the FireSim approach, presented in the remainder of this section has been defined. The approach has been developed for the case of firefighter navigation support as described in Sect. 3.

Figure 1 shows an overview of the approach. The design process consists of a series of simulation techniques that allow groups of users to play out and experience scenarios while using increasingly sophisticated prototypes of novel technologies. The foundation of all of these simulations is created through empirical studies of the context of use in order to identify relevant and necessary aspects for inclusion in the simulations. The first technique is a role-playing simulation where the technologies are simulated with the easiest and most accessible means in order to be quick and agile, as well as to foster participatory design. The second technique is a virtual simulation in which multiple players can interact with interactive virtual prototypes of the technologies under consideration. The third technique is a mixed-reality simulation in which users play out scenarios in a real-world setting partially using

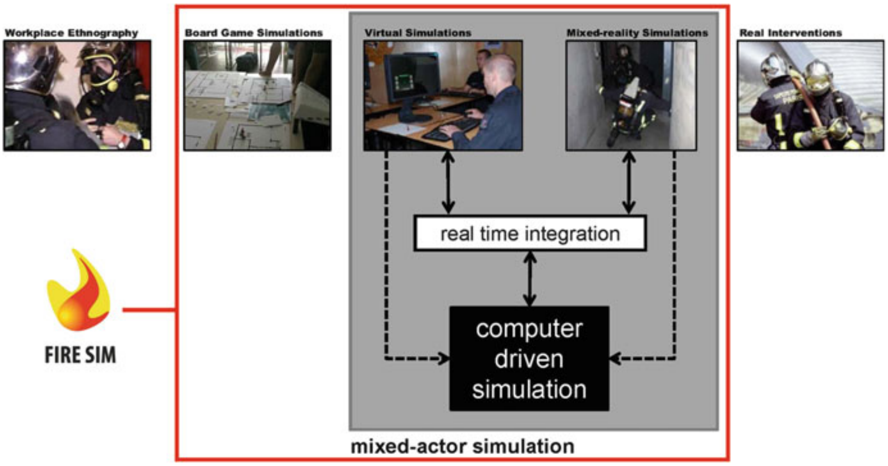

Fig. 1 FireSim approach to simulation-based design

systems and services that are already available as functional physical prototypes and partially using systems and services that are being injected from a synchronized virtual simulation (see Sect. 4.1).

The objective of this approach is to enable usage experiences as quickly and as accurately as necessary for the current stage of a given design process or the kind of question under consideration. Moreover, the different techniques can be used to inform the more sophisticated ones and to validate the less sophisticated ones. The limitation of these techniques is that they are only practical for scenarios of relatively moderate complexity.

For innovation processes in complex socio-technical systems, the topic under discussion here, these techniques have proven insufficient. A tangible example of these limitations would be that these techniques have been used to study the use of the LifeNet tactical navigation system by about a dozen firefighters but not more. This is sufficient to study the main types of interaction occurring in a small to medium-sized intervention. But it is insufficient to study medium to large-scale interventions with possible several dozens of firefighters.

What qualifies LifeNet-supported firefighting operations as an interesting case of a complex socio-technical system is that in such larger interventions phenomena may occur that cannot be extrapolated from less complex ones.

In order to address these limitations, FireSim was extended in the following way. It was extended with the possibility of controlling the firefighters in the virtual simulation by agent-models. These behavioral models for firefighter agents were created using the empirical data obtained through the other techniques.

The first form of use of this extension is to simulate scenarios entirely with agent models, illustrated in Fig. 1 by the computer-driven simulation. As before, the results of these agents-only simulations can be validated against results from the other simulation techniques.

The second form of use consists in having agent-controlled firefighters and human-controlled firefighters interact in one coherent simulation. The human-controlled firefighters can either be virtual ones that are controlled by human players or real ones whose behavior is directly played out by human actors. This is called mixed-actor simulation in Fig. 1. In both cases the players can of course be professional firefighters.

This approach allows extending the complexity of simulated scenarios considerably. Section 4.3 presents a case where a scenario with about 100 agents was simulated. The maximum complexity that can be achieved with this approach obviously depends on the complexity of the agent-models being used, on the hardware on which the simulation is running, as well as on the performance requirements of the virtual simulation. While the real-time capability of this integration enables the mixed-actor simulation, it also limits the performance of the agent-only simulation.

As the focus here is on studying complex socio-technical systems the following sections present a case of a small to medium-scale mixed-actor simulation which was used to create agent-models and then two cases of agent-only simulations to illustrate studies of medium to large-scale scenarios.

4.1 Human-Driven Mixed-Reality Simulations of a Navigation Support System

An application of the mixed-reality simulation technique during a study in October 2011 is illustrated in Fig. 2. The subject of the study was the use of the LifeNet navigation support system during a search and rescue operation by two firefighting units. The study took place in a building's basement with two entry points, two stairs to the ground floor, and a corridor structure in the form of an eight with rooms on both sides of the corridor. The point about this structure is that it affords a certain complexity and corresponding navigational features, i.e. the possibility of multiple paths to the same exit and paths from different squads joining within the environment. Three victims were placed at two different locations and the search and rescue operations were conducted by professional firefighters. The firefighters were equipped with a physical LifeNet system that included all elements except the LifeNet beacons. The system included in particular a display unit that presented navigational instructions. The physical display unit can be seen in image [b] and the interface is identical to the one shown in image [e]. Images [a] and [b] also show that the participating firefighters' vision was artificially impaired to simulate smoke.

Cameras were installed throughout this environment to enable observation of the firefighters' actions in a control room. Image [c] shows this control room. In the top-right corner one can see three of a total of 17 video feeds from the cameras. In the front are two of four virtual simulation stations running. At each of these stations a

Fig. 2 Mixed-reality simulation study of LifeNet supported search and rescue operation

virtual simulation is running of the basement environment from the first-person perspective of one of the four squad leaders participating in the scenario. Image [d] shows a bird-eye view of the virtual environment of this basement. The first-person view is shown in image [e]. At each of the stations a facilitator plays one of these virtual firefighters, replicating as accurately as possible the behavior of the corresponding real firefighter by looking at the video feeds. In the virtual simulation, virtual LifeNet beacons are deployed by the firefighters, the sensing and communication processes between the beacons and the firefighters are simulated and the navigation interfaces are generated as shown in image [e]. As all four simulation stations are connected into one virtual simulation, all firefighters and beacons exist in the same environment and interact with each other. The navigation interfaces generated in the virtual simulations are wirelessly transmitted to the corresponding firefighters and shown on their display units. The result of this process is that a real firefighter moving about in the basement and looking at his interface has the impression of deploying beacons and being able to follow trails of beacons. In addition, the real firefighters are able to send a number of messages by using textile buttons integrated with their jacket. These messages are injected into the virtual simulation and trigger the same actions on the virtual firefighters. This coherent integration of partially virtual and partially real systems and actors makes up the mixed-realty technique and affords the participants with a consistent experience of using the LifeNet system in a real-world setting.

A detailed description of the technique and its application in another study can be found in [10].

Selected results of applying the technique include consistently:

- Agreement from participants that safety can be increased through guidance on alternative paths.
- Agreement of participants that efficiency can be increased through guidance to tagged locations on the shortest possible path.
- Before the study, participants expect their locations to be shown on a map. After the study they state that navigation support without a map is effectively sufficient.
- Before the study, participants show low acceptance of the navigation support. After the study acceptance is significantly higher.
- Before the study, participants typically request automatic deployment of beacons only. After they study, participants voice interest to also be able to manually deploy beacons.
- Identification of many questions and suggestions regarding the current state of the design. For instance, participants suggested connecting the beacons belonging to a path with a line on the navigation interface.
- Benefits for individual firefighters may lead to issues of accountability and resource availability on higher levels of the command hierarchy.

4.2 Computer-Driven Agent Simulations of a Navigation Support System

The empirical data obtained through these mixed-reality simulations, including video footage and log data from the virtual simulations, was used to set up agent-models for firefighters using the LifeNet system.

These models were then used to study performance of task execution against selected parameters describing design options of the LifeNet system and properties of the users or the environment, as explained in Sect. 3.

Figure 3 shows results from one such study. The simulated task was to navigate between two points in an environment similar to the one presented in the last section, following a trail of beacons between two points.

The task performance was studied against two parameters, namely attention of the firefighter and angular error of the navigation support. For both of these parameters models were created based on the literature and properties identified

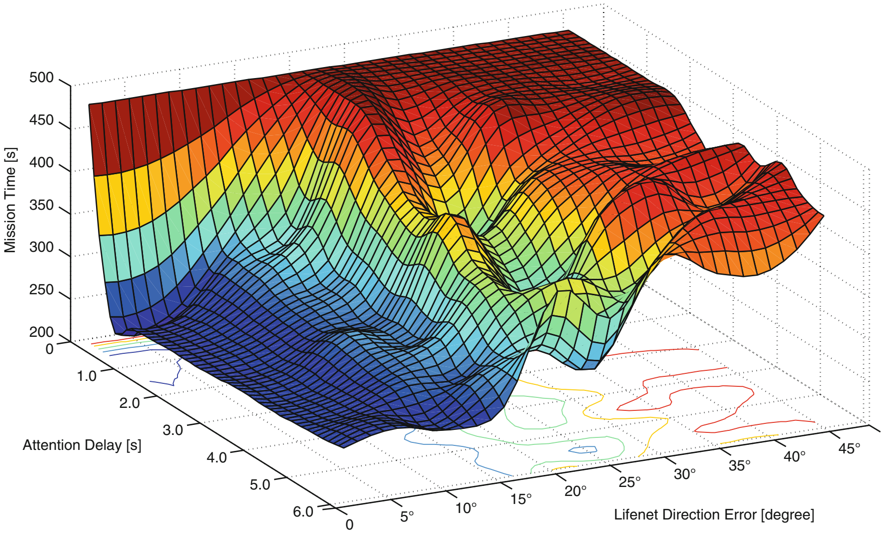

Fig. 3 Results of agent-based simulation of LifeNet supported navigation

through the empirical studies presented in the last section. The attention was defined as the delay between two consultations of the navigation interface and the angular error of the LifeNet system was defined as the difference in angle between the navigational instructions presented to the user and the actual orientation of the path in reality. The task performance was defined as the execution time. Each consultation of the navigation interface resulted in a certain time penalty due to slower or stopped movement. Navigation with angular errors resulted in deviations from the actual paths and, depending on the degrees of attention and error, resulted at times in navigational errors such as missed doors.

The simulations were repeated for a total of 400 parameter combinations within certain ranges of the two parameters involved.

As can be seen in Fig. 3, there is a plateau for small attention delays and high error rates. This is because the task execution was terminated after a certain threshold time. What is interesting about the results is that the task performance does not simply improve with better attention and smaller error. There is a pronounced ridge at about 20° angular error with a significantly better performance at the higher angular error of 25°. The exact reason for this ridge is still under investigation but in some cases it seems to be related to accidental properties of the local building structure. What can be concluded from the figure is that for small errors up to 15°, attention delays between 1 and 6 seconds have little impact on task performance.

4.3 Computer-Driven Agent Simulations of an Evacuation Support System

Another agent-based simulation was conducted for evacuation processes in which civilians are supported by a hypothetical smartphone-based evacuation assistant, called EvacAssist. The same building as in Sects. 4.1 and 4.2 was used in this study and about 100 civilians were distributed throughout this environment. The evacuation was triggered by an explosion and smoke was propagating into the building afterwards.

Based on literature on human behavior in evacuation processes, agent models were defined for the civilians. The EvacAssist system was implemented, consisting of sensors that could detect clogging at the exit points of the building and inform civilians of the estimated delays. The civilian agents were set up to belong to one of two social groups. Each civilian agent was able to observe other agents and identify whether they were moving towards an exit or not. Agents were also able to hear the sound of the explosion within a certain range and to observe smoke, as well as communicate information received over their smartphone to other agents. Certain observations were also capable of increasing an emotional state of fear within an agent. Finally, agents from different social groups were set up to be less inclined to communicate with one another, except if they were very afraid.

The parameter space investigated was defined by measuring the evacuation time against the distribution of all civilians between the two groups and the percentage of smartphone penetration. The evacuation time was defined by the time at which all civilians had left the building. The social distribution was defined by the percentage of civilians in one of the two groups, ranging from 0 % to 50 %. The smartphone penetration was defined by the percentage of civilians having a smartphone.

Figure 4 shows the results of the simulation runs. What can be concluded is that social distribution did not have any significant impact on evacuation time. Analysis showed that contrary to expectations only very few cases of communication occurred that let to better evacuation decisions and the highest numbers of communication processes that occurred did not slow down agents significantly because each individual communication was modeled to take up only 1 second.

While this result needs to be taken as a pointer to improve the agent models, another result is interesting for the system under investigation. Namely that there was a decrease in evacuation time with an increase of smartphone penetration from 0 to about 40 % but no further decrease afterwards. This suggests, within the limits of the models obviously, that smartphone penetration beyond a certain threshold will not increase the benefit. Whether it is actually at 40 % is a different question and this will certainly change depending on the sophistication of the models as well as the scenarios considered. But it is surprising that the maximum benefit is already reached at such a relatively low percentage.

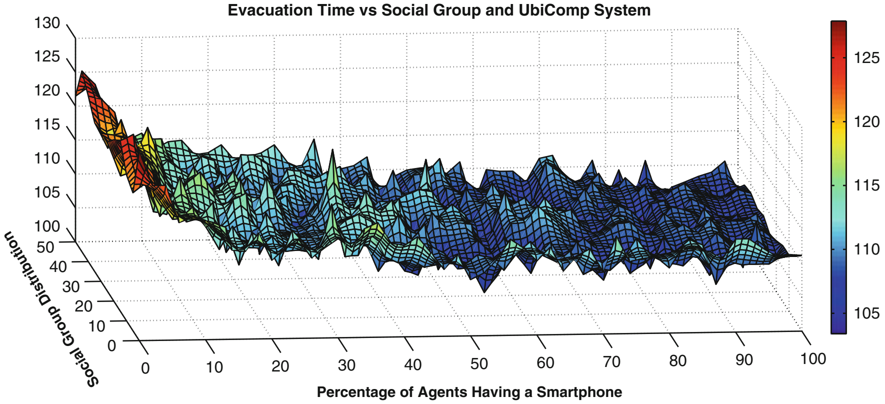

Fig. 4 Results from agent-simulation of AmI supported evacuation

5 Discussion

5.1 Some General Thoughts on Simulations

The simulation that has arguably the highest visibility and penetration in society today is the weather forecast. In its simplest form, a person considers certain factors that can be observed and makes a forecast based on what these factors indicated in the past. Some people in some places can become fairly accurate at this. But they will also frequently fail, namely when the weather is too quickly influenced by factors that they could not directly observe. In its most sophisticated form, observations are extended by networks of distributed sensors, including data obtained from satellites, and these are fed into quantitative global weather models. By making use of data that has been collected over many years, computationally heavy calculations are performed to create a forecast. As we all know, the resulting predictions are generally reliable for a few days in advance and then become increasingly unreliable.

What is of interest to note for the present discussion is that the interpretation and assessment of reliability of such models can quickly become the object of dissent among stakeholders. As illustrated by the recent hurricanes in the US, citizens, municipalities and insurance companies may not easily agree on how to interpret a given weather forecast. More strikingly, a strong political and economic battle is ongoing regarding the validity of models predicting climate change. Unsurprisingly, the interpretations of the parties involved often correlate closely with their interests.

What is at stake here has been demonstrated most blatantly by the recent legal prosecution and conviction of six leading scientists and an ex-government official from Italy [21]. All of them have been members of the National Commission for the Forecast and Prevention of Major Risks. And at a political event a few days prior to the devastating 2009 l'Aquila earthquake they had pronounced that there was low probability for a major earthquake.

As one would expect, this conviction triggered an outcry from the scientific community all over the world, with the most prevalent criticism being that it is in the nature of science that predictions are a matter of probability and that scientists therefore cannot always be right.

Without wanting to analyze this further here, what can be said from looking at a few more reports on the process is that this case is not simply a matter of limited predictive powers, since cautioning studies had reportedly been published. Much rather it seems to be a case of the desired outcome defining the interpretation of simulation results, perhaps in a rather extreme fashion. Whatever further investigations may reveal about its background, this case clearly shows the importance of simulations, their potential role as the basis for political decision making, and the possible issues that can arise from the different interests involved.

Many years ago, when computer-based simulations were still in their beginnings and existed only in very particular domains, Joseph Weizenbaum provided a striking critique of a case of military simulation in which the model was apparently simply tweaked to yield the desired result which was then used to justify the decision of taking military action as being grounded in objective results from a simulation [22]. The critical dependency of simulations with the models they use on the one hand and the interpretation of the simulation results on the other, and how to handle both in a responsible way has been discussed for the case of military operations in [23].

The point here is not to judge any of the above positions. The point is to see that simulations of complex socio-technical systems, even more so than simulations of the weather, earthquakes and the climate, are not only grounded in very limited foundations but are also subject to interpretation. Like any other simulation, they show the implications of the models that they are using, and interpreting them requires understanding and respecting the limits of these models. Like the interpretation of statistics, doing this properly requires knowledge – a kind of simulation literacy. Consequently, responsibility cannot be delegated to a simulation; it stays with the authors of the models and ultimately those who base decisions on their results.

5.2 Simulations as Tools for Experience-Based Design Space Explorations

Section 1 above reported that firefighters were asked how much accuracy would be enough for a localization system to meet their needs. The firefighters had a hard time agreeing on an answer that they felt comfortable with.

Obviously accuracy is an important question that equipment manufacturers need to have some kind of answer for to be able to produce the components of localization systems. But the naked accuracy of such a system is more or less meaningless for firefighters. Of course, perfect accuracy would be best and of course there is a certain accuracy threshold below which using a localization system doesn't make much sense. But then there is also the price tag for a system that achieves a given level of accuracy which might very well mean that only systems below a certain level of accuracy are acceptable even if higher accuracy might be desirable. And this type of consideration can be made for a large number of factors, some of which have been described in Sect. 3.

The key question that firefighters need to answer when assessing this and similar technologies is what they mean operationally. And this is exactly what they tried to do when looking for an answer to the above question: they tried to think of cases where using a system with certain accuracy would have provided a benefit or not. As explained above, this included a case where even a rather high level of accuracy might not have been enough to support a firefighter in a critical situation. A systematic way of investigating the question of accuracy would be to identify a representative set of past interventions that featured some kind of problem with localization or navigation and assess whether a given system would have resolved this problem.

But the more fundamental challenge here is that accuracy is but one of the dimensions of the design space. Limiting the question to localization accuracy is in fact framing the problem in a way that excludes many potential systems. As shown in Sect. 4, many operational requirements of firefighters could in fact be addressed without providing absolute positioning at all and just supporting navigation, allowing for comparatively low levels of accuracy. But the point here is not to judge both approaches against each other; the point is to note that by considering further dimensions of the design space the problem can be framed quite differently. One more example may suffice to illustrate this point: a given level of accuracy that would be unacceptable by itself may become acceptable for the user if an estimate of the degree of accuracy is also presented, enabling the user to consider the potential error for decision making.

But as has been pointed out in Sects. 2 and 3, these questions cannot properly be answered when sitting around a table. They require the experience of putting the respective systems to the test under operational conditions. And whether a certain accuracy, or any other aspect of the design is judged sufficient may heavily depend on other aspects of the design, including operational procedures that may need to be adapted.

To enable this kind of investigation, innovation processes in complex socio-technical systems need to be organized long-term. They do not end with the availability of a first functional system. It is only when functional systems become available that an important phase of the innovation process can start, which is the experience-based transition of the socio-technical system towards a new stable state, the co-evolution of the technology and its users.

Achieving such an innovation process is and has been the objective of user-centered design. But as discussed above, the approach of involving end-users in innovation processes has important limitations due to the involved costs and efforts or even the availability of the relevant context of use, which is particularly true for the complex socio-technical systems under consideration here.

As shown in Sect. 4, experience-based simulations can be instrumental in enabling the exploration of larger design spaces at early design stages at significantly smaller costs than developing fully functional system prototypes. This can help in considering more design alternatives before taking the difficult decision of which ones to actually implement.

But as argued in the beginning of this section, results from such simulations are only indications that can guide explorations and focus the attention on areas that seem to have particular importance. They may help us in being better informed when deciding which design options to further explore through real physical prototypes used in the real world.

Finally, what has also become clear from Sect. 4 is that simulations require more or less effort themselves. Depending on the design question at hand, setting up an appropriate simulation may require more effort than actually building the physical system. To a certain extend this simulation overhead is common to all simulations and can therefore be reduced very significantly by providing a reusable and adaptable simulation infrastructure. For the design of technical systems many simulation tools exist that can be adapted to specific needs. This is not yet the case for designing complex socio-technical systems. For certain classes of design challenges common functionalities exist that would need to be part of simulations. For classes of sufficient interest the simulation infrastructures could be extended to lower the threshold of setting up and conducting simulations that are adapted to the specific purpose at hand.

6 Conclusions

Simulation techniques for the design of socio-technical systems cannot be judged independently of their context of application. They are used in a process involving human beings and they form a methodological eco-system with other techniques that may be used in this process. A given technique may be insufficient if used alone but may become valuable when used in the right combination. Applying simulation techniques always requires embedding them properly in the given design context.

Simulations can be used as tools for thought but they cannot replace thinking. As a consequence this kind of tool should be as democratic as possible in the sense that everybody affected by a socio-technical innovation process should be able to use simulations to show the implications of his or her thoughts on the matter as well as to investigate the models underlying the simulations proposed by others. As explained above this does not only require appropriate technical infrastructures, it also requires a kind of simulation literacy.

Facilitating access to and use of simulation infrastructures for socio-technical innovation promotes the participation of all stakeholders in the innovation process and may thus enrich the discourse with multiple competing models and ways to frame the problems at hand. To this end, comparability of simulation results is another important objective to work towards.

The studies reported in Sect. 4 suggest that experience-based simulations may partially replace direct user involvement in exploring the design spaces of complex socio-technical systems. This is desirable because direct involvement can easily overload many user groups and is often not possible to the desired extend due to the required effort or the risks involved. But as discussed in Sect. 4, there are also significant limitations to the use of simulations for the innovation of socio-technical systems. To a certain degree direct user involvement remains necessary and is in fact a precondition for the possibility of simulation-based techniques.

The potential to reduce direct user involvement by way of simulations has therefore the additional benefit of freeing up users for direct involvement when it is really required, including the grounding and verification of simulations.

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Part III
Transport

Enhancing Future Mass ICT with Social Capabilities

Andreas Riener and Alois Ferscha

1 Socially Inspired ICT

Pervasive and Ubiquitous Computing has developed a vision where the "computer" is no longer associated with the concept of a single device or a network of devices, but rather the entirety of situated services originating in a digital world, which are perceived through the physical world. It is observed that services with explicit user input and output are becoming replaced by a computing landscape sensing the physical world via a huge variety of sensors, and controlling it via a plethora of actuators. The nature and appearance of computing devices is changing to be hidden in the fabric of everyday life, invisibly networked, and omnipresent. Conceivably, next generation Pervasive and Ubiquitous Computing systems will be manifested by ICT (information and communication technology) rich artifacts (like tools, appliances, objects of every day use), and environments (like work and home places, or sports and entertainment locations), cooperatively attempting service provision grounded on elements of social behavior. It is widely claimed, that the operational principles of ICT deployed at massive scale will have to be inspired by the principles of social interaction and engagement. Socio-inspired ICT assumes that future, global scale ICT systems should be viewed as social systems. Such a view challenges research to identify and formalize the principles of interaction and adaptation in social systems, so as to be able to ground future ICT systems on the social paradigm.

In this paper we are concerned with modern ICT in the automotive domain, proposing modalities of social interaction, social conventions and social contexts as the design and operational principles of future generation automotive systems.

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1.1 Social Signaling

Typically, human-human social interactions are influenced by common psychological principles that play out in our lives implicitly, i.e., without any mention of them. When we get born we are already equipped with basic instinctual knowledge of how to socialize, and we immediately start to develop deeper understanding of these psychological principles in order to give us a better understanding of the social interactions that happen all around us and why people act the way they do [1]. To give an example of social behavior, a lot of what we communicate to others is non-verbal, communicating our mood and thoughts through facial expressions, body language, linguistics [2], gestures, etc.

According to [3], *social signaling* is what you perceive when observing a conversation in an unfamiliar language, and yet find that you can still 'see' someone taking charge of a conversation, establishing a friendly interaction, or expressing empathy for the other party. While you cannot understand the words being spoken, you can still interpret and understand the prototypical (and often unconscious) behaviors that humans have evolved to display.

Research in social signaling gained momentum in the 1990s with the studies of Ambady et al. [4]. They analyzed the accuracy of predictions in the area of social and clinical psychology from short observations of expressive behavior and found out that the length of the observation did not yield greater predictive accuracy and that the behavioral channel (face, speech, body posture, etc.) on which the ratings were based was not related to the accuracy of predictions. The socio-ecological model (SEM) [5] is a framework to examine the multiple effects and the interwoven relationship that exists between an individual and his/her environment. While in general the individual is responsible for himself/herself, individual behavior is determined to a large extent by the social environment, such as norms and values, regulations, and (cultural) policies. Related to social interaction, some topics of particular interest are approaches *inspired from biology*, e.g., the absence of a central decision point as like in ant colonies [76], *group communication* (or how to transfer the right information to the right place), *game theory inspired control mechanisms* (evolutionary games represent a model on how strategies can change over time to adapt to changes in working conditions), or *persuasive interaction* (different contextual elements such as the users evolving profile, the current situation and other motivational dynamics (related to personal, social or community-oriented benefits) to maximize users motivation towards assuming positive behaviors against specific contextual conditions [6]).

Social interaction happens on different levels, ranging from relationship (friends, family) to community (people with same desires, goals) and finally society (rules, regulations) (Fig. 1). We start on the individual level by *listening* to "signals" connected to the social world and to look for relevant information. As there are many different social channels providing conversations/information at the same time, *filtering* mechanisms are required to filter out all the irrelevant conversations. While information filters are good at capturing specific conversations/events, much

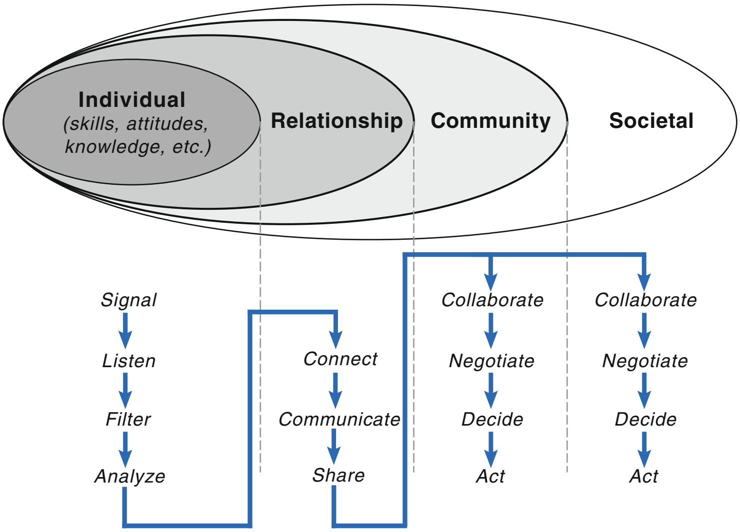

Fig. 1 Socio-ecological model allows to study the influences of multiple levels and contexts to establish the big picture in social interaction (first row). Different stages (capabilities) to consider for social engagement (lower part)

of the advantage of social engagement comes from understanding the ‘big picture’ and how to engage with it effectively; *Analysis* aims to understand “the shape of the haystack rather than locating a specific needle in it” [7]. Until here, information is processed on local car level only, and nothing is shared with others. To form a relationship, a *connection* need to be established with other peers, *communication* is started to request or exchange information, and finally information (about internal vehicle status, driver condition, or infrastructure such as road condition) is *shared* within the group. For this small scaled interaction no central control (e.g., *cloud service*) is required, and there is no negotiation between the involved parties. *Collaboration* with the aim to achieve the global goal, *negotiation*, common *decision making* and finally (concerted) (re)action remain also reserved for larger (community, societal) based interaction as highlighted in Fig. 1.

1.2 Emergent Behavior

A important consequence and the power of social engagement is, that local, individual actions within a “system” can show effects on global scale. The influence of information sharing and collaboration across levels is better known as “emergent behavior” and also referred to as “Stigmergy” [75] (greek: *stigma* = mark, sign, *ergon* = work, action). This coordination concept is based on indirect communication derived from social insects (ants moving on a trail, bees collecting honey or living in a beeyard, termites building a nest) and was introduced by the French biologist *Grasse* in 1959 to refer to termite behavior. Signs left along the trail can be easily detected by passing ants (*signal sensing*) and mapped to their geolocation (*analyzing*). By following the ‘markers’ (*connection*), ants could be guided to the destination point, i.e., food source (*sharing*). A fundamental characteristic of Stigmergy is that communication takes place by means of environment modifications, e.g., by leaving traces (messages, signs, notes) in the surrounding that are sensed by other entities, and that are affecting their subsequent behavior or eliciting a response (*action*). The signs (fragrances, or more specific ‘pheromones’), if not “renewed”, evaporate over time to avoid leaving outdated information in the environment.

This concept could be easily transferred into an automotive context [8], for example, has successfully demonstrated the power of Stigmergy as a tool for coordination in a loosely coupled technical system. Vehicles moving on a motorway can be (from an ICT point-of-view, and with regard to communication and connectivity) considered a loosely coupled system, thus the paradigm of Stigmergy could (and should!) also be applied here [9]. Think of a collaboration and information sharing example on community level, where communication takes place by means of environment modifications. The information exchanged between signs left along the road (i.e., “virtual, electronic containers”) and cars (agents) can be interpreted as kind of social interaction. A car could ‘drop’ information or experience while passing a section (e.g., limited sight due to fog, slippery road, etc.) and other cars reaching or coming close to the spot can read out and analyze the note. This way, and as outlined in Fig. 2, it is possible to provide (proactive) warnings ahead a hazardous region or situation to the driver. If the information/note is not refreshed or confirmed by other cars passing the road segment within a certain time frame, its confidence/credibility declines. This results in up-to date, ‘live’ information about current traffic state (at least in times of high traffic); during off-peak time or on less traveled roads the concept of evaporation may not work that well.

1.3 Social Principles in Mass Traffic

Social interaction in the car domain has up to now be provided only on individual level. Technical advances affecting vehicle handling (e.g., power steering, assisted braking, etc.) and driving comfort (route guidance, driving assistance, on board entertainment, etc.) have led to a strong(er) interrelationship between the driver and the technical systems in a car. With latest achievements in wireless communication technologies the whole new class of vehicle-to-“x” applications have arisen, allowing spontaneous formation of car collectives or *cooperative crowds* to offer services and applications on car-to-car (safety functions, proactive traffic jam avoidance, accident prevention, negotiation of driving parameters), car-to-roadside and car-to-infrastructure levels. The critical question here is, however, if the information technology available in the car actually allows for “real” social

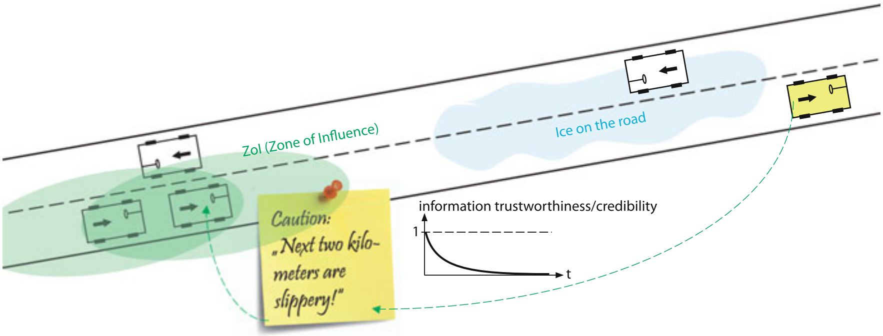

Fig. 2 Example of emergent behavior ("Stigmergy") in the automotive domain. A car could post a digital note (pheromone) so that other cars are warned proactively about a upcoming hazard. Its credibility is removed over time (i.e., evaporating in the comprehension of pheromones and fragrances) in order to provide only relevant, up-to-date information

behavior in networks of cars. According to [10], social aware cars (with abilities and intentions for adaptation) have to cope with individual and group behaviors and goals. The basic entities of such a system are many local actors (driver-car pairs) with (1) *individualism* (habits, customs, character, daily routine, (un)consciousness, personality, emotions, cognitions, physical states, intrinsic and extrinsic behaviors), *restricted perception* of their environment, and a limited *capacity of action* as well as (2) *collectivism* (social grouping, long and short term social behaviors, social practice, both prejudices and tolerance, fashion, tradition, social etiquette). What has been observed so far is that most of the stated principles have been seriously neglected in present systems and that ethics need to be built-in in any solution in order to provide ethical sensitivity to each of the above aspects. To approach an answer for *individualism*, a number of (social) criteria characterizing human behavior and/or reputation need to be validated. Attributes to consider include the ability to communicate and interact, willingness to negotiate, own cognitive abilities, self-manage behavior history, good/bad reputation, judgment, ability to assert oneself, forget/forgive, rapid assessment and decision making, and learning/adaptation capabilities. We will come back to these attributes later in the article. With regard to *collectivism*, cars are socializing to achieve a global optimum (*the goal*) based on a cost (fitness) function that concerns the environment of the problem in its totality. The difficulty in traffic is, that different time scales are evident (driving action: seconds, emergence of a jam: minutes to hours; change of weather: hours to days; legal regulations: month to years), that driving is a highly dynamic task (negotiation, re-distribution of the decision to local actors, behavior adaption, etc. is often not possible in the due time), that there are many (local) actors with maybe individual behavior, restricted perception of their environment, and a limited capacity of action involved, and that the context and its boundary conditions are continuously changing (traffic situation, jams/accidents (driver fell asleep), infrastructure failures (traffic lights), weather conditions (dry to snow storm), etc.) [11, 12]. Furthermore, in order to provide stable solutions (interplay of individualism and collectivism) it is a necessity to perfectly understand the reality to be faced, i.e., the context and its boundary condition in which the scenario is embedded into.

From a sociological point of view, a *collective* is a group of entities that share or are motivated by at least one common issue or interest, or work together on a specific project to achieve a common objective (*work collective*). Collectives differ from cooperatives in the way that they are not necessarily focused upon an economic benefit or saving (but can be that as well) [13].

The term *collective behavior* in its current used form was employed by [14] to refer to social processes and events which do not reflect existing social structure, but which emerge in a "spontaneous way". Collective behavior, a form of action, takes in general place when norms are absent or unclear, or when they contradict each other [15].

Preceding *collective behavior*, Blumer first introduced the notion of a *circular reaction* where responses of individuals within a crowd reproduce the responses of others around them, reflecting stimulation back and forth and thereby causing its intensification. Circular reactions signal the existence of a state of social unrest – the initial process of elementary collective behavior [14, 16].

Formally, but also depending on the context, a collection may refer to terms like set, class, or family, i.e., a group of associated items or 'things'. In the automotive domain a collective may be understood as vehicles with common interest expressed by (i) same origin (city, parking lot, etc.), (ii) same target (exit ramp on a motorway, parking lot on an airport, towards the downtown area, or to a shopping center), (iii) same driving route or direction, equal driving speed, (iv) same type of car (fuel driven, electric vehicle, hybrid; car, truck, bus), (v) same emotional state of the driver (relaxed, tired, drunk, stressed), (vi) same reason for traveling (going to vacation, shopping, working), and which want to achieve individual improvements (driving time, fuel consumption, reduced stress or enhanced driving pleasure, safety) by benefiting from the group knowledge or by adapting the group (goal).

Extending on these networked systems-of-systems collaborating 'only' to achieve or optimize a certain goal (*work collectives*), *collective adaptive systems* (CASs) are understood as highly complex systems featuring many units/nodes/vehicles which each having its own individual properties, objectives, and actions, and operating at different temporal and spatial scales [17]. Decision-making is distributed and possibly highly dispersed, and interaction between the units may lead to the emergence of unexpected phenomena.

They are "open" in that nodes may enter or leave the collective at any time, and boundaries between CASs are typically fluid. Collective adaptive systems reflect large socio-technical processes (*social phenomena*) influenced from most likely non-linear, local behavior – as traffic is. They are hard to understand and comprehend in its full variants, and it is even more problematic to predict its behavior – nevertheless, one of the central goals of CASs is the prediction of the underlying complex systems. We see great potential for CAS to be applied to a automotive setting, as this domain is well-defined by parameters such as (a) traffic regulations, (b) road geometry/infrastructure, (c) physical rules (acceleration, braking distance, etc.), (d) driver characteristics (novice/expert, male/female, young/old) and condition (mentally stressed, angry, fatigue, high-spirited). But even in this confined setting, results may vary a lot depending on external factors like cultural aspects (e.g., different driving style of drivers from Italy, Iceland/Scandinavia, China, or the US) or place of investigation (traffic rules, e.g., speed limits, defined on national level, left-hand/right-hand driving, etc.). It will also be important to understand all classical attempts that have been performed so far and how did they fail [18, 19].

1.4 Social ICT Systems Architecture

Weather models have been studied for quite a long time, but not very successfully as they comprise highly complex, non-linear phenomena. This was also the main reason why it was almost impossible to implement authentic weather models using classical approaches. Quite recently, CAS technique allowed for the first time to implement reliable weather models. At least for small areas and within in a short time horizon, temperature, rainfall, sunshine duration, wind strength, etc. can be predicted rather accurate. Traffic fluidity seems somehow related to weather change; that’s why we hope that well established weather models can be taken as starting point, and adapted to also predict socio-technical phenomena appearing in road traffic (e.g., traffic jams, stop-and-go waves).

Looking on the implementation details, two issues known as *forward* and *inverse problem* (Fig. 3) have to be considered in collective, social systems. A traffic related example for the class of *inverse problems* is the goal to achieve a global optimum of the traffic flow (i.e., homogeneous flow, maximum throughput, jam avoidance). This is of particular interest at peak traffic times, for example from rural districts towards the downtown area in the morning (or out of the city in the evening). Commuter cars are entering the city according to their personal preferences (behavior) such as flexible work schedule, different time of day, and by using many different roads. Significant adjustments in the time of departure (or the planned arrival time) are not made, neither by the drivers themselves (not willing to leave 6 a.m. if known that traffic jams will start at around 6.30 a.m.) nor by the employers in shifting core working times (i.e., to ask for clocking in 20 min earlier or 30 min later), thus it is left alone at the individual drivers to find an optimal schedule day by day. That it is actually possible to reach work place (home) without any jam or delay can be observed during the holiday season – only a few percent of employees are away, and former massive traffic jams simply vanish into thin air. The optimization problem is highly complex, as not only a single car (driver) will change its commuter behavior based on past experience; it will be almost all drivers (with flexible time program) that shifts time of departure a little from day to day, resulting in a changed global traffic situation.

With regard to *forward problems*, examples can be indicated that results in emergent behavior. Driving of a single car could influence all the other drivers in vicinity. If the one “labeled” car starts to increase its speed, even above a given

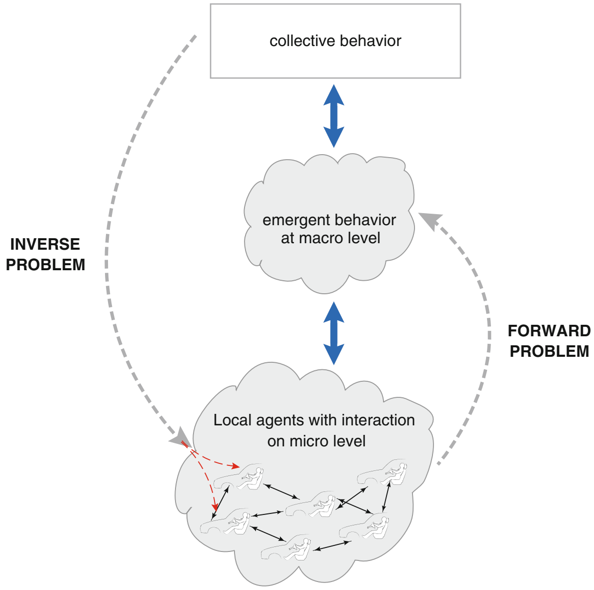

Fig. 3 Forward and inverse problem in socializing cars (from [71], p. 26)

speed limit, all or most of the following cars will also do so. This is actually confirmed by [20] who found out that speeding is a problematic behavior anchored in almost any driver. A second instance of speeding is known as “the pressure to speed up”. Elaborated by [21] there is evidence that the driving speed of a driver is influenced by several factors with the most important being a pressure from other drivers, approaching with higher speed from behind, to speed up. The own behavior affect on his/her part the traffic ahead, and so on, leading in the end to the typical stop-and-go waves of traffic.

1.5 Potential and Pitfalls of Socially Aware Vehicles

1.5.1 Goals (of Socially-Aware Traffic)

- **Driving safety**, e.g., “Vision Zero” (manifests the long term visions and road safety goals of the European countries [22]),
- **Sustainability**, for example, concerted driver behavior should have the potential to allow for improvements such as reducing global fuel consumption or CO_2 emission,
- Increased **driving experience and pleasure** by adopting autonomous driving, traffic shaping (adaptive lanes, i.e., lane usage dynamically adapted based on demand), or other concepts as highlighted in section “Use Cases” below,
- **Social forgivingness**, i.e., “[..] the willingness to anticipate a potentially unsafe action of another road user, and to act in such a manner that negative

consequences of this potentially unsafe action are prevented or in any case limited" [23],

- **Enhanced self-assessment**, based on the fact that a driver emotes all the time and that certain emotional states might have a (negative) effect on road safety; if the driver is conscious about his/her state (or the states of other drivers in vicinity) this could lead to improved road safety,
- **Better prediction** of upcoming situations such as traffic quantity, lane usage, weather conditions, etc. and their influence on local driver behavior.

1.5.2 Pitfalls on Socializing Cars

Beside the potential the concept of mass traffic influenced by social agents (cars) holds, there are also lot of critics arguing that socially inspired actions by or recommendations of technical systems might compromise safety, privacy, etc. and prevent admittance for the "normal" driver due to high initial cost. The most crucial points against the utilization of social capabilities in mass traffic are indicated in the following list, and the importance of these items were actually confirmed in a focused workshop [24] 1.5 pt.

- **Privacy.** What information is shared with other cars or a central system. Can the driver control what is shared, or is it "all-or-nothing"? Does a driver has to opt-in, or is he/she forced to opt-out?
- **Security.** How secure is the system? Can it be hacked, e.g. by manipulating physical infrastructure such as traffic lights, what is the consequence if hacked?
- **Connection Technology.** Significant investment in technology is needed, especially for vehicle-to-infrastructure (V2I), e.g., sensors in each and every traffic sign, connection to traffic lights, induction loop sensors, etc.; this is very expensive. Who will fund this? (the government might not be able to fund it due to "Big Brother" concerns of all the road users)
- **Increasing Digital Divide.** A polarization between supporters and opponents is expected. How do you create vehicles or driving experiences for everyone with two polar extremes? There are also concerns about the initial cost of entry, e.g. latest technology appears on new, flagship, or high-end vehicles, which is contradictory to the assumed early adopters (youth "Facebook generation", who may not purchase a (new) vehicle); One option to overcome this problem of equipment cost too expensive for the "normal" driver is a sort of subscription model (e.g., lease the hardware and pay a monthly utilization fee for services subscribed to)?

2 Evolution of Social Interaction

2.1 The First Wave: Disappearing Interpersonal Interaction

While in former times extended families where living together on the countryside, this changed a lot with increased technological advance (actually starting with the industrial revolution in the beginning of the nineteenth century). After their job, people where sitting alone in their flats and over the time their social behavior and communication abilities degenerated. The situation has become particularly aggravated with broad emergence of ICT in the twentieth century – human individuals spent more and more time in using the computer, watching TV, playing with video consoles, etc. In 1996 the "*Tamagotchi*" handheld digital pet was initially launched, a computer device that lets the player care for the pet as much or as little as he/she chooses. The "outcome" depends on the player's actions and playing with this device can be interpreted as a simple form of social interaction. As of 2010, over 76 million *Tamagotchis* have been sold world-wide. This number is a clear indication that humans need some kind of social interaction.

2.2 The Second Wave: Globalization and Virtualization

With the availability of powerful backbone networks together with high penetration of personal computers, the Internet has opened a whole new world of opportunities for each and every individual user. While in the early days information gathering (*Altavista*) and shopping (*Amazon*, *eBay*) was the focus of users, people are nowadays using applications/games to escape into virtual worlds (*Second Life*) and to live there their life with whatever character they like. These days, Internet-based grocery stores deliver food and all other daily needed products, fashion stores ships clothings, . . ., virtual pastors/churches aims to serve religious needs of these people, and companies worldwide have accepted their employees to carry out teleworking. Time has come that people can manage their whole life from their computer, without leaving the home a single time.

2.3 The Third Wave: Social Relations

In the first years of "connectedness" users were sharing files through the Internet (using services such as *eMule*, *eDonkey*) and chatting (often in private networks just as in student dormitories such as *ICQ*, later improved to *Skype*). With increasing and everywhere connectivity (e.g., cable networks, wireless LAN/WiFi, mobile cell phone operators, satellite based communication) and emergence of Internet-enabled mobile devices such as cell phones, PDAs, Smartphones, iPad, etc., the floor was opened for the whole new class of social services providing up-to-date information of its users on every spot of the planet. Social network services (*Xing*, *Facebook*, *Twitter*) emerged, connecting people globally based on common interests, political opinion, etc. The strengths' and broader establishment of such services was (and is) further enhanced by rural depopulation and increasing anonymity of the individual in large (Mega) cities.

2.4 Transition to the Socially Inspired Car

2.4.1 Passive (First) > Active (Second) > Connected (Third Wave)

The evolution in automotive assistance systems started some 50 years ago with passive safety systems (first wave) to survive accidents and continued with technological advancements with active safety systems (from the old-style antilock braking system (ABS, 1978) to modern collision avoidance systems) to prevent crashes (second wave). The third wave referred to as V2V/V2X communication started some years ago pushed by projects such as PReVENT (PReVENTive and Active Safety Applications), NOW (Network On Wheels), EVITA (E-Safety Vehicle Intrusion Protected Applications), CVIS (Cooperative Vehicle-Infrastructure Systems), etc., and the CAR2CAR Communication Consortium. (Network) communication was established with built-in GSM modules and V2X/V2V was promised to offer huge potential regarding improvements in driving safety, comfort, and much more. Unfortunately, services based on V2V/V2X were mostly realized as manufacturer specific applications such as remote inspection, phone based control of the auxiliary heating system, mileage based car insurance, later also to share information and media, play network games, and chat between cars.

On the other side, however, the past few years were finally dominated by the broad emergence of wireless communication (IEEE 802.11p/WAVE) which led to Internet connectivity at reasonable cost even in the automotive domain. Nowadays almost each new car is connected to the Internet – the transition from formerly independently acting drivers and cars to connectedness with 'the rest of the planet' has taken place. (Even if the coverage of wireless vehicle communication technology on a global scale is, according to [25], still some years away, this is mainly a technological issue and actually will happen.)

Back in 2010, IBM conducted a survey of drivers in mega-cities around the world [26]. Thirty percent of the more than 8,000 respondents reported increased stress from traffic, 27 % increased anger, and 38 % reported having canceled a planned trip due to anticipated high traffic. The numbers are not really surprising – we all know from our own experiences that traffic density and likelihood (and duration) of jams has considerably increased in the past decades. The question is now, however, what needs to (or could) be done to resolve this issue? Its not just to add another lane to the 5-lane interstate or to build a new road. It is also not to change over to hybrids or electric vehicles or to make public transportation or other alternative ways of traveling more appealing. These all are small steps toward more efficient traffic, but with expected impact only for the short term. After a while the improvements are most likely compensated or even overtaken by the further growth in mobility (i.e., increasing number of licensed cars). As a direct consequence from more cars on the road and also a expected change in the use of the car (increased use for social activities [27], more flexible working schedules, leisure activities), traffic will become increasingly busy and traffic will also be distributed more evenly over time. This means the "off-peak" hours between the rush hours in the morning and afternoon will increasingly fill up. It is clear that, when so much traffic has to be accommodated, the potential for conflicts will also rise. From these numbers, and by using existing traffic control/steering technologies, we can extrapolate that the daily commute will get worse in the next time – completely new steps are required to tackle this problem.

According to [26] technology can help. Due to recent advances in wireless communication, road sensing infrastructure, and data processing capabilities we are now capable of collecting data from moving vehicles in real time, and relate it to traffic conditions sensed by induction loop sensors integrated into the road or overhead cameras. By merging all the data in intelligent traffic management centers (TMCs) and using complex analytics we can understand large, complex systems of transportation networks. Large volumes of data can be used for predicting upcoming traffic hazards and allows for active management of the transportation networks by using, for instance, intelligent transportation systems (ITS) such as traffic steering intelligence (TSI) to keep people moving more efficiently [28]. Globalization has also found its way into the transportation domain and the vision of a global traffic management system is not that far away.

Another proposal to speed up traveling was made by Wegman et al. [27], who have argued to separate the infrastructure for freight transport and normal cars. Their recommendation is based on the fact that freight transport vehicles are moving by far slower as compared to normal cars. The situation is even worse on a motorway where one lorry overtakes another, blocking the whole road for all the following vehicles. By separating the infrastructure for these two means of transportation the problem could be solved and the average traveling speed of 'normal' vehicles should increase while at the same time the travel speed should get more harmonious. As a consequence, traffic should become more efficient by reducing fuel usage caused by stop-and-go traffic (i.e., brake/acceleration loops).

To get further insights into the potential and difficulties of connected vehicles on large scale, the National Highway Traffic Safety Administration (NHTSA) in the U.S. has launched in summer 2012 a real-world test involving nearly 3,000 cars, trucks, and buses using volunteer drivers in Ann Arbor, Michigan [29]. According to this report, vehicles are equipped to continuously communicate over wireless networks, exchanging information on location, direction, and speed with an update rate of 10 with other similarly equipped cars within in a range of about 300 m. A computer analyzes the information in real time and issues danger warnings – for example on impending collisions – to drivers, often before they can see the other vehicle. Even if restricted to a relatively small area, e.g., around crossings or roundabouts, such a system could offer ways and means to prevent road accidents and make driving safer. However, in the end it will a lot depend on how drivers respond to the warnings – and the Ann Harbor test should find answers to this issue.

To force safety, more advanced versions of V2V systems could take over control of a car by applying brakes when the driver ignores or reacts too slowly to a warning. But a broad application of sort of auto pilot might also be criticized by the public as drivers would most likely not be willing to accept restriction in personal liberty. Another issue to consider is, that once traffic is fully under control of computer systems and network communications, the potential for hacker attacks and/or intruders rises. Imagine, for instance, an add-on device installed in the car and sending a false signal to all cars within reach, stopping them so that the user can drive through empty crossings without waiting times, or more dangerously use the device to induce mass collisions at crossings. Another nightmare scenario would be the targeted control/generation of gridlocks from everywhere at the planet and at important traffic junctions to support e.g., escape after criminal activities.

2.4.2 The Next Wave: Socializing Cars

With increasing and everywhere connectivity and emergence of Internet-enabled mobile devices such as cell phones, PDAs, Smartphones, iPad, etc. some years ago the floor was opened for the whole new class of social services providing up-to-date information of its users on every spot of the planet. Numerous social network services emerged, connecting people globally based on common interests, political opinion, etc. Looking into the vehicular domain, these days more than one billion of cars are in operation worldwide according to a study released by [30] (2009: 965 millions) and it is estimated that the actual stocks will further increase to more than two billion cars in 2030 [31] (with main growth shifting from industrial to BRIC countries [32]). This is actually more than the number of active users of Facebook, which was 901 millions in March 2012. This offers tremendous potential for social services in cars, but might also be the source for additional distraction. What we discover in vehicular interfaces today is a still increasing number of sensors and actuators, more and larger displays, and – enabled by Internet availability and content stored in the *cloud* – feature-rich applications (‘*Apps*’) that have found their way into the car; the driver is more and more unable to cope with all this information. To counteract issues such as high mental demand, cognitive overload, performance losses, etc. the current research trend is coined by the catchwords “social intelligence”, “social signal processing” – the ability of a system (or human being) to understand social behavior and manage social signals of an interacting person, and the like. In the long tradition of human-computer (and driver-vehicle) interaction, computers have been socially ignorant – they have not accounted for the fact that humans decisions are always socially inspired [33]. Next-generation computing and automotive interfaces need to include the essence of social intelligence to become more effective and safe [33]. Therefore it is to be questioned why not should the ‘car’ relieve the ‘driver’ by taking over some tasks and accomplish them as efficiently as the human driver by application of social intelligence? With socially behaving cars we mean social inspired services beyond Facebook & Co. that creates true value for the information provider. (Up to now, Facebook users provide status information, social status (feelings), and much more (photos, etc.) to all the users in their network; but they do not get benefit out of it – what is the worth of yet another “friend” in the network (which you have never met or talked to before) or another “I like it!” to a written comment?)

This trend (called the *fourth wave* in the evolutionary history) will, on top of communication technologies, continue with the integration of social capabilities into mass traffic, allowing cars to automatically resolve conflicts, negotiate with each other, behave as a collective to optimize characteristics such as driving time/efficiency (e.g., waiting time in traffic jams), road charge to pay, to address the topic of environmental protection (i.e., reduction of fuel consumption or CO_2 emission), to raise safety on the roads on a global scale, to increase driving pleasure and experience, and much more.

Thinking of more complex scenarios (see also use cases below), it would be possible, for instance, that cars, other road participants, and infrastructure within a network exchange information such as “throttle down, red light ahead”, “attention, pedestrian intends to cross at the crosswalk” or “don’t make the turn, oncoming traffic is too fast”. Another application, extensively studied in our own simulation experiments [34, 35], is a kind of recommender system based on global traffic information, letting drivers know when the change from one lane to the other is desired, at which point in time and at what level of speed it is considered best to enter the motorway on the entrance ramp, or when overtaking is unsafe because of oncoming cars on the main road. Similarly, and as described in the *overtaking*, *backout* scenarios below, information about cars around a curve or behind other obstacles that the driver can’t see yet, could be delivered to a vehicle (and/or the driver), and used to adapt steering behavior.

By using on-board sensors, connected vehicles could also issue warnings about potential dangers to other cars behind. To detect potholes a simple accelerometer from the Smartphone or on-board computer can be used [36] and (concerted) deviations in the steering angle or GPS position should provide an indication of an obstruction on a otherwise straight road segment. If a vehicle at some distance ahead applies the brake hard a system alert can be issued to all the cars behind to avoid (mass) rear-end collisions and a “slippery road surface” warning could be relayed to all drivers in a certain region if at some point, e.g., on a bridge ahead, several cars have applied their brake during the past time (recognized by a sensor in the power brake unit) and at the same time the CAN bus provide information that traction was lost. Depending on the outside temperature this might have been caused by road ice or oil slick. All these ‘static’ information can be used, if centrally collected and processed, by traffic management centers (TMCs) to increase safety, improve road throughput, express recommendations for alternative routes, and much more.

In this book chapter we are basically not addressing social interaction between drivers (e.g., using Facebook on the Smartphone or in-car display while driving

[37]), but are rather focusing on the automotive domain as one field with huge potential on enabling social interactions. As like for humans, it would be relatively easy for a car to provide status information all the time (location, speed, driving destination, etc.) using on-board information systems, navigation device, and GPS information. Furthermore, it would be possible for the car to exchange sort of social information (e.g., feelings and emotions) by taking information from diagnostics systems such as engine control unit (ECU) or powertrain control module (PCM) into account (error codes, condition of engine, clutch, etc.). (Last but not least could also the mental/social state of the driver be determined and used for car status adaptations). Some issues to consider might be:

- A car's social status update might be used for other, friendly, i.e., cars in same vicinity, same route or destination, similar driving (= driver) behavior, etc., cars to receive information such as a speed warning on icy road ahead, reroute recommendation on traffic jam or blocked route, etc. or to ease car sharing concepts or car pooling service (same route).
- A social car would require a social environment (intelligent roads with dynamically changing lanes; road signs adapting to the driver, etc.); one step further: social cars are not feeling well on the absence of other social cars (similar to human individuals; they cannot survive in isolation without other humans).
- Capabilities of social cars: (i) "**learning**", e.g., a jam every workday in the same region and at the same time can be learned → the car would recommend an alternative route (in particular relevant for drivers using a rental car in an unknown area) and (ii) "**remembering**", road sign with certain speed limit + cold temperature outside (i.e., ice on the road) → even when adhering to the speed limit it is most likely that an accident would occur while cruising through a sharp turn; this fact should be remembered for the next winter (cross linkage to "learning"?: → next time in this situation: further slow down in order to drive safe) ("Route Buddy", "Sensory Bubble" concepts [37, 38]); (iii) "**forgetting**", (consider the same situation as before) in case an accident happened, forget about that incident after some time (e.g., after the winter has passed); this social behavior should avoid a car to be fearful and drive too slow in summer times (dry tarmac, temperature $> 0\,°C$).
- Speed-safety curve, i.e., slowing down to 0 km/h does not increase safety to 100 %. Quite the contrary is the case for example on motorways: driving too slowly increases crash risk significantly.
- "Smart road concept": Dynamic reconfiguration of the road network, for example, by changing lanes per direction inbound/outbound depending on time of day or road usage.
- "Smart signs concept": changes the maximum allowed speed based on the context; reduces maximum speed on approaching novice driver or increases the same when a professional driver is in close-by; a "overtaking denied" message is popping up on a detected lorry or jam etc. in the curve ahead, "overtaking permitted" can be shown even on poor visibility if the sign detects no other car in that area ("Intelligent Traffic Guide" concept [37, 38]).

3 History of Mass Traffic

3.1 Sustainability of ICT in Disconnected Cars

Road traffic has grown over the past 125 years in an almost uncontrolled manner leading to different concepts of road networks with junctions, roundabouts, different categories of roads, etc. where vehicles are moving either on the right-hand or left-hand side of the road in a non concerted fashion. This (on a global scale) chaotic behavior has led to the traffic we observe today with only minor efforts put on radical improvements. With globalization, more and more cars on the road, more flexible patterns of use of the individual vehicle operator, etc., time has come to apply improvements on the large scale.

Solutions to large scale traffic problems offered today are rather shortsighted and far from optimum. To give an example, on detected traffic jam the personal navigation device (PND) automatically calculates and proposes a alternative route. The problem is, however, that the rerouting algorithm works equally in all navigation systems at least of a certain manufacturer and all the cars equipped with these devices are recommended the same diversion route. What happens in the end is, that a "new" traffic jam emergences on the detour while on the main route it is possible to drive through without any problem. Much better would be a common decision making and a negotiation which car goes where, maybe based on incentives, to establish kind of load balancing on all the roads. This could be achieved by a kind of "collective brain" gathering input from all the cars in a common area of interest and featuring common decision making and negotiation on the route or lane taken by each individual driver within the collective (e.g., all the cars in the same city, all cars on the motorway driving in the same direction or with same destination). Of course, this includes also the control of traffic lights, speed limitations, and traffic signs to optimize and steer the traffic flow. A further expected impact is that sort of collective understanding of the traffic situation together with a concerted behavior modification of drivers should have the potential to enable improvements such as reducing global fuel consumption or CO_2 emission.

A prominent example is UPS and the route planning technology it uses to deliver packages. UPS learned through time studies that avoiding left-hand turns saves time, conserves fuel, lowers emissions and increases safety. Since 2004, UPS has rolled out technology that automates the process for minimizing left-hand turns, and UPS managers combine personal and historical experience with computer programs to design delivery routes. With this strategy UPS saves about three million gallons of gas per year [39, 40]. Minimizing left turns is actually fuel-efficient in a couple of ways: In 2011, NC State University conducted a study to determine whether "superstreet" intersections result in faster travel times. (At a "superstreet", all left-hand turns from side streets are re-routed so that drivers must turn right and then make a U-turn.) Researchers found that compared to conventional traffic designs, superstreets reduced travel time by 20 % overall. As travel time is almost proportional to fuel use, such a strategy could save lot of money (and also CO_2

emissions). The reason for this huge effect is that at some intersections the delay for left-turning vehicles is so long that those drivers will save time and gas by finding some other way, such as making three right turns [41].

3.2 Social Factors in Mass Traffic

Vehicles on the road may have become ‘smart’ during the last time, but unfortunately they are dumb and have to be controlled by an individual. Each and every individual (*the driver*) has its own personality and the internal state of a driver changes by different reasons from one moment to the next. This is a source of unpredictable and unsafe behavior. Legislatory regulations and traffic control can prevent danger caused by alcohol, drugs, maybe fatigue but there are other sources that (temporarily) influences the normal competence of a driver that might not (yet) be detected (e.g., stress or rage). The current mental condition of a driver together with the actual driving situation determines how capable a road user is to cope with the task requirements [42]. For safe traffic participation, the task capability of a driver must be sufficient to cope with the task requirements. To ensure this, a driver has to assess its own task capabilities (*state awareness*) and adapt it correspondingly in order to meet the actual requirements. The latter are determined by environmental factors that can be sensed, and the driver in order to drive safely should self-adapt (e.g., by driving faster or slower) to the situation. “Driving safety” is however also a fuzzy parameter that requires reasonable *risk assessment* by the driver (which cannot be taken as given at all times and for all traffic participants). Advances in sensor technology has alleviated the detection of driver state and ITS have enabled to inform other road participants on detected deviations.

Another factor that might be considered is (social) *forgivingness*. Traffic is a social system in which humanoid road users interact with each other and where it is important that they allow for each other’s shortcomings – but not by any means: errors must still be recognized as ‘wrong’ so as not to lose the corrective effect. If forgivingness in traffic (or “the willingness to anticipate a potentially unsafe action by another road user and to act in such a way that negative consequences of this potentially unsafe action are prevented or at least limited” [43]) is established, more competent road users could allow, for example, the less competent road users to commit errors without any serious consequences [44]. In order for a (willing) driver to be capable of acting with social forgivingness he/she must (i) have the correct expectations of the situations he is in, (ii) be capable of assessing the intentions of other road users correctly, and (iii) have the capacity to adapt his own behavior. The *willingness* to act in a socially forgiving manner is often influenced by external (traffic) factors, such as for example the length of the green phase on a traffic light on a busy junction (if the light turns green only for a very short time, the willingness of a driver to act with social forgivingness would most probably be low too).

3.3 Socializing Cars: Implications from an Online Survey

The research presented in [37] compares the state of the art of drivers' current in-vehicle technology use and investigated their needs and wants for plausible new vehicle area network (VAN)services.

Regarding the **ownership of the car**, our survey found out that most of the vehicles driven are owned by a single person (the driver) or are family (Austria: 97 %, US: 90 %, South Korea: 86 %). This has also implications on potential social capabilities used in the car. As they are family run, it would be much easier to connect the vehicle behavior to the driver(s) and to configure it based on driver's preference, as compared to rental cars with day by day individual drivers, and thus much harder assessment and use of a car's behavior or recommendations. One of the most salient differences in our survey came from the **type of transmission**. Ninety-six percent of Austrians used manual, whereas 76 % of Americans and 83 % of Koreans used automatic transmission. This finding itself is not unexpected, however, the implication it has on the car use, the driving style, or the workload required for vehicle operation might affect the use and perception of innovative in-vehicle technologies or social services.

Another important finding of the survey is that **drivers' mental capacity and conditions** depend heavily on the presence of passengers. Passengers can on the one hand collaborate on a driving or secondary task and reduce the driver's workload, but can on the other hand also distract the driver with non-driving related conversation, use of multimedia appliances, etc., which potentially generates a negative effect on a driver's affective states. Coming back to the study, the majority of the respondents answered that they have "sometimes" one or more passenger(s) (Austria: 53 %, US: 76 %, South Korea: 44 %). Specifically, only a few participants answered "always" (Austria: $n = 1$, US: $n = 0$, South Korea: $n = 2$), which lets to implicate that a **car is often a private space** and thus, in-vehicle technologies may need to be personalized in terms of not only physical fit, but also interior setting (ambient light, temperature, entertainment system configuration), navigation setup, etc., just like for smart phones.

One of the first applications proposed for network of cars was "**car pooling**". As in most cases a driver would not know who is the passenger he is a giving a lift, and the person looking for a car pool does also not know the drivers, it is important to investigate how people think about driving with an unfamiliar passenger. Overall around 10 % of the respondents answered that "car pooling" is not at all desirable. On the other side, approximately half of the survey participants (Austria: 66 %,US: 45 %, South Korea: 56 %) thought the car pooling is good, but actual experience of a car pool varied much stronger (Austria: 18 %, US: 38 %, South Korea: 31 % of them). Given that interacting, socializing cars include relation to unknown others, this distinction may be a critical predictor for the acceptance rate of V2V services. Asked for why they do not want to car pool, 85 % of Austrians and 53 % of South Koreans answered simply because it is a troublesome duty and Americans mainly answered that it is hard to do because of timing or opportunity issues. (Only very

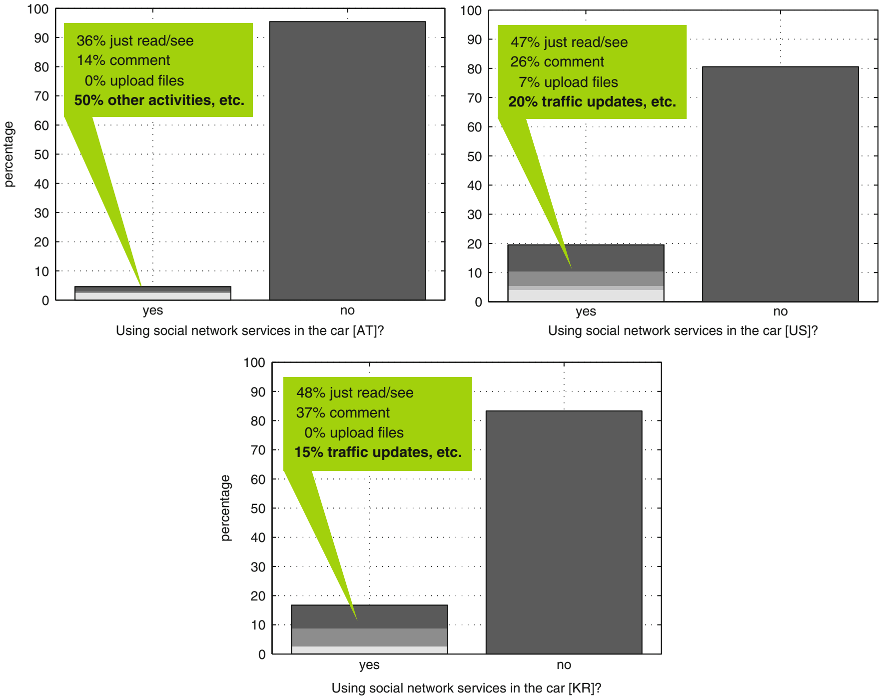

Fig. 4 About 20 % of people who use social services (AT: 62 %, US: 85 %, KR: 85 %) use them also while in the car (Austria lags behind). Basis: car usage survey May 2012, 225 participants, [72]

rare answers where given related to safety, security, or privacy issues.) The counteract the indicated problems, from the perspective of connected vehicle services an easy solution could be provided with a community-based car pool application, such as for example “Carticipate”.[1]

Regarding current use of “**social network services (SNS)**” about 85 % of Americans and South Koreans and 62 % of Austrian study participants uses them already. But only a low fraction of about 20 % (Austria: 5 %, US: 26 %, South Korea: 17 %) also do so in the car (Fig. 4). Most of the participants used multiple SNS, and Facebook was the most popular one across the three countries (Austria: 93 %, US: 100 %, South Korea: 93 %). More interesting is, however, that not only the status of a friend or a driver with same commuting pattern, etc. is tracked (Austria: 36 %, US: 64 %, South Korea: 48 %), it is rather that drivers comment on the statuses of others (27 %) or *tweet* information such as traffic updates (26 %) while operating the car. 35 % of South Koreans answered explicitly that they write comments on SNS as well in car (not necessarily while driving). This information emphasizes that driving today is likely to cause high visual and/or manual demands

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[1] http://www.crunchbase.com/company/carticipate, Retrieved November 2nd, 2012.

on a driver's resources (as predicted already 20 years back by Wierwille in his seminal paper [45]), and that it is a challenging task (particularly for the Korean market) to design in-vehicle user interfaces (to be perceived intuitively) and make interaction more safe.

One category of the survey was dedicated to (16) new **in-vehicle service concepts** (answers requested on a 5 point Likert type scale; 1..worst, 5..best). The top rated concepts are "Intelligent Traffic Guide (V2I)" (4.38), "Sensory Bubble (IV, V2I)" (4.17), and "Free Parking Slot/Parked Car Finder (V2I)" (3.72), and all these concepts are deeply related to the primary task of driving (in terms of information that they want to share with other drivers). These results clearly show that drivers are still concerned more about the primary task than other services. In other words, drivers in all three countries are still more interested in technologies that will keep them safer, instead of 'Facebook' updates. Moreover, all of the these three services are V2I, which might indicate that drivers consider vehicle-to-infrastructure services as more important and needed concepts compared to other services. When it comes to the differences among countries, Korean drivers generally tended to respond more positively than the other two countries. Overall, it seems that Koreans are open to new in-vehicle services, whereas Austrians are more conservative (or sensitive) to privacy and security issues of in-vehicle technologies. Americans seem to lie between them depending on the case.

Technology use in the car. Currently, the most pervasive use of technologies in the car involved listening to music, using phones, and navigating. In general, use of technologies mainly focused on secondary tasks (e.g., navigation) or tertiary tasks (music, phone) rather than on driving tasks. Remarkable is that 36 % of South Koreans answered that they watch video or TV in the car. In fact, watching TV or DMB (Digital Multimedia Broadcasting) in the car is very popular in Korea and most vendors provide that functionality in PNDs or telematics systems (e.g., Hyundai Motors, http://worldwide.hyundai.com/WW/Main/index.html or iNavi, http://www.inavi.com/). Interestingly, 21 % of Americans answered that they play a game in the car. People do not yet seem to do office work in the car that much (about 4 % across countries). It is not clear whether this is mainly because people do not want to do office work or the task is inconvenient to do in car, or other reasons. Asked in an open question about preferred applications/services, 28 % of Austrians answered a "speed trap" and 17 % wanted to have a "black box" (i.e., event data recorder; EDR), 9 % answered a "traffic jam warning system", and another 9 % wanted an "autopilot". Other interesting answers included a "head up display (HUD)" (Austria: 5 %) and "tactile feedback in the steering wheel" (Austria: 4 %). Twenty-one percentage of Americans wanted to have a "speed trap" and 17 % of them wanted to have a "road condition or traffic information system". Sixty-one percentage of Koreans wanted to have a "black box" and 14 % of them wanted to have "navigation related applications". EDRs or black boxes are not visionary equipment, they already exist and some vehicle manufacturer install them in their cars (EDRs are today only mandatory equipment in commercial aircraft). The result of this survey coincides with the ambition of the US National Highway

Traffic Safety Administration (NHTSA) that would like to see EDRs in all vehicles [46] and might accelerate the aim to install them nationwide.

Participants were also asked to rate their general thoughts about **vehicle-to-vehicle communications** using a five point Likert-type scale. The results showed that they were generally positive to V2V communications (Austria: 3.7, US: 3.3, South Korea: 4). Again, Korean people were the most positive of all. For the updating information methods (automatic update when available ("push") vs. update only when you want ("pull")), participants preferred in-between those possibilities, that is, specific customization for case by case (Austria: 46 %, US: 48 %, South Korea: 50 %). While Austrians generally were more conservative on other issues, around 30 % of them preferred automatic update, which is much higher than the others. Koreans showed higher preference for requiring authentication (36 %).

The top three wish list of information to be shared via V2V communications included road condition (Austria 38 %, US: 76 %, South Korea: 92 %), navigation (Austria: 28 %, US: 45 %, South Korea: 47 %), and POI information (Austria: 16 %, US: 45 %, South Korea: 56 %) while entertainment showed a relatively small portion (Austria: 7 %, US: 10 %, South Korea: 1 %). Participants seemed to **prefer sharing driving-related information** rather than non-driving data. Other answers included information about radars/police control, car information (speed, how many persons on board, child/elderly on board?, etc.), parking space information, braking info (emergency brake), traffic jams, safety relevant information (Austria), "you forgot to turn off your blinker", "your coat is hanging out under the door", etc., (USA); traffic expectation based on route data, measurement of the distance between cars, lane change (Korea). Austrians considered "privacy" (29 %) and "security" (22 %) as the most critical barriers for V2V communications, whereas Americans (62 %) and Koreans (47 %) considered "safety" as the most important factor. These differences in drivers' concerns could/should be reflected in in-vehicle services and interfaces with a different design focus even with the same functionality. Few participants considered network reliability or information reliability as a critical variable for V2V services. (It has to be noted that the large differences, in particular for "safety" and "security", could also stem from the translation of the English survey into German language.)

To recapitulate, the high dynamicity of driving coupled with plethora of information around all the time and spontaneous decisions to be taken by the driver are likely to cause additional mental load, elicit (negative) emotional stress (*anger*), and – as a consequence – alters the internal *mental state* of the driver. This has an impact on how information is perceived by the driver, as information is judged based on the current emotional state, assessed based on the character of the person (e.g., choleric/apathetic), and finally enriched with desires or specifications (e.g., how to reach a destination in time, without road charge or jam, etc.). All these factors might have an impact on the action taken by the driver and need to be considered in a model representing the driver in order to provide efficient and, above all, proper feedback and assistance. The most critical issue is to create a appropriate emotional driver model to ‘understand’ why a certain driving action is carried out, what the driver is feeling, or what he/she is expected to do next.

4 Towards Social Cars

With this section we would like to give an overview of sensor technologies and in-vehicle networking techniques available to collect information in and around the modern car. We clearly want to point out that we are here not talking about the rationale of humans while driving with assistance systems and how a driver might affect vehicle operation or and nearby traffic (at least not explicitly).

4.1 Enabling Technologies

The increasing “pervasiveness” of information/communication technology (ICT) offers means to monitor and control vehicles, the roadside, and the infrastructure in real time using, e.g., wireless communication technology (802.11p/WPAN), GPS technology for route guidance, UMTS communication for talking on the phone and establishing reliable Internet connections, advanced driver information/assistance systems (ADAS, IVIS), traffic counters/induction loop sensors to estimate driving speed, road throughput, jams, etc. The availability of all these technology has enabled the implementation of a CAS in the automotive domain. Figure 5 shows its complex structure including nested local/global loops of either implicit or explicit actions (perception or sensing, reasoning and decision making, interaction and communication, and responses or feedback). The specialty in a CAS is that all the subsystems are decentralized but following a unified goal. To give an example, cars (more precisely “car-driver pairs”) are moving on a motorway with limited field of view and variable local adaptations such as speed variation to meet traffic rules or lane changes. All the cars in a region move in the same direction and follow a global, the collective, goal (i.e., high throughput, fluid traffic, no traffic jam, road safety). In order to cope with such complex systems with highly interwoven adaptation on the local level, enabling technologies beyond state of the art need to be identified, adapted, and applied.

The principle of collective adaptation regarding a goal function (for each individual) is the ability to self adapt and the behavior of the entities in the collective (e.g., driver/car pairs for the vehicular domain) is human inspired, e.g., corresponds to the rationale of humans by perceiving information from the environment, relating the information to goals and expectations, and combine/negotiate the observations with goals to adapt the behavior of the car/driver. In each and every step, the reached state is related to the goals to achieve and compared whether or not it is closer to the goal or more far away compared to the previous state (i.e., on the right way…). A goal could be either static or dynamic, meaning that it

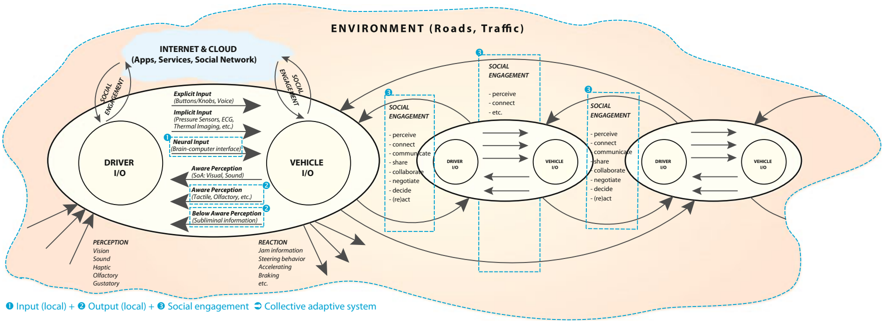

Fig. 5 A collective adaptive system for transport and possible channels of information exchange

changes over time and could also disturb the original plan, for example, when it starts raining the driver will desist from his original plan of playing golf and drive to another location, on the emergence of a disaster almost all the original goals will be dropped and replaced by a new goal "reach home/take the family/find a safe place".

To give a more tangible example, motorway merging as shown in [47] has only a single goal function, e.g., to pass the region as fast as possible (maybe "keep road safety high or above a certain threshold level" could/should be added as second goal). The process for a single vehicle is as follows (1) movement (approaching the entrance ramp), (2) decision making (decide whether or not it is safe to change to the upper lane), (3) action (perform the lane change or wait), (4) revision (now closer to the goal? here: obviously true). We have developed a model to simulate vehicle movement based on real motorway data (vehicles per lane, movement speed, lane changes, etc.), and to optimize road throughput based on the before mentioned goal (optimized/concerted behavior of all cars in the region).

It should be pointed out that collective traffic optimization does not necessarily need to be limited to road networks. Cars are moving in networks of roads/streets, but there might be higher level factors that influences the behavior of a network of cars, such as a common work place, tourism attractions, or entertainment. In addition, when thinking of cars as social entities they should behave like that. Perception/reaction should thus go beyond the current weather, traffic jam or accident reports, but also include "social" characteristics such as the aim of the drive (from home to work, go on vacation, drive to the shopping center, take a day off and drive to a Spa, etc.) as different targets would exhibit different behavior.

4.2 *In-Vehicle Information Processing*

To better understand which types of information are available in the car, and where to apply possible solutions, we start with a historical overview of information processing in the car. In the early days vehicles were controlled by mechanical and pneumatic means with almost no possibility of intervention by the driver. With technological advances, electrical sensors/actuators and first information systems emerged in the car. The first solution to cope with the rising complexity of vehicle operation was to establish simple point-to-point in-vehicle networks to interconnect the different sensors and actuators in a car with controls in the dashboard, later extended with a simple engine control unit (ECU) acting as central "server". In the 1980s the increasing number of distributed sensors, actuators, as well as the information/assistance systems in and around the dashboard disallowed the further usage of discrete wiring to connect one element to another. Efficient in-vehicle networks based on serial protocols (such as CAN, MOST, FlexRay) were developed to further afford sharing of more and more information and to manage all the resources as effectively as possible. In the 1990s, several service and assistance systems were integrated into vehicles, as for instance powertrain control modules (PCM) together with on-board diagnostics (OBD), electronic brake force distribution (EBD) system, the electronic stability program (ESP) [48], etc. At about the same time cell phones and car navigation systems found their way into the car (the first GPS-based navigation systems were offered by Pioneer and Mitsubishi Electric in 1990). Later, the whole class of heterogeneous pervasive and ubiquitous technology driven devices/interfaces (gaze control, speech interaction, haptic I/O, etc.) popped up in the car. The last 10 years were finally dominated by the broad emergence of wireless communication (IEEE 802.11p/WAVE) and everywhere Internet connectivity, connecting formerly independently acting drivers and cars to 'the rest of the planet'. These days more than one billion of cars are in operation worldwide (2009: 965 millions), more than the social network Facebook has active users (March 2012: 901 millions), which offers huge potential for services based on interconnected, socializing cars, but might also be the source for additional distraction. What we discover in vehicular interfaces today is a still increasing number of sensors and actuators, more and larger displays, and – enabled by Internet availability and content stored in the *cloud* – feature-rich applications that have found their way into the car (Audi, for example, supply customers with *Apps* via their own App Center [49]); the dashboard progressively "*mutates to a sink of condensed information*" and the driver is more and more challenged and unable to cope with all the information.

4.3 In-Vehicle Networks

In-vehicle networks facilitate the sharing of information (and resources) among the different, distributed sensors, actuators, and the information/assistance systems in and around the dashboard (Table 1). In the early times of in-vehicle communication, wiring between the devices was implemented as discrete point-to-point connections (e.g., in a star topology with central controller) [50]. However, with an increasing number of sensors and actuators to be served in a vehicle, *discrete* wiring to connect one element to another resulted in complex, bulky car wire harnesses. Beside increasing difficulty to install (and maintain) all the wire connections, the sheer

Table 1 Automotive network classifications and usability for social interaction

Network type	Class A	Class B	Class C	Class D
Speed	$<$ 10 kbit/s; low speed	10–125 kbit/s; medium speed	125–1,000 kbit/s; high speed	$>$ 1 Mbit/s
Application	Convenience features, e.g., trunk release, electric mirror adjustment	General information transfer, e.g., instruments, power windows	Real-time control, e.g., power train, vehicle dynamics	Multimedia applications, e.g., internet/ cloud computing, digital TV, hard real-time critical functions such as X-by-wire
Representative	–	LIN, J1850	CAN	MOST, FlexRay
Social capabilities	Listen	Listen	Listen, connect, react	Share, collaborate, negotiate, decide, react

quantity of wires significantly increased the weight of the vehicle, leading to a performance drop of the vehicle as well as to increased fuel consumption. (While vehicles manufactured in 1955 contained 45 m of wires, this number exceeded the 1 km limit in the early 1990s [50]. Today's high-end vehicles features more than 4 km of wiring, already realized using a serial protocol [48]). A further issue of wire length is, that the longer the length of a cable the more the voltage drops, resulting in reliability loss of sensors/actuators farther away or let them even turn out completely. Together with the voltage drop goes a decrease in the maximum bus transmission rate (for example for the CAN, the maximum transmission rate is specified as 1 Mbit/s for networks up to 40 m and is reduced to 125 kbit/s for distances up to 500 m and further to 50 kbit/s for transmissions up to 1 km). First experimental systems using either a centralized or distributed network topology emerged in the early 1980s, with the first productive system being SAE J1850 (protocol specification for class A and B networks based on GMs Class 2 and Ford's SCP protocols [50]) in 1987. Bosch started to develop its controller area network (CAN) in 1985 [50], with first implementations in silicon available from 1989 on [51]. One of the first commercial vehicles equipped with the CAN bus was the Mercedes Benz 600SEL in 1991 [50].

Vehicle data buses interconnect components inside a vehicle, the most widely used protocols being CAN, LIN, (MOST, FlexRay). Conventional computer networking technologies such as Ethernet and TCP/IP are only rarely used. The **CAN bus** is internationally standardized as ISO 11898. It is a vehicle bus standard based upon a message protocol designed by Bosch [51] (starting 1983) specifically for automotive applications (i.e., includes assurance of message delivery, assured time of delivery, EMF noise resilience, redundant routing, etc.). The protocol that allows microcontrollers and devices to communicate one with each other within the network without a dedicated host controller was officially released in 1986 by the Society of Automotive Engineers (SAE) (standard SAE J1979, equivalent to ISO

15031-5), and built from then on by diverse chip manufacturers. The current specification CAN 2.0 was released by Bosch in 1991. According to [52], a modern upper class vehicle is a distributed control system in which thousands of signals are exchanged by up to 70 ECUs. To reduce costs for cabling the different distributed nodes on the one side, on to allow new (intelligent) sensors and actuators to be added at a later time, all of them are inter-connected via a modular, scalable network. Today, the CAN bus standard is used for connecting all the different electronic control units in vehicles, such as, for instance, engine control unit, transmission, airbags, antilock braking system (ABS), automatic cruise control (ACC), etc. On different buses (see below) also the door locks and windows, climate control, seat control, audio systems, mirror adjustment, battery and recharging systems for hybrid/electric cars, etc. are connected with the CAN network. Some of these form independent subsystems, but communications among others are essential. A subsystem may need to control actuators or receive feedback from sensors. The CAN standard was devised to fill this need. CAN bus is one of the protocols used in the **on board diagnostics** (OBD, OBD-II) standard and OBD-II parameter IDs (PIDs) are codes used to request data from a vehicle, used as a diagnostic tool. SAE standard J/1979 defines many PIDs, but manufacturers also define many more PIDs specific to their vehicles. The OBD-II standard has been mandatory for all cars and light trucks sold in the United States since 1996, and the extended EOBD standard has been mandatory for all petrol vehicles sold in the European Union since 2001 and all diesel vehicles since 2004 [48, 53].

The **local interconnect network (LIN)** is a cheap and slow speed serial network protocol used for communication between in-vehicle components that do not require high bandwidth, such as door locks or power mirrors. It was very popular in times where the CAN bus was too expensive to be used for every component in the car. LIN (Table 1) is implemented as master (microcontroller) with typically up to 12 slaves. In modern cars LIN has little significance, might be used for small, local sensor networks that are connected to the CAN (or any other back-bone network).

FlexRay is a recent flexible and fault-tolerant protocol for communication in distributed systems within the automotive context. Its flexible network topology (star or bus topology or combination) features scalable fault-tolerance [54]. FlexRay enables communication with up to 10 Mbps and is expected to replace CAN in the future [53].

Media oriented systems transport (MOST) is a protocol used for the transmission of streaming data (e.g. analog/digital audio and video from the entertainment system) and other packet-based data such as information from the Internet. The MOST cooperation was founded in 1998, and it has been commercially used since 2001. MOST can provide nearly 25 Mbps over optical fiber [55].

4.3.1 Driver Monitoring

The success of socially aware, large scale traffic systems depends also on reliable driver monitoring and behavioral analysis. This includes new sensor modalities/technologies for implicit input, sensing of the physiological state of the driver, but also models to accurately analyze and interpret the data including noise reduction and outlier detection functions, and optimization of sensor placement to optimally detect interesting features. With respect to this problem field, we have long time experience in prototype development and testing in the wild. For example, we have experimented with sitting posture detection and activity recognition systems (“PressureSeat”), have studied the influence of ECG on drivers mental states [56, 57], have compared the influence of different notification channels on reaction time [58, 59], or the usability of diverse gestural interfaces to support the driver [60, 61]. Recently, we developed a prototype for a three-dimensional guidance system for the driver, composed of a glove with integrated 6-DOF positioning sensor technology and vibrotactile actuators. The purpose of the “DriverGlove” system is to guide a driver’s hand to point-shaped hidden spots in 3D space without distracting from the main task of driving. Such a guidance system can make it possible, for example, to deploy a dynamic, user configurable “command center” with virtual/hidden control elements, thus to clean up/slim down the dashboard to the most important controls, and to move all the other controls into the open space within right hands reachability. Furthermore, we have spent lot of resources on looking on the impact of ambient intelligence (AmI) technology on driving behavior [34, 62, 63].

Given all the sensors, technology, and data available, a lot of scenarios could be developed for using them to influence road traffic (Table 2).

- CAN bus data (speed, rpm, brake pressure, CO_2 emission, position of accelerator pedal, etc.) together with precise GPS position, the communication stack (history of vehicle-vehicle communication, Internet use, cell phone use, etc.), and authenticated driver (social security number, age, gender, experience) can be used by insurance companies to calculate a risk based insurance rate or by the government to collect taxes based on personal carbon dioxide profile. In case of an accident, the course of events can be reproduced or replayed, and the culprit(s) can be ambiguously identified.
- By detecting the current workload or the free capacity of the driver (mental state, level of arousal, attention detection using ECG/EEG/pressure/etc. sensors or thermal imaging), the in-vehicle information systems can be automatically adopted to only show a certain amount of status indicators, or to limit the possibility for vehicle-vehicle communication (if involving the driver) or to prohibit incoming calls (except for emergency calls).
- As already stated before, this day more than one billion cars are running on the planet (in comparison to Facebook which has exceeded 900 million users in spring 2012), and all these cars have a unique engine serial and vehicle identification number equal to the MAC address of a computer. This allows for vehicle identification in a network of connected vehicles. In addition, a history log (errors in the engine, other in-vehicle messages, visits to the car workshop and inspection work performed, etc.) is stored in each and every car, or at least in the databases of car manufacturer. That’s why manufacturer these days knows exactly what the driver is doing, when, where, and why a car was in the garage and what was repaired, etc.

Table 2 Components of social engagement and technology coverage

Social component	Required bandwidth	Technology (in the car)	Technology (Outside the car, e.g., infrastructure)	Availability
Listen/sensing	Low speed, serial, fault tolerance might be required	Any in-car sensor (LIN, CAN, MOST, FlexRay)	Environmental sensors in the car (RDS, outside temp.), soft sensors (internet weather service), cloud services	Fully available
Information filtering	None (on-board processing) or GSM/internet connection	ECU (or add-on processor)	Raw data upload to central/cloud services and processing (filtering)	Fully available
Analyzing	None (on-board processing) or broadband GSM/internet connection	ECU or special μC	Central/cloud services; processing of local/individual and collaborative data	Fully available
Connect	Depending on the service rather low	OBD or other in-car interfaces (car-driver I/O)	WLAN 802.11p, GSM, VANET [74], satellite communication	4 G (Mobile WiMax, advanced LTE); requires infrastructure replacement, but will happen before 2020 (between 2012 and 2015(?))
Communicate	As before; requires reverse channel	As before	As before	As before
Share	As before; higher bandwidth required	As before; C2C specialty: emergence of vendor specific networks (central server, dedicated clients)	Increasing use of cloud services	As before
Collaborate	Depending on the service medium to ultra high speed (real time interaction!)	New controls and dashboard design required; HUD as standard equipment	Emergence of new concepts, e.g., Stigmergy and others (see “Use Cases” below)	Problem (in case of Stigmergy) of where/how to post a note; how to read out; how to define (technically) the influence zone (ZoI)?

Negotiate	As before; requires to include ECC and trusting mechanisms	Voice/weight of an individual driver? Single entity (vehicle) decision based on what rule set?	Decisions on global scale (how, what; recommendations/ liability)	In-car technology to ensure security and trust
Decide	As before	Objections (from local driver)	Objections (global system on disregard of individuals)	Possibilities for intervention
(Re)act	Low bandwidth but real time behavior (overrule)	Manually (the driver), automatic (the car: power steering+, etc.)	Global control/surveillance? (1:n connection; in case of problems connection needs to be established fast, few milliseconds delay might cause disasters; better: continuously maintained; hand over to next control center (hand shake))	Separate highly secure connection channel

Beside pure technology coverage, it has to be noticed that social engagement and socially inspired interaction is always context sensitive and furthermore needs to talk about issues such as security, safety, etc.

5 Prospective Use Cases

A traffic light (jumping to red on one street, and to green on the orthogonal route) might be a simple trigger for the emergence of collective driver behavior. All the drivers approaching the road crossing would immediately know what this activity means and reply with a corresponding (re)action. The one facing the red light would apply the brakes and stop in a way to avoid rear-end collisions and other hazards, drivers on the other street would accelerate and pass the crossing safely. The conflict resolution/negotiation is (usually) working even in extraordinary situations, for instance when an emergency vehicle is going straight over the crossroad. With the concept of socially enhanced traffic, similar behavior should be rendered possible in future driving considering more complex situations, involving more distributed vehicles, and with social behavior of humans transferred to their cars to achieve objectives on global as well as local levels (see also Table 2).

In the following, a number of concrete example scenarios are outlined to better accentuate our approach of socially inspired traffic and the potential its application might have on future traffic. We start with a easy to follow collective information discovery system, and introduce then step by step more complex scenarios such as traffic shaping, collective negotiation, electronic signage, or distributed information maps.

5.1 Collective Information Discovery

A basic concept of socially inspired vehicles might arise from collective information discovery while on the ride. Vehicle parameters such as speed, steering angle, brake pressure, etc. are continuously monitored, processed, and forwarded to a cloud service. In order to provide reliable service, the software has to filter out false positives using a series of algorithms. Of interest are any services (*Apps*) that warn or inform from certain problems on the road that might cause accidents or car damages, such as potholes, road works ahead, traffic jam, ice on the road, etc. The first two items are more or less static while the latter requires fast adaptation and information to be delivered to the user in (almost) real time. Take, for example, a pothole detection application (in this case, false positives might be things like manhole covers, train tracks at railroad crossings, or speed bumps) aimed at supporting the driver in getting aware of possible hazards. (A different service could be used by the road maintenance authority to systematically repair all the mapped potholes.) Potholes are known to be potential safety defects that risk

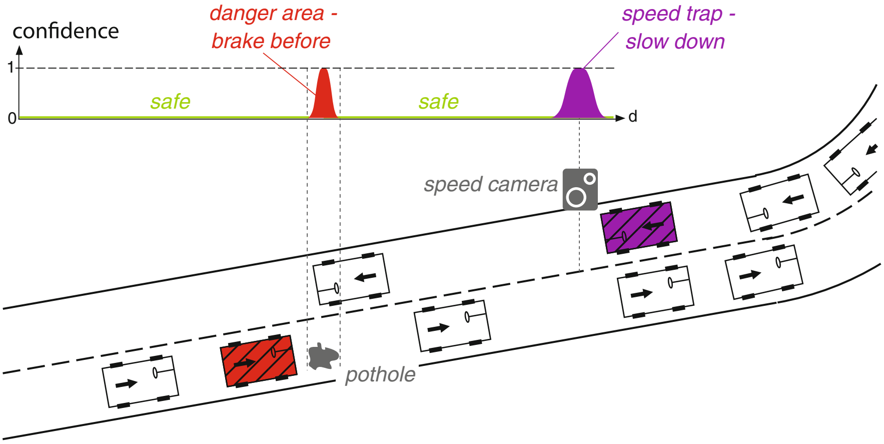

Fig. 6 Collective information discovery: frequency of braking on or before a certain point can be used to warn drivers about potholes or speed cameras

causing accidents or at least car damage if not observed in sufficient time by the driver [64]. Drivers run the risk of losing control of their car or blowing out a tire when they drive over these potholes, making them to one of the top causes of car accidents [65]. To give a concrete example, in 2005 the state of Michigan had more than 7,500 pothole related damage claims filed against it [66]. From this review it follows that such a service is badly needed to continuously increase overall road safety (Fig. 6).

There is already some work ongoing in this field. A ‘pothole detection app’ for phones has been proposed back in 2008 [66]. The system used GPS and accelerometer data to assess road surface conditions. Using accelerometer data (i.e., mainly from the z-axis) lead to several problems, for example, sunk-in manholes with eroded edges or borderline expansion joints on bridges generated mistakenly a pothole detection. Another similar *App* called “Street Bump” is tested these days in the Boston (US) municipal area [67]. Both systems require, before starting a trip, to launch the app and place the phone on a steady position inside the car. In “Street Bump”, confidence for a pothole is reached if at least three people hit a bump in the same spot. Another interesting and innovative device has been launched as the “Coyote system”.[2] It is sort of (standalone) social enabled service that allows to “see” Coyote users (scouts) in the vicinity, and to push information implicitly (traffic jam is automatically derived from zero speed while on the road) or explicitly (such as location of speed cameras; has to be initiated manually with a button press on the device). Satellite technology is used to instantly provide traffic light and fixed/mobile speed camera locations, warn about speed limits, traffic incidents, or nearby school zones, etc. (Fig. 7). A built-in GSM/GPRS Modem constantly

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[2] http://www.coyotesystems.co.uk, retrieved October 29, 2012.

Fig. 7 The "Coyote" socially enabled driver support system

communicates with the Coyote server to obtain right information at the right time (based on vehicle location and movement speed).

The class of systems/applications proposed in this work does not involve or require a (smart)phone or any other extra device for data collection, transmission, and user notification. Data gathering is done fully implicit from in-vehicle or environmental sensors delivered e.g. via the CAN or any other in-car bus, and is transmitted via a Internet connection to the cloud service. Each individual driver can set up the threshold confidence level above a information/warning is "displayed" (depending on the importance of the information, via symbol in the dashboard, audio icon, tactile feedback in the seat or steering wheel, or any other attentive or non-attentive source). Technically, and in particular for informational items that changes rapidly, a approach known as "Stigmergy" (see 1.2 Emergent Behavior, Table 2) could be used to deliver the information to the driver.

5.2 *Traffic Shaping*

The idea in "traffic shaping" (Fig. 8) is that the individual lanes in multi-lane roads could be grouped based on demand (altered most likely by temporal condition; could also be adapted in case of accident/jam in the surrounding, special events (concerts) or on the start of the summer holidays). Such a dynamic reconfiguration of the road network is technically already feasible. 'Real' road painting on the streets could be replaced by augmented reality overlays in the vehicle's windscreen, e.g., by applying the concept of "head-up displays (HUD)" (think of full windshield coverage) or by using special add-on devices such as "Wikitude Drive" (a fully functional mobile AR navigation system with global coverage and light weight turn-by-turn navigation), Fig. 9.

5.3 *Collective Negotiation: Filter into the Stream of Traffic*

Consider a situation where two single lanes are merging into one lane as indicated in Fig. 10. In order to increase throughput or traffic fluidity (a important demand in times of high traffic), a optimal merge of vehicles approaching the merging point

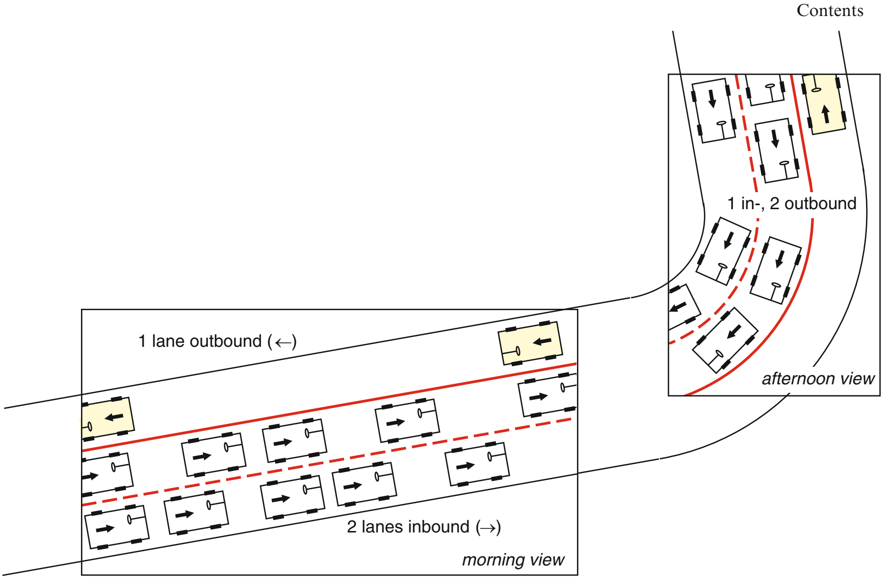

Fig. 8 Concept of "traffic shaping": dynamic reconfiguration of road network, e.g., 2:1 (inbound, outbound) in the morning, 1:2 in the evening

Fig. 9 The "Wikitude Drive" application overlays video captured through the camera with driving instructions and virtual road painting

via these lanes should be achieved by letting cars pass in an alternating manner I (left scenario in the figure). The optimization problem could be solved best by a collective adaptive system (CAS). Based on sensed vehicle data (location, speed, inter-car distance/headway) in a certain region, the negotiation routine could provide information on when to merge/how fast/etc. to the different cars (drivers) but could also be used in a autopilot mode where it takes over control of the car, adapts driving speed and inter-car distances in order to merge without hard braking/ acceleration actions and by keeping road safety high. Beside on merging ramps of motorways (where traffic on the on-ramp and rightmost lane on the main road have to merge into a single lane), such a scenario can also be found in real driving in roundabouts. Roundabouts are important to consider, as more and more are built instead of traditional street intersections (alone in the US, about 1,000 roundabouts have been built recently). This is motivated by the fact that they produces a 65 % average drop in vehicular delays, are more aesthetically pleasing, and cost much

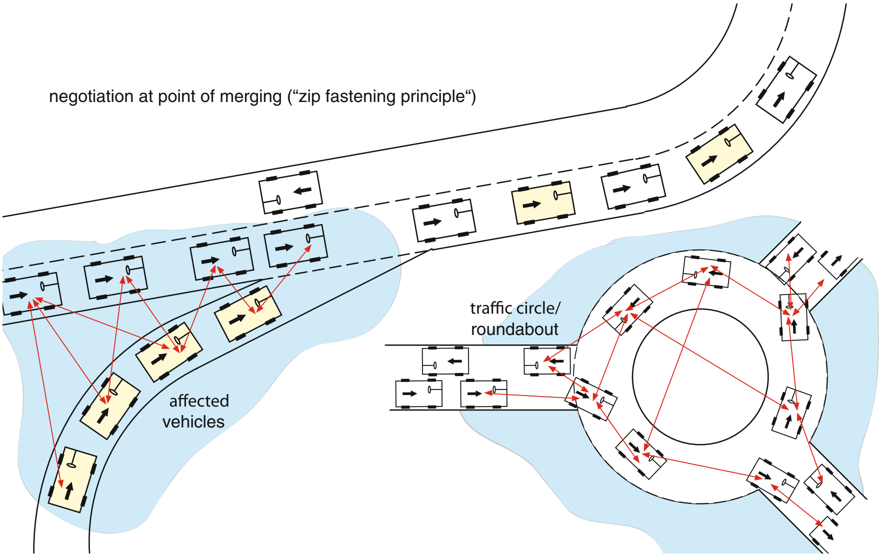

Fig. 10 Social behavior of negotiation/adaptation in a collection of cars (Adapted/extended from [73])

less to construct than stoplight intersections. The problem is, however, that drivers are anxious about merging with roundabout traffic [68], but this could probably be addressed by technology.

5.4 *Electronic Signage: Full Augmented Reality Driving*

The vision for the future is that road signs, traffic lights, etc. are disappearing from the roads. They are no longer required as augmented reality overlays (using a kind of head-up display covering the entire front windshield) would show all the relevant information (and maybe much more than what can be found at roads today) to the driver. For the long term, also road paintings and lane markings would no longer be required; robust, precise, and sophisticated telemetry systems together with AR overlays would safely guide the driver (and hides, dependent on the measured workload level, a larger or smaller fraction of driving unrelated information). The technology is, in general, available today (see for example the "Wikitude Drive" application [69]; Fig. 9) but still, current road markings, traffic signs, and traffic lights etc. will remain on our roads for a longer time; not to support the driver or provide additional information, but as markers that are being used by currently established driver assistance systems such as the lane departure warning (LDW) system and others that uses road paintings to detect deviations from the (optimum) track. Despite the flexibility of such a system, a full "electronic signage system" poses also several problems, for example regarding traceability. If you receive a

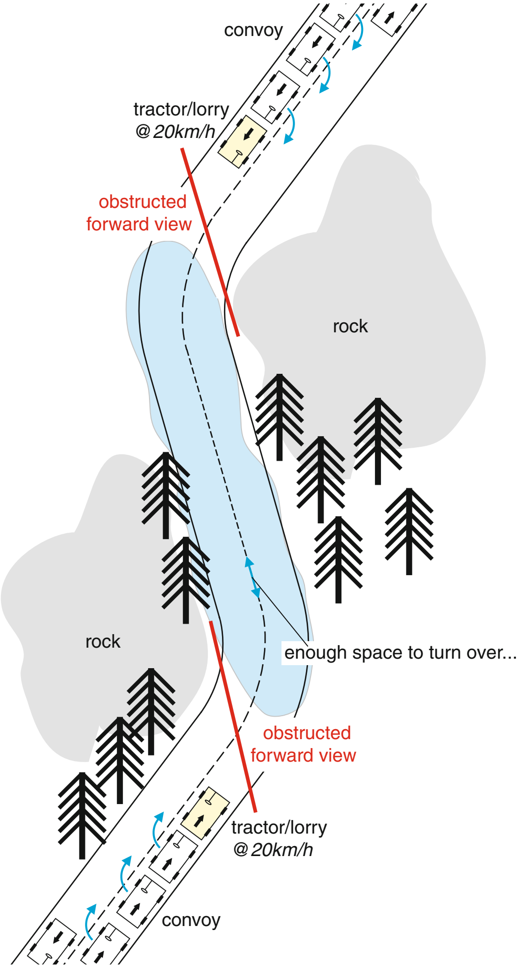

Fig. 11 Extended forward view and negotiation allows for overtaking in situations with limited/no sight

speed trap fine, how would it be possible to provide evidence that there was a speed limit announced and which was the maximum allowed speed? Even more critical are "virtual traffic lights". On accidents at a road junction, how to find out who's traffic light showed 'green' and who's showed 'red' color, or who was allowed to drive into the crossing and who not?

5.5 *Overtaking with Obstructed Forward View*

The overtaking situation outlined in Fig. 11 is one that appears frequently on intertwined roads. Consider a two-way (rural) road with single lane per driving direction and a lot of winding curves; the general speed limit of the road could be in the range 80–100 km/h. As shown in the figure, there is obstructed forward view in both directions caused by rocks, trees, etc. along the road. Given the case that, for example, tractors or lorries are moving on both sides of the road (directions) at very low speed, these two vehicles are responsible for the emergence of convoys of cars behind them. Most of them have the desire to driver faster, i.e., a high willingness to overtake, but could not pass the lorry due to bad vision. One problem evident here is that after some time the one or other driver might lose his/her patience, sheer out of the lane, starts to overtake, and generate by this a severe safety issue. Consider the same situation once again, given that there is enough space for safe overtaking (even if the field of vision is limited). Now a collective adaptive system component is installed in each and every vehicle traveling on this road, having the ability to send/receive information from all other devices in that region, to negotiate, and to come to the consensus which car(s) should overtake (e.g., emergency vehicles are preferred as opposed to normal cars; overtake in return for monetary compensation of others, etc.), and which ones should stay in the line.

Negotiation between cars in the crowds 1 and 2 (Fig. 11) has to consider, amongst other, the following questions:

- What is the best time to start overtaking?
- How does a car manifest the interest for overtaking?
- Which one of the two crowds should overtake (the longer, the shorter)?
- Are there any privileged vehicles in the autocade (emergency ambulance in time pressure)?
- You want to overtake? Move on, I have time…
- What metric to use for negotiation? For example, if there are seven cars in the first crowd and five cars in the second crowd, the overall benefit for overtaking is higher in crowd 1 (if there is enough space/time that all cars in crowd 1 can pass); let cars in crowd 1 start to overtake?
- Etc.

A scenario similar to the previous overtaking situation is to back out of a house' gateway. Again, collective adaptation could help to ease the process and to increase the safety of the car backing out as well as of all other road participants. Negotiation between the car backing out and the cars approaching on the main road, e.g., let the nearest car pass, advice the next (three) cars to throttle down and stop, inform the cars farther away that cars in front will stop, back out and move on (Fig. 12).

5.6 Proactive Reaction Using Distributed Information Maps

Events from the CAN bus or from other in-car buses (MOST, FlexRay, etc.) can be aggregated and extended with information coming from the environment to finally obtain deeper knowledge about driving behavior. This information can then be used to advise the driver or to warn other drivers nearby. More concrete, the CAN bus, for instance, delivers information when (and how often) a driver is pushing the brake pedal. Considering GPS information is available, this information could be mapped

Contents

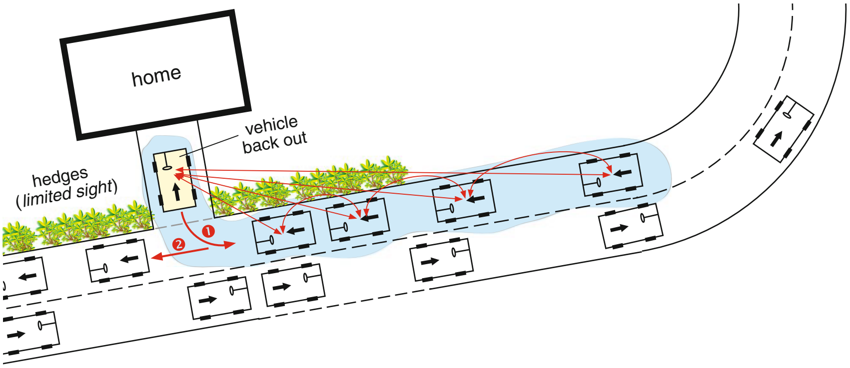

Fig. 12 Collective adaptation to allow safe back out from a doorway (Extended from [73])

Contents

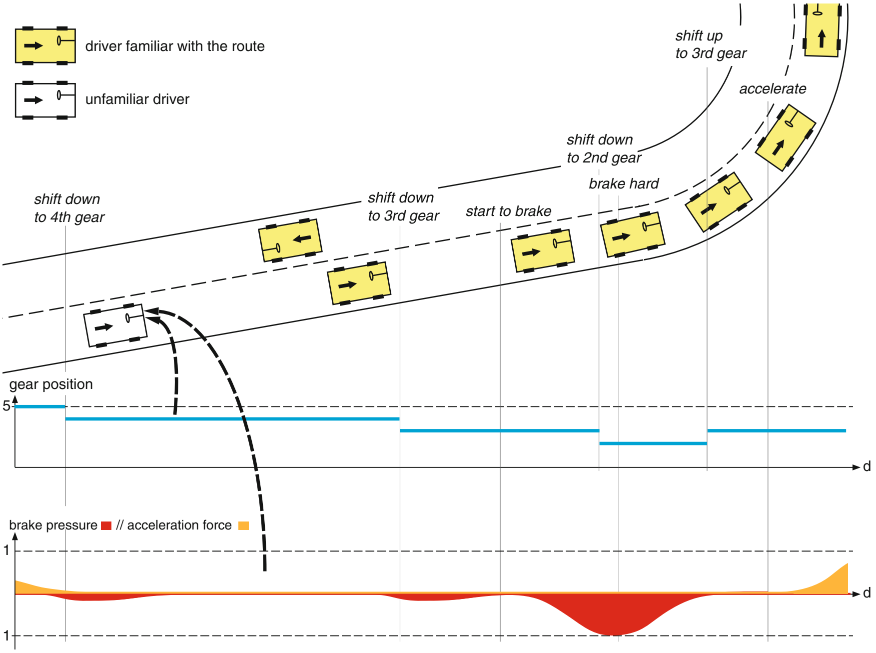

Fig. 13 “Danger map” built up from the braking behavior of all the cars in a certain area. The red danger area is built up/refined over time from braking information of all the other thousands cars passed during the last time (or at same environmental conditions such as temperature, sunshine, rainfall, etc.)

to a geolocation (position on the road stretch). Collecting this information for all cars (*car-driver pairs*), a distributed “information map” could be built up for a certain region as outlined in Fig. 13. This map could indicate, for example, regions as *hazardous* where lot of drivers apply the brake (hard), whereas a straight motorway section in which not a single driver pushes the brake pedal or make hard turns is considered *safe*. Dependent on the "sensors" utilized, gathered information cannot only be used to detect hazardous situations and to initiate appropriate actions, but also for improvements in vehicle operating in terms of driving economy or pleasure. The information from the map can finally be translated into driver information, warning messages, or even automatic reaction of the car in case of imminent danger.

5.6.1 Economic and Safe Driving

To give a more tangible example, it is well known that cycles of braking/accelerating significantly contributes to the overall fuel consumption. According to the US Department of Energy [70] could anticipative driving (i.e., avoidance of speeding, rapid acceleration, unnecessary braking) lower average gas mileage by about 33 % at highway speeds and by 5 % intra-urban. A simple yet effective application would be a "braking/accelerating recommender system" operating based on the fact that drivers familiar with a place or region knows best how to drive on the route (e.g., optimum point of braking before and acceleration in the curve) while non-locals would never have this anticipative behavior/knowledge and would most likely brake too late (and thus waste lot of energy) and also start to accelerate at the wrong point. We feel confident that providing the aggregated "expert knowledge" of drivers familiar with the route to unfamiliar drivers in the form of steering recommendations (e.g., when and how strong to apply the brake, when start again to accelerate, which gear to engage) would lead to a more harmonic flow of traffic, save fuel or optimize carbon dioxide emissions, and increase pleasure of driving Fig. 14. A early work showing the potential of such a recommender system is [57], where the authors have tried to "manipulate" steering behavior of drivers by notifying them about their current driving performance as compared to the optimum.

Speaking from familiar (or experienced) drivers, they would also be aware of road characteristics (such as curves and their radius, dangerous junctions, etc.), they would know the sections where overtaking is possible, and they would know all the dangerous areas (e.g., regions susceptible to wind, bridges exposed to black ice and other areas prone to tarmac freezing, or road layout behind a blind summit). A new driving assistance system could take advantage of this knowledge by providing non-locals with in time information on how to safely pass through a route, e.g., information about critical road segments or where to overtake. With these advices we can easily achieve increased driving safety.

The variance in gathered data (directly influencing the accuracy of advices) could be further narrowed by using data only from highly experienced drivers (e.g., with more than 15 years driving experience, more than 30,000 miles driven per year, or a minimum usage of the specific route of x times per month), and skip data sets of familiar but novice drivers.

Other examples of local/global information maps built up from individual vehicle (driver) behavior, in-car and environmental sensing, etc. include 2 pt

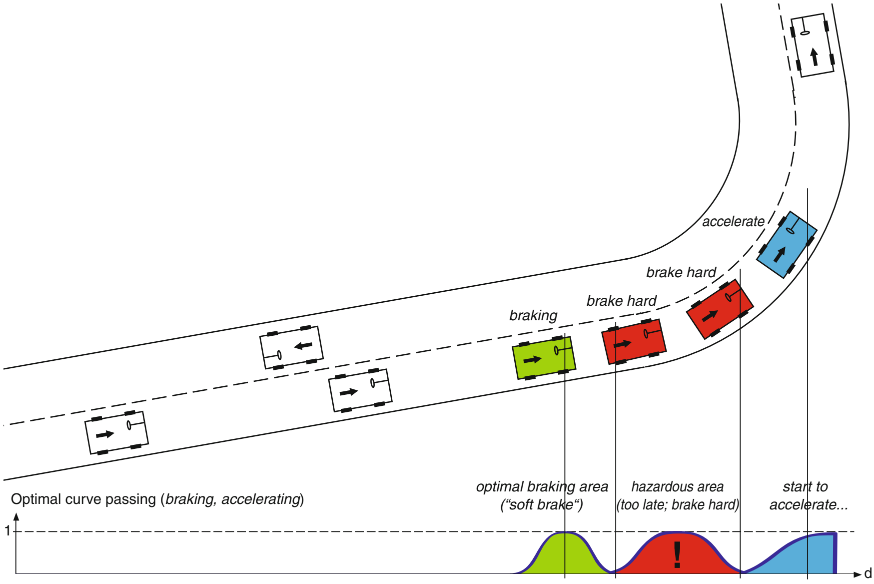

Fig. 14 Driving advices from familiar drivers would help non-locals to optimize driving behavior (braking/accelerating) and thus to feel increased pleasure of driving and optimization in carbon dioxide emission (or fuel consumption)

- A weather map (combine outside temperature sensors of cars, tarmac surface sensors, speed of windscreen wipers to indicate strength of rainfall, rear/front fog lamps to detect foggy areas, local weather forecast derived from the Internet, etc.)
- Question: would the additional information, e.g., on danger zones ahead, change the driving behavior of individuals (higher average speed, road rage, etc.)?
- A distributed "slippery radar" could be generated by combining CAN-bus information confirming that the brake is applied with information indicating that traction is lost (due to icy road or oil slick). The outside temperature sensor is finally used to distinguish between ice (temperature below zero degree Celsius) or oil film, and the driver is warned or the vehicle initiates an action ("soft" braking, etc.).
- Etc.

6 Potential Impact

By putting the driver rather than technology in the center of efforts with regard to complexity reduction in vehicle operation, we see great potential to revolutionize traffic in Europe and to achieve the long term visions and road safety goals of the European countries (e.g., "Vision Zero" [22]). In particular, we expect that drivers have a more relaxed driving experience and feel pleasure while controlling their cars. This ‘individual behavior enhancing’ add-on of vehicles offers huge chances on the market for (European) automobile manufacturer (with expected much higher impact than yet another assistance or driver information system). A further expected impact is that sort of collective understanding of the traffic situation together with a concerted behavior modification of drivers should have the potential to enable improvements such as reducing global fuel consumption or CO_2 emission. This could be achieved by a kind of “collective brain” gathering neural input from all the drivers in a common area of interest and featuring common decision making and negotiation on the route or lane taken by each individual driver within the collective. Of course, this includes also the control of traffic lights, speed limits, and traffic signs to optimize the traffic flow.

7 Conclusion

We have identified some of the most crucial problems in vehicle operation today and have come up with a number of possible solutions to establish human-computer confluence in the automotive domain. This concept should be understood as a specific instantiation of human-computer confluence working towards the goal of understanding the symbiosis between drivers, cars, and infrastructure within a region of interest and from a global point of view. This covers not only sharing of information about an oil spill on the road, in particular it includes reasoning about driver states and social or emotional interaction, and can be achieved, for example, by modeling driver behavior, studying distributed negotiation processes, performing driving studies and simulations, and relating their results to observations made in reality. A number of concrete example scenarios were outlined to better accentuate the potential and beneficial effects the application of driver-vehicle confluence might have on future traffic. These are, for example, reduced traveling times, lower fuel consumption/CO_2 emissions, or a more relaxed style of driving (i.e., improved driving experience and pleasure).

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Emerging Phenomena During Driving Interactions

Christian Maag

1 Background and Research Question

1.1 Criteria for the Evaluation of Road Traffic and Levels of Analysis

In recent years, the developments in traffic and technology caused an increasing interest in the analysis of interactions between road users. Therefore, there is a growing demand for understanding driving behaviour and analysing interactions between road users. Because traffic is a complex system with many interdependencies, side effects and emerging phenomena should complete the observation of direct and elementary impacts of any modification brought into this system.

This becomes especially important, if advanced driver assistance systems (ADAS) are studied that often promise to make traffic smarter. But is this promise true? Under which circumstances do drivers and traffic profit from such systems and which (maybe negative) side effects could emerge? These questions point to the methodology on how to evaluate driver interactions and road traffic and the influence of new ADAS.

Three criteria that often influence each other in an interdependent manner should be analysed when it comes to the question, if traffic is optimised by whichever measure: traffic safety, energy efficiency, and emotional climate (including driver stress, workload, and comfort). These evaluation criteria can be analysed on different levels of investigation: individual level, group level, and system level (see [1]). As a consequence, the following 3 by 3 research matrix stretches out (Table 1):

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Table 1 Research matrix defined by the two dimensions 'evaluation criterion' and 'level of investigation'

		Evaluation criterion		
		Safety	Emotions	Efficiency
Level of investigation	Individual			
	Group			
	System			

In the following, each cell is explained in more detail:

- Individual x Safety: Individual safety can be measured by headway, time-to-collision, time-to-line-crossing, and similar variables. These measures indicate a driver's safety more valid than near accidents or accidents, as both are very unlikely events.
- Individual x Emotions: Individual emotional state includes feelings like frustration, reactance, anger, joy, flow, workload, stress, fatigue, and others. They often go along with driving and can be measured by e.g. asking drivers using a rating scale.
- Individual x Efficiency: Efficiency on an individual level is measured as energy consumption of the vehicle or travel time to reach a specific destination.
- Group x Safety: Safety in a group of drivers includes parameters like speed variation, minimum of time headways, converging trajectories, or driving conflicts.
- Group x Emotions: On a group level, driving behaviour is called emotional optimal (or cooperative), if a driver supports another driver (called partner) in reaching the partner's driving intention (e.g. by letting him pull in into the main road). This could mean to put aside own interests for a while. As an effect, the emotions of the affected drivers could change (e.g. reduction of anger, thankfulness, joy in driving).
- Group x Efficiency: On a group level, driving behaviour is called efficient (or professional), if a driver behaves in a way that he increases the efficiency of driving in his direct surrounding area (e.g. by allowing a driver who wants to turn left to do that, if this driver hinders drivers behind him that want to proceed straight ahead).
- System x Safety: This cell contains what is usually called traffic safety. It implies the prevention and reduction of accidents and near accidents. It is the most important criterion for the evaluation of traffic systems.
- System x Emotions: The overall emotional atmosphere of all drivers (in a given traffic system, not just a specific situation) is called emotional climate. This implies that negative and conflicting interactions, frustrations, and situations of high workload and stress should be reduced.
- System x Efficiency: Traffic flow is one characteristic of efficiency on a system level. Other possible characteristics are e.g. energy consumption and travel times.

The different cells of the matrix are interdependent and influence each other. Therefore, no overall optimization is possible and trade-offs have to be made. Better emotional climate for example normally leads to optimized traffic safety, because frustration and anger increase risky and reckless driving. But cooperative driving could also lead to negative effects on system level as it could – depending on traffic volume – reduce traffic flow and increase overall travel times [2]. If traffic volume is below a limit that is specific for the current situation (e.g. reduction of number of lanes on a motorway, T intersection), cooperative driving enhances emotional climate. The receiving partner feels comfort and thankfulness. Traffic efficiency is not altered, if the traffic volume is significantly below the theoretical maximum load of the considered road. But if traffic volume increases above this maximum load, actions of cooperative driving could negatively influence traffic. Although the partner still profits from the cooperative behaviour and reacts with positive emotions, other drivers could be hindered and react with frustration and anger. As a consequence of this interdependency, the positive effect on emotional climate by cooperative driving becomes less pronounced with increasing traffic volume. Finally, cooperative driving could result in degraded emotional climate, because many drivers are hindered, if one drivers benefits from a cooperative interaction. A professional and "perfect" driver is cooperative and enhances emotional climate on the roads, but with increasing traffic volume he analyses the potential consequences of cooperation and chooses non-cooperative driving, in order to reduce interruptions in traffic flow that reduce traffic efficiency.

The different analysis levels of the research matrix can be analysed using different methodological approaches. Several research methods were developed to respond to this demand [3]:

- Experimental runs with real drivers in naturalistic situations on real roads: Experimental runs in real traffic allow studying authentic driving behaviour of several road users in naturalistic situations. However, the uncontrollable conditions make the realization of test situations in real world traffic very difficult and driving in safety-critical situations is highly problematic because of ethical reasons.
- Driving simulation with exposing human drivers to simulated traffic: With driving simulation it is possible to determine the effect of different traffic conditions on a human driver. This method is beneficial, because conditions can be controlled and desired test situations can be generated. Furthermore, due to the simulated conditions, the realization of safety-critical situations is possible. A disadvantage is that the analysis of interactions between drivers is limited, because the surrounding traffic is just simulated. Multi-driver simulation was used as a new and innovative research tool. This kind of driving simulation puts several human drivers simultaneously in the same simulated environment and allows the measurement of driving behaviour of single drivers as well as from a group of drivers [4].

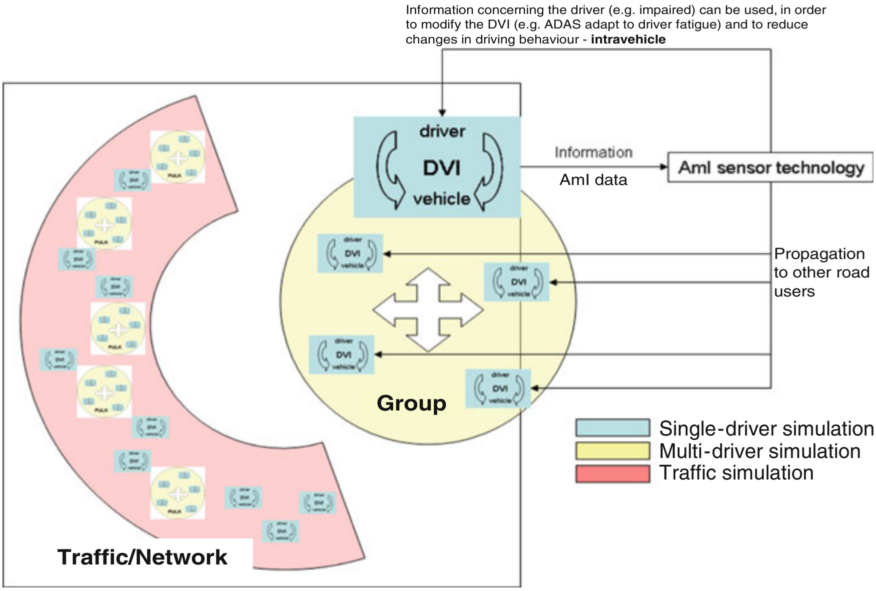


Fig. 1 Relationship between research question and methodological approach

- Traffic flow simulation that aims at simulating and predicting traffic situations under various conditions: Traffic flow simulation allows the investigation of how single drivers influence other road users. The opportunity to analyse a lot of vehicles in the same situation under controlled conditions is a benefit of this method. However, the traffic flow simulation uses models for driving behaviour and does not consider real drivers which might react differently (e.g. concerning car following or lane change).

Depending on the research question, the right methodological approach should be chosen. This is illustrated by Fig. 1.

In the following, it is shown how different areas could be analysed by using the innovative instrument of multi-driver simulation. In this context, the potential of several ADAS (other term: ambient intelligence devices; AmI devicees) is studied.

1.2 Ambient Intelligence

1.2.1 Ambient Intelligence and Car Driving

The scientific area of ambient intelligence results from the miniaturisation of computers and the embedding of computing power in many objects of daily life (e.g. mobile phones, cars, GPS navigation). Therefore, terms linked to ambient intelligence are pervasive computing or ubiquitous computing. Mostly, ambient technology is linked to miniaturised and embedded information and communication technology, further characterised by "intelligence", network connectivity, and advanced user interfaces [5].

The science of ambient intelligence explores technical possibilities to improve the way how environments could help people and how technology could help society [6]. Cook et al. [6, p. 278] describe: The "basic idea behind Ambient Intelligence (AmI) is that by enriching an environment with technology (e.g. sensors and devices interconnected through a network), a system can be built such that acts as an 'electronic butler', which senses features of the users and their environment, then reasons about the accumulated data, and finally selects actions to take that will benefit the users in the environment." All in all, Cook et al. [6, p. 279] define ambient intelligence as "a digital environment that proactively, but sensibly, supports people in their daily lives".

According to Cook et al. [6] ambient intelligence technologies are based upon interaction with the environment. The AmI system perceives the state of the environment and the users by using sensors. Examples of sensing real world characteristics are position, location, velocity, direction, and physiological parameters. Subsequently, the AmI system reasons about the gathered information. It models user behaviour (e.g. driving behaviour), predicts activities (e.g. driving manoeuvres), and makes decisions (optimal solution for a given situation, intervention yes or no). Finally, the AmI system acts by executing actions (e.g. braking) or affecting the system user (e.g. giving recommendations). For supporting the user the AmI system must be easy to live with. That means that the human computer interface (HCI) must be easy to understand and use. In order to be accepted by individuals and society, security and privacy issues must be taken into account. This touches questions of ultimate control, data usage, privacy issues, and sensor reliability.

Some research is also spent into the modelling of cognitive states of humans by observing their behaviour [7]. By that, AmI devices could assist and guide humans according to their underlying cognitive states causing the behaviour.

Different applications of AmI are discussed, for example:

- Smart home: Increasing safety, comfort, and economy in the house.
- Health monitoring and assistance: Supporting people with mental and physical challenges.
- Transportation: Advanced driver assistance systems and telematics.

Concerning the application field of transportation and driving, ambient technology comprises systems that deliver information to the driver that

- Cannot be perceived by himself without this technological system,
- Informs about the surrounding traffic area, especially other drivers intentions and weaknesses,
- Gives information or recommendations, assists the driver, or controls driving parameters, and
- Is based on systems that are highly interconnected.

Three examples (that will be analysed in more detail later during this chapter) for AmI systems in the vehicle are:

- Hazard warning system: This system warns the driver if a sudden braking manoeuvre of a lead vehicle is very likely.
- Cooperative merging information and recommendation system: This system gives recommendation for an optimal merging from a slip road onto the motorway.
- Efficient cruise control system: This system supports the driver in efficient driving by automatically reducing speed in curves, due to speed restrictions, and during car-following.

What are the major future developments in the area of information and communication technology (ICT)? A report [8] makes a prognosis regarding future ICT innovations by asking more than 400 international experts from science, politics, and economics using the Delphi method (experts are asked in a multi-step approach, giving them information about the results of the previous step). Concerning the automotive area – a key industry in Europe – the results show that current technology trends are intelligent driver assistance systems, light-weighted safety concepts, green engine technology, and mobile ICT systems. Following the experts, ICT in the car will rise up to 50 % of value added (currently modern cars have a portion of 20–30 % of ICT added value). Especially cooperative systems – ICT systems that are able to exchange data with other systems, central servers, and the infrastructure – have a high potential in increasing traffic safety and efficiency. According to the experts, in future the car will be a multi-functional and multi-modal node that transmits hazard warnings and traffic related advices as well as personalised information and entertainment. But when will these future developments become real? When will 50 % of all new cars be able to communicate traffic and environment related content? Answering this question, 39 % of the experts predict the period 2020–2024, 31 % the period 2025–2030, and 13 % the period 2015–2019. Nobody doubts that this innovation will become real at all. According to the report, the most important barriers for implementation are the necessary investments into infrastructure (Road Side Units), missing standards, high costs, issues of data privacy, and technical problems.

1.2.2 Advanced Driver Assistance Systems (ADAS)

In the last years, a variety of ADAS were introduced in the market [9]: From safety systems that support the driver in safety-critical situations and stabilize the car (e.g. antilock brake system), over comfort systems that reduce the workload of the driver (e.g. cruise control), to information systems that carry out secondary tasks and give the driver important information (e.g. navigation system). Another banding of these systems is based on the level of intervention from information over recommendation and assistance to control [10]. Besides the intended safety and comfort issues

[11], such systems are discussed because of their effects on the traffic flow and environmental effects [12].

Up to now, most of these ADAS are related to a single vehicle, e.g. the detection and control of distances to preceding vehicles or lane departure warning. Such assistance functions fulfil to some extend the same tasks as the driver. Therefore, the role of the driver changes from acting to monitoring, i.e. the driver observes system performance and intervenes only, if something is suboptimal. This could lead to new problems, e.g. reduced vigilance and situation awareness [13,14]. At the moment, more and more ADAS are developed that are based on the communication between the vehicle and other vehicles or the infrastructure (so called C2X technologies). These ADAS lead to information presented to the driver that can be relevant and valuable but cannot be verified by the driver (e.g. alternative route suggestions because of traffic or weather conditions).

The next steps of the technological development [12] – that is driven by better sensor technology and faster data analysis – will lead to even more tasks of driving that are fulfilled partly or fully by assistance systems (e.g. lane keeping assistant, lane change assistance, stop & go ACC, collision warning, traffic sign detection, fatigue warning). The consequences for driving safety (and also enjoyment of driving; [15]) must be analysed very carefully before such systems are brought to the market.

This makes one aspect crucial: The technical development of ADAS has to be tailored to the skills and limits of the driver. Assistance systems must be developed that are easy learnable, comprehensible, and usable. In addition, the driver is confronted with many new demands (e.g. learning the usage and functionality of the system). At the same time, assistance could help many drivers by compensating individual limitations and handicaps (e.g. automatic parking for older drivers). As a consequence, driver assistance systems on the one hand put new demands on the driver by on the other hand giving him new possibilities to keep and broaden the own behaviour repertoire.

2 Methodology of Multi-driver Simulation

2.1 Hardware and Mock-up

The SILAB multi-driver simulation is manufactured by WIVW (Wuerzburg Institute for Traffic Sciences GmbH; www.wivw.de). Up to five subjects can drive simultaneously in the same virtual driving environment and interact with each other (Fig. 2).

Every visual system has 150° horizontal field of view, provided by three LCD displays with 22″ screen size and a resolution of 1,680 × 1,050 pixels each. The rear-view mirror as well as left and right outside mirror are shown in these LCD displays. The update frequency of the simulation is 60 Hz. The mock-up consists of a force feedback steering wheel with accelerator and brake pedal. An additional

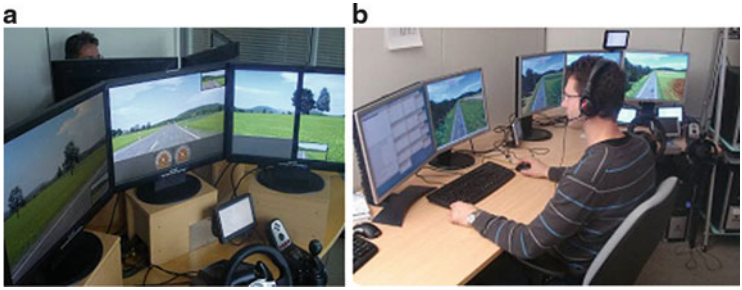


Fig. 2 (**a**) Mock-up and scenario of multi-driver simulator and (**b**) workplace of the experimenter for monitoring the behaviour of the four test drivers

touch screen with 800 × 400 pixels can be used for driver input (e.g. answering questions), secondary tasks, and ergonomic studies.

For sound simulation and communication with the experimenter a headset is used. The computer network of the multi-driver simulation consists of 25 personal computers connected via gigabit Ethernet.

2.2 *Simulation Software and Driver Panel*

The software SILAB that is used by single-driver as well as multi-driver simulation creates a realistic impression of driving including a complex simulation of vehicle dynamics, modern image generation for urban, highway and rural scenarios, and numerous models for the behaviour of other traffic participants, including vehicles and pedestrians. SILAB is highly scalable, from a simulator consisting of one PC, a monitor and a steering wheel used in video games up to a driving simulator that has multiple image channels and a motion system.

During simulation, a comfortable graphical user interface allows the modification of all parameters and the observation of all data. In addition, all parameters can be changed automatically, depending on driver‘s position in the road network.

For the simulator studies subjects are chosen from a driver panel already trained in simulator driving [16]. This training is important, in order to make the test drivers familiar with the handling of the simulator and to reduce the problem of simulator sickness.

3 Exemplary Studies of Emerging Phenomena During Driving Interactions

In the following, different experiments are presented that all deal with emerging phenomena during driving interactions studied by using the innovative approach of multi-driver simulation (main focus of study in brackets):

Fig. 3 Screenshots of the experimental conditions during the study ‘Braking convoy’ (*left*: braking convoy on right lane of motorway; *right*: non-braking convoy on right lane of motorway)

- Braking convoy (study of indirect and emerging effects in a complex traffic situation)
- Group driving (study of driver-to-driver effects in a group of drivers)
- Braking car (study of safety effects of ADAS on a group of drivers)
- Merging assistant (study of emotional effects of ADAS on a group of drivers)
- Efficient Cruise Control (development of an innovative ADAS and study of effects on energy consumption)

3.1 Braking Convoy

As an introductory example, this study highlights that non-trivial interactions between road users could emerge that are not easy predictable. In this experiment, the effects of right lane events on the behaviour of drivers on the left lane of a motorway are studied.

3.1.1 Methodology

The experimental situation is realised on a motorway section with a length of 3,500 m. The motorway is characterised by straight sections, slight curves and some slight elevations (Fig. 3).

In each section the four subjects that participate simultaneously in the study follow a lead vehicle on the left lane of the motorway (Fig. 4). In doing this, they pass a convoy of vehicles driving on the right lane of the motorway. The lead vehicle in front of the subjects has a speed of 120 km/h; the convoy on the right lane has a speed of 72 km/h.

The two experimental conditions of the study vary in the behaviour of the convoy on the right lane of the motorway. During the first condition the convoy brakes down from 72 to 40 km/h (also indicated by braking lights and starting after 1,500 m); during the second condition the vehicles on the right lane proceed with a speed of 72 km/h.

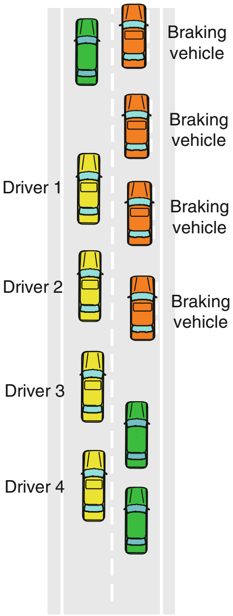


Fig. 4 Schematic illustration of the driving situation during the study ‘Braking convoy’

As dependent variables the driving behaviour of the four subjects on the left lane (e.g. speed, acceleration, braking) as well as subjective ratings of the subjects concerning anger and difficulty of the situation is analysed.

Four groups with four drivers each, i.e. a total of 16 drivers (6 female, 10 male), took part in the study. All had some training in the multi-driver simulation, in order to be accustomed to driving with that kind of simulator. They have an average age of 30.8 years (SD = 4.8 years). Their driving experience was between 2,400 and 25,000 km/year (mean = 8,994 km/year, SD = 5,465 km/year).

3.1.2 Results

Hundred meters after the beginning of the braking manoeuvre the position of the accelerator pedal of the four vehicles (F1–F4) driven by the subjects on the left lane as well as the speed of these vehicles is measured. The results show that the drivers step off the accelerator (Fig. 5 left), if the convoy on the right lane brakes compared to the experimental conditions without a braking manoeuvre performed by the vehicles on the right lane. Furthermore, there is a tendency that subjects reduce speed as a consequence of the obvious traffic disturbances on the right lane (Fig. 5 right). But this effect is not statistically significant.

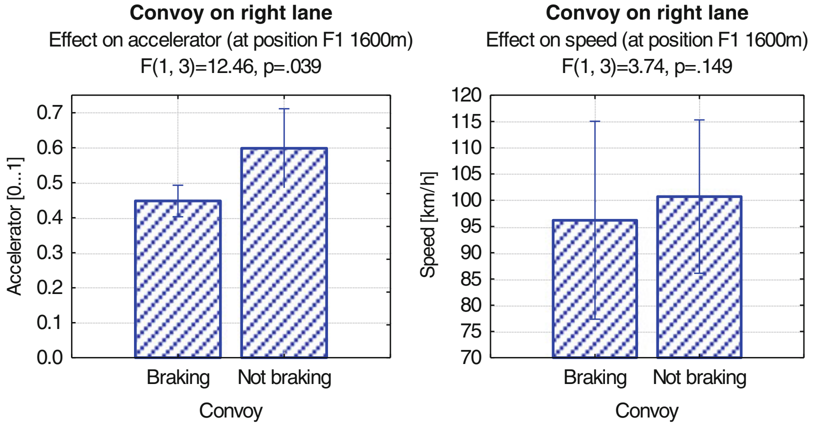


Fig. 5 Effect of braking convoy on accelerator position (*left*) and speed (*right*)

3.1.3 Discussion

The results indicate that events on the right lane of a motorway could have effects on the driving behaviour of the drivers on the left lane. This is somewhat surprising as there is no direct need for the drivers on the left lane to react to the braking convoy on the right lane. Nevertheless, drivers assume that there must be some obstacle or traffic disruption that forces the drivers in the right lane to reduce speed. As a consequence, they expect it as more likely that a similar traffic disturbance will also become real for the left lane.

All in all, this experiment shows that emerging and non-trivial effects can be found, if driver behaviour in complex situations is analysed. Most of the current traffic simulation models do not include such lane-to-lane influences.

3.2 Group Driving

This second study moves the attention to effects that emerge within a group of real drivers during relatively simple driving manoeuvres. It mainly asks what kind of influence the position in a group of drivers has and how and by which parameters this influence, if any, can be described.

3.2.1 Methodology

A group of four drivers has to complete five experimental runs (Baseline 1, Baseline 2, Group driving, Leading car 1, Leading car 2) with 27 km length each

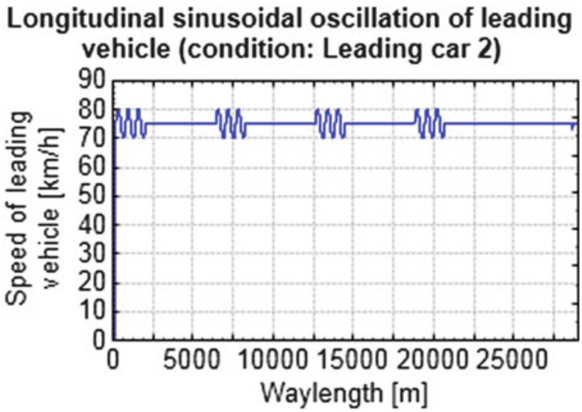


Fig. 6 Speed plot with sinusoidal oscillations of leading vehicle during experimental condition 'Leading car 2'

(description in the chronological order as during the study; all five experimental conditions are driven in the same order of drivers/vehicles):

- Baseline 1: Four drivers drive individually with a speed of 80 km/h for about 20 min in an undisturbed condition (rural road, straight course, no third party traffic).
- Baseline 2: Four drivers drive individually for about 20 min in an undisturbed condition following a leading car that drives 75 km/h with passing not allowed (rural road, straight course, one leading SILAB vehicle, no passing).
- Group driving: Four drivers drive as a group with a speed of 80 km/h for about 20 min in an undisturbed condition (see above) with passing not allowed (like e.g. during driving to a common destination).
- Leading car 1: Four drivers drive as a group for about 20 min in an undisturbed condition (see above) following a leading car that drives constantly 75 km/h with passing not allowed (like e.g. during driving to a common destination).
- Leading car 2: Four drivers drive as a group for about 30 min in an undisturbed condition (see above) following a leading car with passing not allowed (like e.g. during driving to a common destination). Leading vehicle with a longitudinal sinusoidal oscillation (75 ± 5 km/h; one oscillation lasts 30 s; procedure: three oscillations lasting 1.5 min and a subsequent break of 3.5 min; procedure is repeated four times per route; see Fig. 6).

All parts are driven with a speed of 80 km/h (respective 75 km/h following a leading car). The speed limit is 80 km/h. Nevertheless, drivers No. 2–4 are allowed to drive up to 100 km/h, in order to catch up with the vehicle in front.

The driving variables of most interest are: (1) lateral deviation, (2) headway, time-headway, (3) steering behaviour, (4) speed, (5) acceleration, (6) time-to-collision.

In order to beat boredom, a radio playing a local station is installed in the driving laboratory. The four drivers are not allowed to speak with each other, have to turn off their mobile phones and always have to keep lane as well as visual contact.

The four test drivers (one woman, three men) have an average age of 33.75 years (SD = 9.74 years) and an average driving experience of 8,500 km/year.

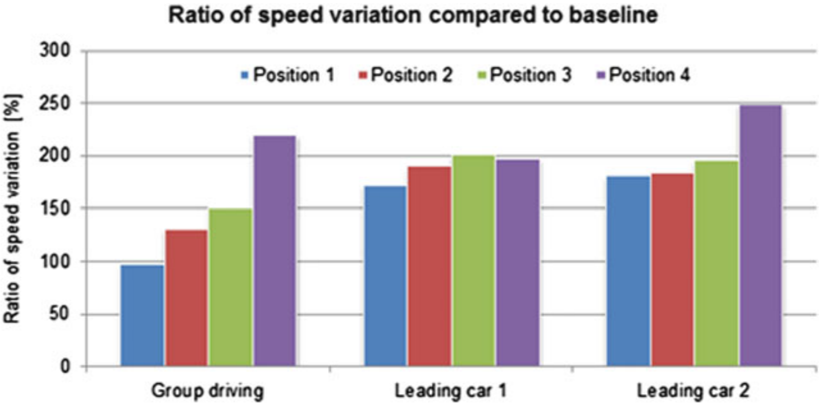


Fig. 7 Ratio of speed variation compared to baseline (division of standard deviation in a specific condition by the average standard deviation in Baseline 1 and Baseline 2)

3.2.2 Results

In the baseline conditions, the four drivers show inter-individual differences in speed variation. The standard deviation of speed varies between 0.98–2.17 km/h in Baseline 1 and 1.91–3.65 km/h in Baseline 2. Moreover, the speed variation is higher in the group conditions compared to Baseline 1.

Furthermore, the analysis shows that during the multi-driver conditions, the speed variation depends on the group position (Fig. 7). In general, the standard deviation increases with the position in the group of drivers.

During normal driving in Baseline 1 the subjects show maximum decelerations of 0.5 m/s^2 (i.e. drivers decelerate just by releasing the accelerator). When the drivers follow a constant driving leading vehicle in Baseline 2 the maximum deceleration increases up to 2.8 m/s^2. During the multi-driver conditions the maximum decelerations raise up to about 8.0 m/s^2 (i.e. full braking). Similar to the deceleration behaviour, the maximum accelerations are higher when following a leading vehicle. As a consequence of the effects of group driving on acceleration and deceleration, the standard deviation of acceleration depends on the position in the group of drivers. The drivers in the positions 2–4 have a higher variation in acceleration than the leading driver in the conditions Group driving 1 and Group driving 2 (Fig. 8). Especially, the last driver has an increased variation in most experimental conditions.

Figure 9 presents the speed of all vehicles during the oscillation periods in the experimental condition ‘Leading car 2’. On the basis of the method for measuring driving performance during car following developed by Brookhuis and de Waard [17] the time series are analysed in Table 2 by using spectral analysis.

The three formally independent parameters [17] that are extracted are:

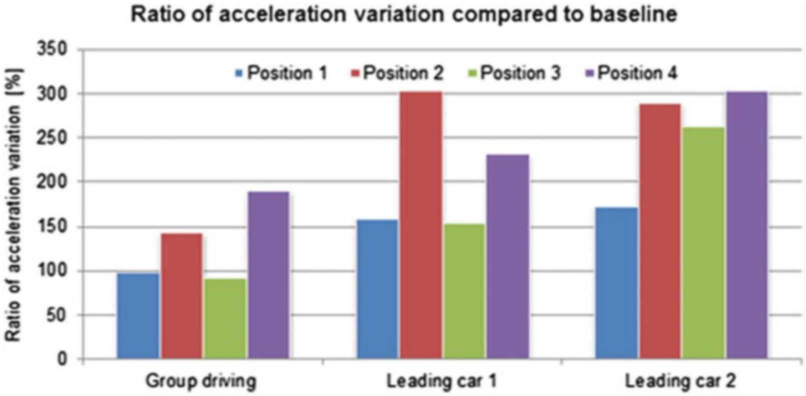


Fig. 8 Ratio of acceleration variation compared to baseline (division of standard deviation in a specific condition by the average standard deviation in Baseline 1 and Baseline 2)

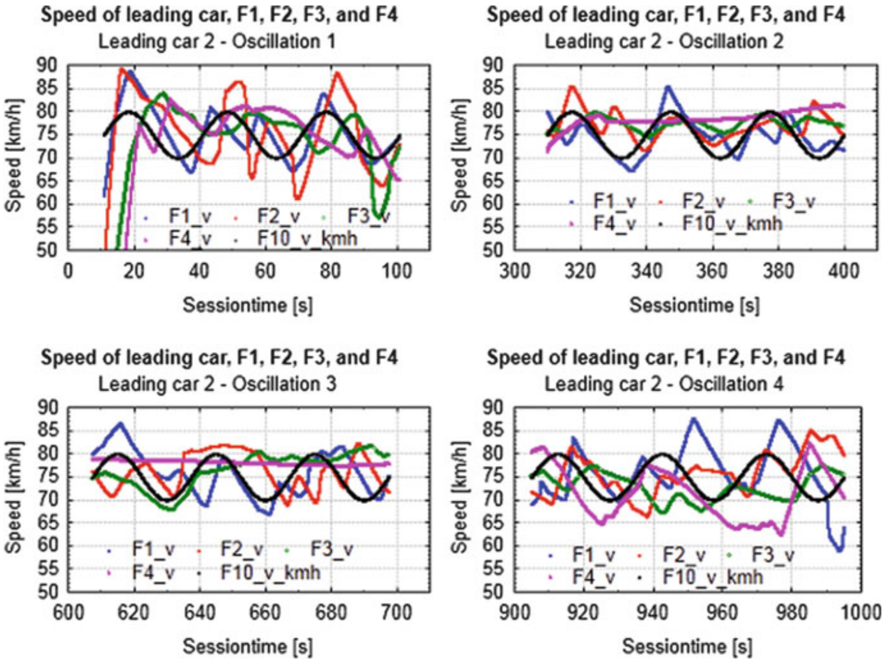


Fig. 9 Speed of leading car and test drivers during the four oscillations (Leading car 2)

1. Coherence as a measure of accuracy of the driver's speed adaptations (a coherence of 1 is perfect and indicates two speed signals that match exactly)
2. Modulus or gain as an amplification factor between the two speed signals that indicates the magnitude of overshoot in reaction

Table 2 Car following measures for the four oscillations and the relationship between all four pairs of vehicles (leading car-F1, F1–F2, F2–F3, F3–F4)

	Independent variable	Dependent variable	Period [s]	Ordered number	Gain	Delay	Coherence
Oscillation 1	Speed of leading car	Speed of F1	30	1	0.874	4.2	0.962
	Speed of F1	Speed of F2	30	1	0.643	3.1	0.983
	Speed of F2	Speed of F3	30	1	0.750	3.6	0.855
	Speed of F3	Speed of F4	30	2	1.020	4.9	0.983
Oscillation 2	Speed of leading car	Speed of F1	30	1	1.079	5.2	0.936
	Speed of F1	Speed of F2	30	1	2.184	10.4	0.866
	Speed of F2	Speed of F3	30	1	1.188	5.7	0.694
	Speed of F3	Speed of F4	30	2	1.158	5.5	0.932
Oscillation 3	Speed of leading car	Speed of F1	30	1	1.217	5.8	0.967
	Speed of F1	Speed of F2	30	2	0.861	4.1	0.714
	Speed of F2	Speed of F3	30				
	Speed of F3	Speed of F4	30	3	14.623	69.8	0.693
Oscillation 4	Speed of leading car	Speed of F1	30	1	0.684	3.3	0.909
	Speed of F1	Speed of F2	30	1	1.450	6.9	0.728
	Speed of F2	Speed of F3	30	4	0.115	0.6	0.250
	Speed of F3	Speed of F4	30	2	1.232	5.9	0.880

3. Delay as an estimation of reaction time to the decelerations and accelerations of the lead car

The method has proved its applicability in different studies using car following tasks and measuring the performance of drivers under different experimental conditions (e.g. [18]).

Concerning the four oscillations during the Leading car 2 condition the results show (Table 2) that the original period (or frequency) of 30 s for one oscillation carried out by the lead car always passes on to F1. For the first oscillation this period is carried over to F3, for the second oscillation to F2, and for the fourth oscillation to F2. During the third oscillation already the process of car following between F1 and F2 has its closest coherence for another period. The typical reaction time (‘delay’) lies between 3 and 6 s.

An analysis of the car following parameters for vehicles not following each other yields very low scores for coherence. Therefore, further data is not reported here.

3.2.3 Discussion

Subjects driving in a group, i.e. following a leading vehicle and followed by another vehicle, behave differently than drivers who drive uninfluenced by others. The pilot study described above assesses the possibility of studying these effects by using the multi-driver simulation.

An analysis of driving parameters shows that during the multi-driver conditions, the speed variation depends on the group position. Drivers who are at the back of the group show more variation of speed than drivers further ahead. In addition, the variation of acceleration is often highest for the driver at the last position in the group. There seem to be some effects that build up from position to position. As a consequence, the last driver has to accelerate strongly, in order to catch up with the other drivers or has to brake significantly, in order to avoid an accident.

The time-series analysis using spectral analysis shows a typical reaction time to speed changes of the leading vehicle of 5 s, and some influence of a longitudinal oscillating leading vehicle not only on the following vehicle but also on the vehicle following in the second.

3.3 Braking Car

Is multi-driver simulation also appropriate to study direct and indirect effects of ADAS on several drivers? This question is answered by the third experiment that analyses the effects of a system that warns the driver that a hazard is likely to emerge (Hazard Warning System, HWS).

3.3.1 Methodology

The HWS works by placing a virtual danger sign (similar to a three-cornered road sign with an exclamation mark in the centre) on top of the roof of a vehicle that is likely to perform a surprising driving manoeuvre (Fig. 10 left). This surprising and hazardous manoeuvre is realized by a lead vehicle that makes a sudden braking manoeuvre from 83 km/h down to 47 km/h.

Under study are three different warning regimes (Fig. 10 right):

- Early warning: The warning is activated early, i.e. 13 s before the braking manoeuvre of the lead vehicle starts.
- Late warning: The warning is activated late, i.e. at the same time when the braking manoeuvre of the lead vehicle starts.
- No warning: The lead vehicle brakes suddenly without any warning.

These different experimental situations alternate with car-follow situations without any braking of the lead vehicle in a randomized manner. If braking, the exact position of braking varies, in order to reduce predictability. Analysed are the consequences for drivers' behaviour and safety depending on the position in a group of drivers. Therefore, in each section four subjects follow a leading vehicle.

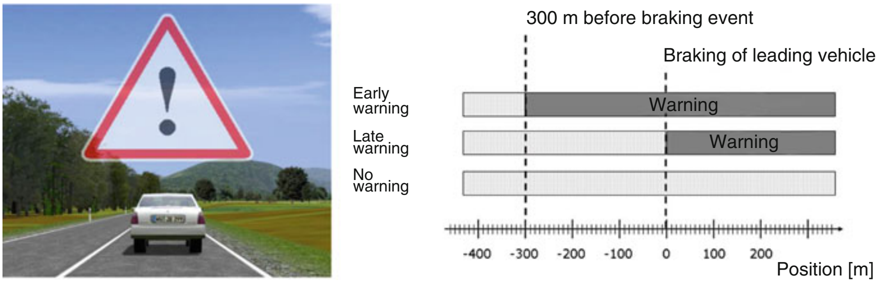


Fig. 10 Illustration of the virtual danger sign of the HWS (*left*) and the three different warning regimes (*right*)

Fig. 11 Screenshots from the study 'Braking vehicle' with the rural road where the driving takes place (*left*) and illustration of the vehicles taking part in the scenario (*right*)

The experiment takes place in the multi-driver simulator on a rural road with a length of about 39 km (15 sections with a length of 2,600 m each). The road layout of the rural road is characterised by straight sections, slight curves and some slight elevations (Fig. 11).

As dependent variables the driving behaviour of the four following subjects (e.g. speed, acceleration, braking, TTC, time headway, reaction time) as well as subjective ratings of the subjects concerning anger and difficulty of each situation are analysed.

Four groups with four drivers each, i.e. a total of 16 drivers (6 female, 10 male), took part in the study. All had some training in the multi-driver simulation, in order to be accustomed to driving with that kind of simulator. They have an average age of 30.8 years (SD = 4.8 years). Their driving experience ranged from 2,400 to 25,000 km/year (mean = 8,994 km/year, SD = 5,465 km/year).

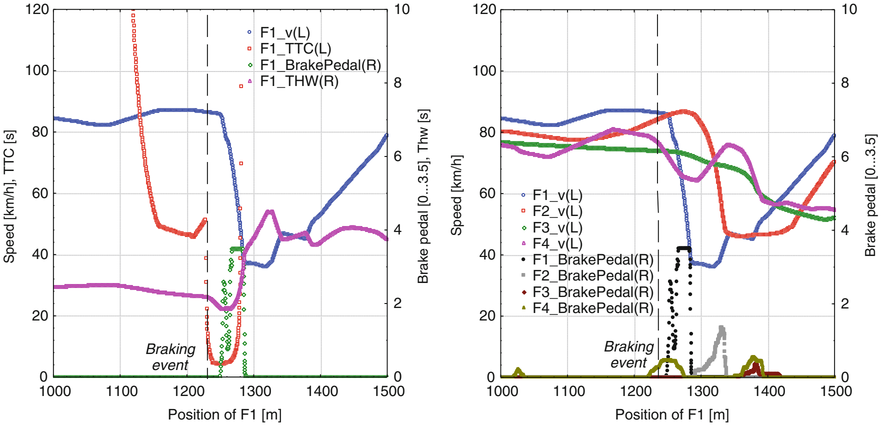


Fig. 12 Exemplary event during the study ‘Braking vehicle’ under late warning regime with an illustration of the driving parameters of F1 (*left*) and F1–F4 (*right*)

3.3.2 Results

An exemplary event of the experimental condition with late warning regime is illustrated in Fig. 12. At position 1,230 m the leading vehicle carries out an abrupt braking manoeuvre. According to the late warning condition, the HWS warning appears at the same time as the leading vehicle begins to reduce speed. This hazardous manoeuvre of the leading vehicle can be seen in the left graph of Fig. 12. It is characterized by the fast reduction of the TTC of F1 from around 50 to 5 s. The driver of F1 reacts some seconds later, presses the brake pedal strongly, and reduces speed. As a consequence, the time headway increases.

The right graph shows speed and brake pedal for all four vehicles. After F1 has reacted, the driver of F2 brakes moderately. The drivers of F3 and F4 carry out only slight braking manoeuvres; they mainly use drag torque for decelerating.

Figure 13 shows the same situation under the early warning regime, i.e. the drivers are informed several seconds before the leading vehicle presumably carries out an abrupt braking manoeuvre. Because the driver reacts anticipatively to the upcoming hazard, F1 has a greater time headway at the beginning of the event (Fig. 13 left). As a consequence, the driver of F1 has to brake less hard and reduces speed just from 80 to 55 km/h.

The right graph of Fig. 13 shows that the speed variance is less for all four drivers under the early warning regime compared to the experimental condition of late warning. All in all, the situation seems to be less dangerous than with late warning (or no warning at all).

An analysis (ANOVA for independent groups) of all experimental runs shows that the early warning has an influence on the time-headway at the point of braking (Fig. 14 left). With an early warning, F1 increases its time headway by 0.7 s.

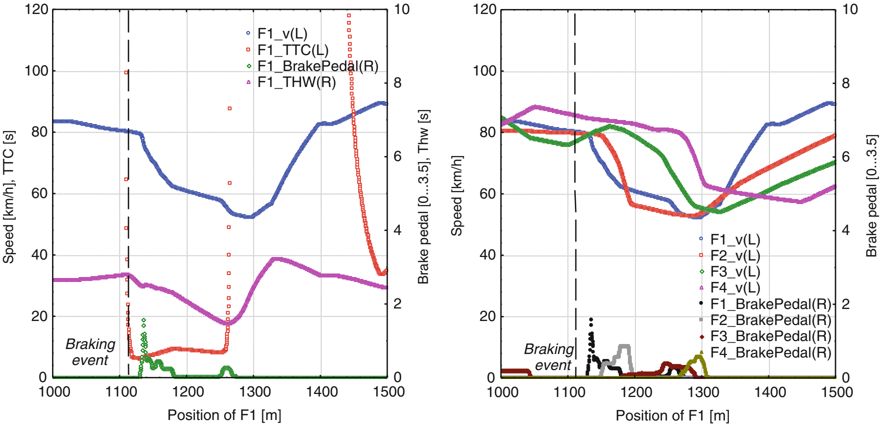


Fig. 13 Exemplary event during the study ‘Braking vehicle’ under early warning regime with an illustration of the driving parameters of F1 (*left*) and F1–F4 (*right*)

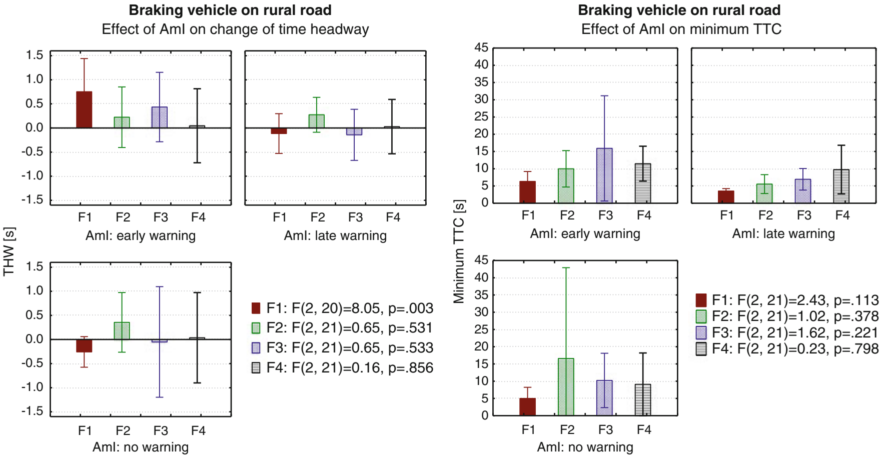


Fig. 14 Effect of the different warning regimes of the HWS on the change of time headway in the 300 m section before the event (*left*; positive figures represent an increase in time headway) and minimum TTC (*right*) during the study ‘Braking vehicle’

The drivers of the other vehicles are not influenced by the early warning in a significant way.

The minimum TTC (Fig. 14 right) after the braking of the leading vehicle indicate some tendency that the late warning condition is the most dangerous one, especially for the first driver following the leading car. Nevertheless, the effects are not statistically significant.

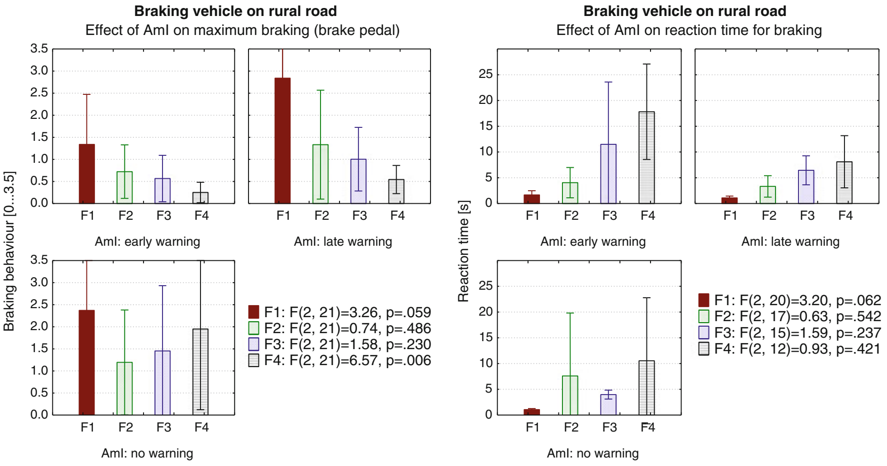


Fig. 15 Effect of the different warning regimes of the HWS on maximum braking (*left*; operation of brake pedal) and reaction time (*right*) during the study 'Braking vehicle'

An analysis of the maximum braking after the sudden deceleration of the vehicle in front of the group of vehicles shows that the driver of F1 has to brake significantly less in the early warning condition in comparison to both other conditions (Fig. 15 left). A similar effect is found for the last vehicle in the group (F4), but F4 benefits also from the late warning condition.

The results also show that the driver of F1 has to react faster in the late warning and no warning conditions (Fig. 15 right) compared to the early warning regime, because the initial time headway is smaller than in the early warning condition.

3.3.3 Discussion

In summary, the AmI device assisting the driver by giving an early warning that a hazard may occur (e.g. because a leading vehicle brakes abruptly) could lead to safer roads. Especially, the first driver following the hazardous vehicle is able to respond anticipatively and increase time headway when he gets a warning by the HWS. As a consequence, this driver does not need to brake as fast as with no or late warning. Although drivers react later in the early warning condition, the resulting minimum TTCs are greater than with late or no warning. Negative emerging effects of an early or late warning on the drivers of F2–F4 did not appear.

This study shows that the multi-driver simulation is an appropriate tool to analyse the effects of an ADAS on several drivers. By that, non-trivial effects on indirectly affected third drivers could be put in the focus of experimental research.

3.4 Merging Assistant

The following study answers the question which effect the usage of a Merging Assistant on drivers' interactions and emotional response has? Similar to the example of the HWS, again an ADAS is under study. But the main differences are that emotional effects of an ADAS are studied and the assistance targets in directly modifying interactions between a group of drivers driving on different lanes.

The development and analysis of such a system assisting drivers during merging interactions is particularly interesting, because merging (besides other interactions) could be stressful and a starting point for driving conflicts, anger and aggression on the road.

A study preceding the one reported here asked the subjects to choose an appropriate gap for merging from a slip road onto the motorway. This choice was made by the subjects from two different perspectives: (1) as drivers driving on the slip road with the intention to merge and (2) as drivers already driving on the through lane of the motorway.

During this preceding study each subject approaches a merging point on the motorway by driving either on the through lane of the motorway or on the slip road. In addition to these two vehicles, eight additional vehicles – generated by the simulator for presenting a realistic environment – drove on the through lane of the motorway. The situation was solved by removing all vehicles (except for the subject's) before any driving actions became necessary.

The parameter used for describing merging situations was TTC-difference and is based on a time-to-collision (in this case: time-to-beginning of the merging area) calculation of the vehicles involved in the merging interaction. It was calculated as follows: $\text{TTC-difference} = \text{TTC}_{\text{merging vehicle}} - \text{TTC}_{\text{vehicle on motorway}}$. The TTC for both vehicles (merging vehicle, vehicle on the motorway) was calculated relative to the beginning of the merging area (i.e. beginning of slip road). Therefore, positive values imply that the vehicle on the through lane of the motorway reaches the merging area earlier than the merging vehicle, negative values vice versa.

The effects of perspective of driver (merging vehicle on the slip road vs. vehicle on through lane of motorway) and TTC-difference between merging vehicle and reference vehicle on through lane (relative to the beginning of the merging area; from -1.4 to 0.2 s) on the evaluation of appropriate gaps for merging are presented in Fig. 16. The results suggest that a perspective bias exists that makes conflicts between drivers during merging more likely. Each driver assesses the current situation on the basis of his current driving intention – leading to a more egoistic behaviour. Subjects who are already on the motorway were less likely to evaluate the gap in front of them as appropriate compared to subjects who want to merge from the slip road onto the motorway. For a TTC-difference of -1.0 s about 95 % of the merging drivers on the slip road evaluated the gap in front of the reference vehicle as appropriate; in contrast to that, for the same TTC-difference just about 80 % of the drivers (of the reference vehicle) on the through lane of the motorway

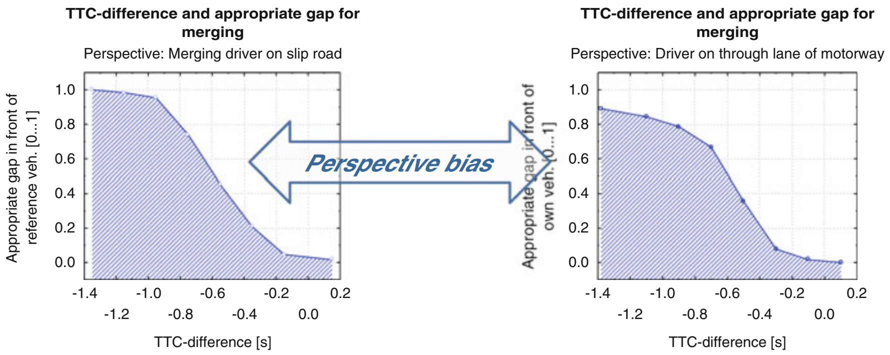


Fig. 16 Effect of TTC-difference on appropriate gap for merging (*left*: perspective of a merging driver on slip road; *right*: perspective of driver on through lane of motorway)

Fig. 17 Scenario of the study 'Merging assistant' with activated merging assistant (*left*) and without any assistance (*right*)

evaluated the gap in front of them as appropriate. This difference shows that the subject's perspective influences the gap evaluation, with own intentions leading to egoistic evaluations.

3.4.1 Methodology

The study following this important finding, had the objective to measure the emotional effects a merging assistant could have in reducing driving conflicts during merging interactions. As soon as the subject enters the slip road, that device recommends an optimal gap for merging (assessed by reducing the necessary decelerations). The recommendation is presented by an enhanced reality item that is directly projected into the specific gap and can be seen by all drivers (Fig. 17). Subjects are instructed that they are not obliged to follow this recommendation made by the Merging Assistant.

Fig. 18 Layout of the used motorway section during the study ‘Merging Assistant’

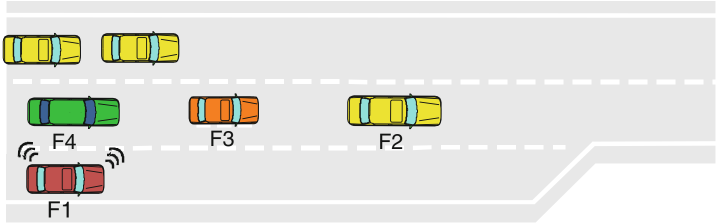


Fig. 19 Schematic representation of scenario in study ‘Merging Assistant’

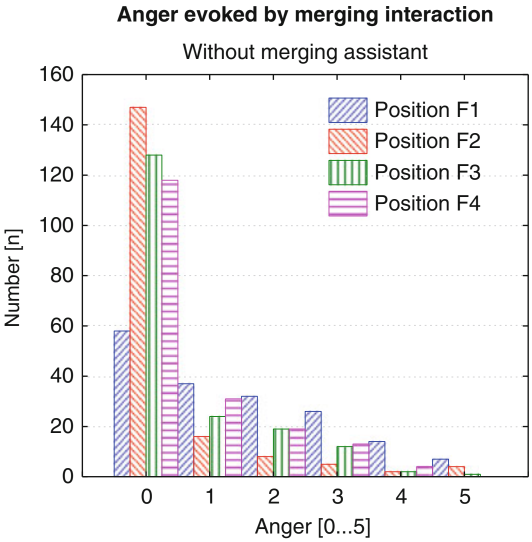
The study takes place on a motorway section (Fig. 18) with two lanes per direction, one exit ramp, and one merging lane. The overall length of the section is 1,150 m. The length of the road that can be used for merging from the slip road onto the motorway is 115 m. This layout results in relatively high pressure/urgency for lane changing. Each experimental situation is realized on one section.

Four subjects interact with each other in the same scenario at the same time. Together, they approach a merging point on the motorway and are located either in the merging vehicle on the slip road or in one of three vehicles on the right lane of the motorway (Fig. 19). In some situations the drivers are assisted by an ADAS that gives a recommendation concerning the most appropriate gap. At the end of the situation and after the driver on the slip road has merged onto the motorway, he has to leave the motorway again. Subsequently, the next situation starts.

Therefore, two independent variables are realised: (1) with versus without Merging Assistant and (2) perspective as merging vehicle versus first vehicle on through lane versus second vehicle on through lane versus third vehicle on through lane. Moreover, by variation of the position of a pace car on the right lane of the motorway it is guaranteed that not every situation is similar to the situation before. This variation makes the simulated merging interactions more realistic.

The analysis of the experiment yields descriptive information about the merging interactions between four drivers and the according emotional response. All in all, the following dependent variables are measured:

Fig. 20 Anger evoked by merging interaction without merging assistant (*n*: number of events/situations; anger rating: 0 not at all, 1 very low, 2 low, 3 medium, 4 high, 5 very high)



- Choice of gap: Gap chosen by the merging driver (and therefore solution of the merging interaction) (simulator data)
- Interaction between drivers: E.g. time of merging and headways after the merging interaction has taken place (simulator data)
- Anger response: Anger evoked by the merging interaction (question presented via touch display)

Four groups with four drivers each, i.e. a total of 16 subjects (5 female, 11 male), took part in the study. All had some training in the multi-driver simulation, in order to be accustomed to driving with that kind of simulator. They have an average age of 38.1 years (SD = 12.5 years; min = 22 years, max = 63 years). Their driving experience was between 3,000 and 54,000 km/year (mean = 14,938 km/year, SD = 11,766 km/year). The portion of driving done on the motorway varies between the drivers with a minimum of 0 % and a maximum of 60 % (mean = 34.7 %, SD = 19.1 %).

3.4.2 Results

Is a Merging Assistant able to reduce conflicts and negative emotions during merging interactions? All in all, the results show that merging interactions are not generally characterised by high levels of negative emotions. The answers for the subjects on the through lane of the motorway indicate (F2–F4; Fig. 20) that they feel no anger at all or only very low levels of anger. Just the driver on the slip road (F1) indicates that he feels in average at least very low to low anger. That does not

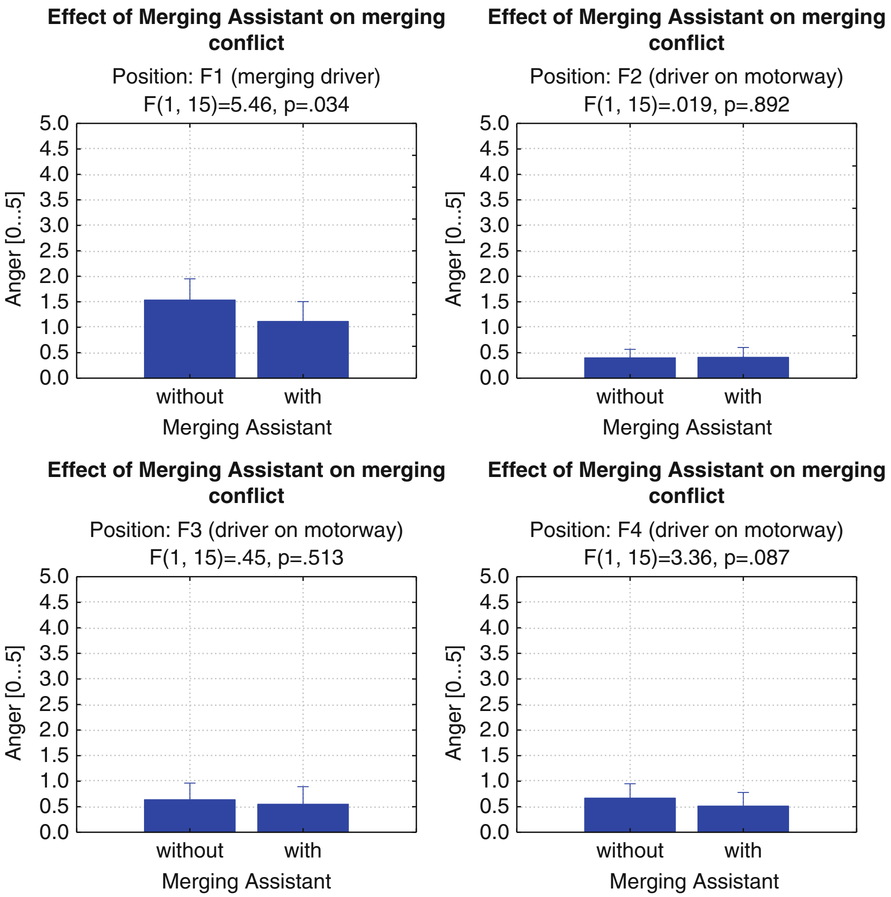


Fig. 21 Effect of merging assistant on anger felt by test drivers during merging interactions in all four positions (F1: merging driver; F2–F4: drivers on motorway)

exclude that some interactions come along with significant conflicts and anger responses.

Furthermore, the results show that a Merging Assistant reduces the anger felt by the driver on the slip road, namely F1 (F(1, 15) = 5.46, p = .034; Fig. 21 top left). All test drivers on the through lane of the motorway (F2, F3, F4) are not influenced by the Merging Assistant (F2: F(1, 15) = 0.19, p = .892; F3: F(1, 15) = 0.45, p = .513; F4: F(1, 15) = 3.36, p = .087). Partly, this is due to ground effects.

A detailed analysis of the effects of the merging assistant on all 16 drivers taking part in the study revealed that every second subject trying to merge onto the motorway benefits from the assistance (Fig. 22). Maybe, this positive influence on only half of the drivers is due to some potential for optimisation of the used merging algorithm. This especially concerns to the moment a recommendation of a

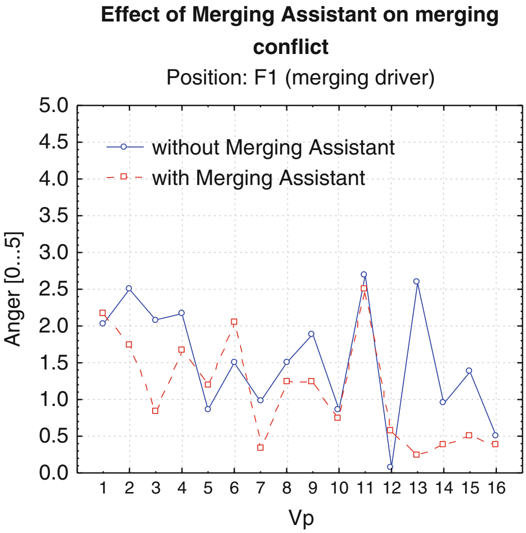


Fig. 22 Effect of Merging Assistant on anger felt by individual test drivers driving on the slip road and trying to merge onto the motorway

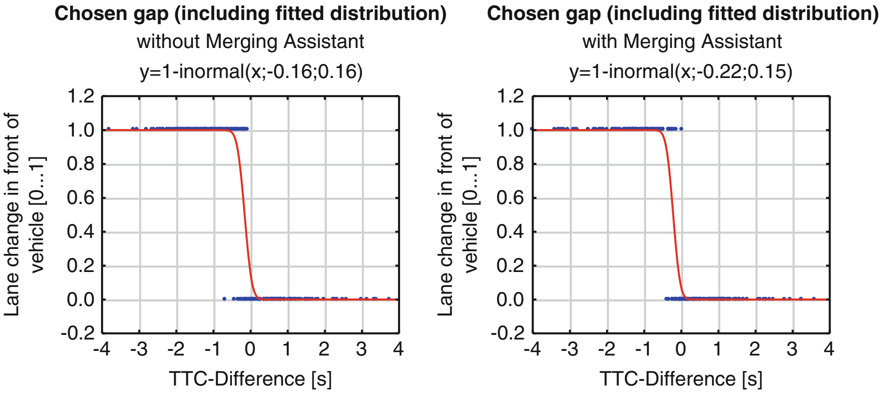


Fig. 23 Gap chosen by subjects without Merging Assistant (*left*) and with Merging Assistant (*right*)

gap for merging is given. The system under study displayed the optimal gap when the merging driver passed the beginning of the slip road; nevertheless, an earlier recommendation would be evaluated more positive by the drivers.

Which gaps are chosen by the subjects depending on TTC-difference and assistance by the AmI system? Figure 23 shows how often drivers choose a gap in front of another vehicle on the right lane of the motorway.

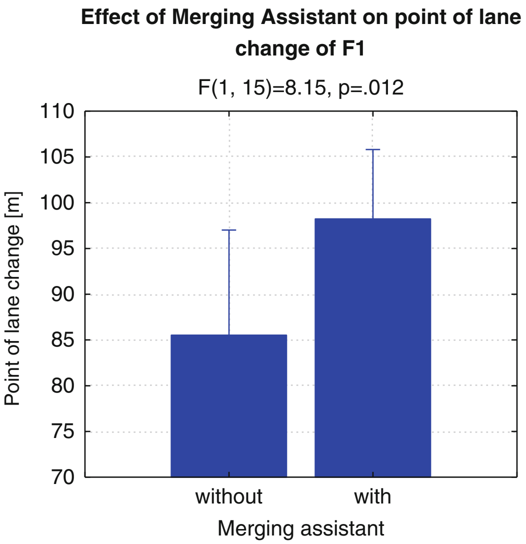


Fig. 24 Effect of merging assistant on point of lane change (measured as distance from the beginning of the slip road; F1: merging driver)

The results show that there are just minor differences between the two conditions with and without merging assistance. This implies that the Merging Assistant does not generally change the target gap the drivers on the slip road would like to merge into. This further explains why emotional effects on the drivers on the through lane do not emerge. For them the interactions stay very much the same – independent if a Merging Assistant recommends an optimal gap or not. The emotional effects on the driver on the slip road seem to be a consequence of the fact that an 'objective' device supports the choice that they already made.

But does a merging assistant change the merging interaction itself in terms of moment of lane change or headways of vehicles involved in the merging interaction? The results show that the Merging Assistant leads to a later lane change (Fig. 24). Whereas drivers without any assistance change onto the right lane of the motorway after driving 85 m on the slip road, the drivers assisted by the AmI system change lane approx. 13 m later. An explanation for this effect could be that the drivers wait for the recommendation of the Merging Assistant and as this recommendations comes relatively late (with the beginning of the slip road) the lane change itself is initiated at a later point.

Nevertheless, this does not have any effects on safety. An examination of all headways (rear and front) of all four vehicles driven by test drivers does not reveal any significant effects of the Merging Assistant. This is also shown by the following box plots (Fig. 25).

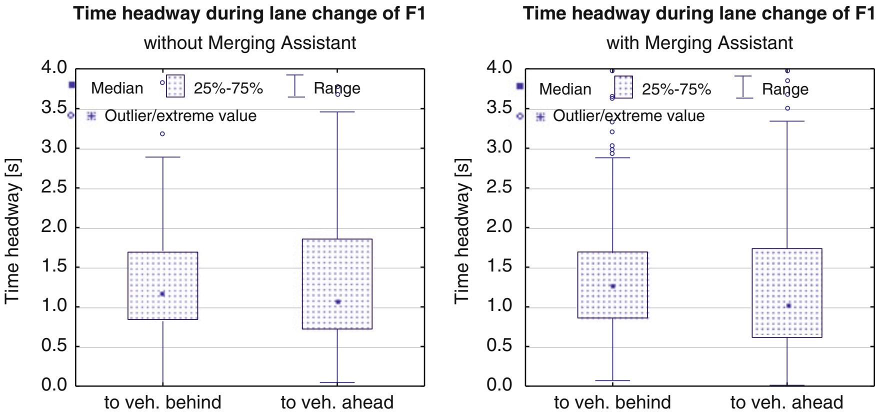


Fig. 25 Time headway during lane change without Merging Assistant (*left*) and with Merging Assistant (*right*)

3.4.3 Discussion

The analysis of a system assisting the drivers interacting in merging situations shows that only the driver on the slip road profits by such a system. This driver feels less anger compared to the condition of being not supported by a merging assistant. Nevertheless, the final discussion with the subjects yielded the result of a more fluent merging and less conflicts for all affected drivers.

Analysing the driving interactions shows that drivers normally merged into the gaps recommended by the merging assistant. Moreover, they merged somewhat later during the condition with Merging Assistant; but no effects on headways (front, rear) emerged. This leads to the assumption that safety is not negatively affected by a Merging Assistant. As a consequence, a Merging Assistant could lead to significant improvements of traffic safety and traffic climate by reducing the potential for conflicts during merging interactions on the motorway.

3.5 Efficient Cruise Control

The study analyses a new type of cruise control system called Efficient Cruise Control (ECC). This system has the objective to make driving smarter and greener and can be characterised as an improved ACC system.

A traditional ACC system is equipped with sensors that detect objects in front of the vehicle and adjusts the vehicle speed in a way that a defined time headway is guaranteed. If no object is detected in front, the vehicle drives with a speed set by the driver. Modern ACC systems work properly in a full range of speed from 0 km/h up to 150 km/h including stopping the vehicle due to stop and go traffic (and to accelerate again).

The ECC system analysed in the following enhances the functionality by integrating road topography and traffic rules. Besides objects in front and a speed set by the driver the following data is used as input:

1. Road curvature: Depending on the radius of the curve and a (predefined) maximum lateral acceleration the system calculates a speed for driving through the curve.
2. Speed limit: The system detects traffic signs that indicate speed limits (including town entrances) and adjusts the speed in a way that the vehicle does not exceed the speed limit.
3. Traffic lights: Position and current state of traffic lights are detected and the vehicle comes to a halt in front of the traffic light, if the state is ‘red’ (starting again has to be done manually by the driver).
4. Intersections: In front of intersections with a stop sign the vehicle comes to a halt (starting again has to be done manually by the driver).

Later versions of the ECC could also include slopes, further types of intersections, weather conditions etc. into their decision of an appropriate speed. The expected effects from the ECC system under study are reduced energy consumption compared to manual driving as well as traditional ACC systems, increased safety due to guaranteeing safe headways and proper behaviour in front of intersections, and enhanced comfort as the driver does not need to control the speed of the car in many situations.

The following sections give examples how a driving simulator can be used for developing and evaluating such an ECC system. The focus is laid on the methodological approach and much less on the first results, because the ECC system is currently (June 2012) in a prototype state of development.

3.5.1 Methodology

As the reduction of energy consumption is one key objective of the ECC system, the development using a driving simulator needs to be based on a validated vehicle model. This vehicle model has to reflect the energy consumption at different velocities and under different load conditions. The vehicle model used in the following describes a fully electric vehicle and includes the main parts chassis, power train, vehicle dynamics, and energy storage system. The chassis including brakes and steering is based on a Tata Vista EV. The energy storage system models a Li-Ion battery with a maximum capacity of 25 kWh. The motors of the powertrain have a power of 50 kW and 1,550 Nm maximum torque. The energy is converted inside the electric machines to a movement of the wheels using fixed transmission without gear box. When the power train gets the command to brake, kinematic energy is stored inside the battery (recuperation). Besides recuperation, vehicle speed can be reduced by applying the hydraulic brakes.

During the process of developing an innovative ECC system several decisions have to be made. Two examples are presented in the following and apply to the

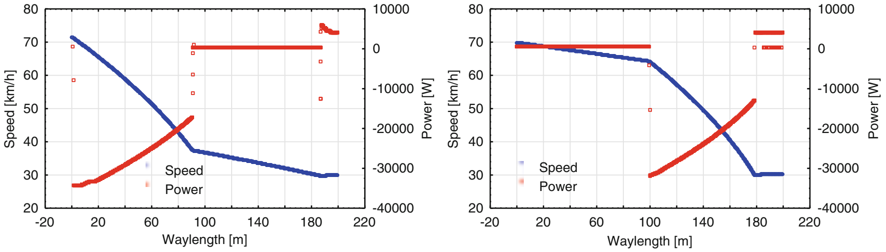


Fig. 26 Speed profile and recuperated power for the two different strategies that can be used to reach a new target speed (*left*: 'recuperation before sailing'; *right*: 'sailing before recuperation')

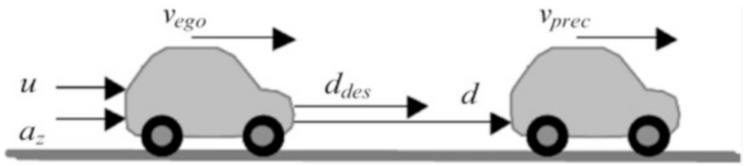


Fig. 27 Controller algorithm of an ACC system ([19]; u is the desired vehicle acceleration [m/s2], Δv is the difference between the velocity of the preceding and the equipped vehicle, Δd represents the headway error or range [m] as difference between the desired headway and the actual headway, kv and kd represent damping and stiffness, az is the disturbance acceleration caused by e.g. road slopes, wind, etc., u is an additional term)

characteristic of (1) reducing speed in order to reach a new target speed and (2) following a lead vehicle.

How should electric braking to a target speed be done? Basically, two different strategies are possible: (1) 'recuperation before sailing' with the vehicle braking electrically and a minor adjustment to target speed afterwards and (2) 'sailing before recuperating' with the vehicle sailing up to the point where maximum recuperation is necessary in order to reach target speed in due time.

Testing these two strategies in the driving simulator yielded the result that recuperation before sailing is more energy efficient than the other strategy. An example for decelerating the vehicle from 70 to 30 km/h within a road section of 200 m is shown in Fig. 26. The recuperated energy is 40.1 Wh for recuperation-sailing compared to just 35.7 Wh for sailing-recuperation. Therefore, this characteristic of the vehicle is implemented in the parameterization of the ECC system.

Which parameters for an ACC controller for car following are efficient? In order to answer this question, different values for damping and stiffness (kv, kd) are analysed while following a lead vehicle. According to Venhovens et al. [19] a typical controller for an ACC system works as follows (Fig. 27):

$$u = k_v \Delta v + k_v k_d \Delta d - a_z + \overline{u}$$

In order to derive optimal values for damping and stiffness, several parameters were tested using scenarios with different speed behaviours of the lead vehicle (e.g.

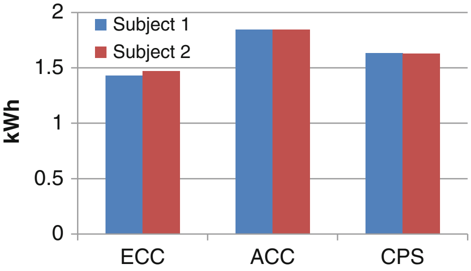


Fig. 28 Energy consumption of an electric vehicle with Efficient Cruise Control (ECC), traditional advanced cruise control (ACC), and manual driving using a combined pedal solution (CPS)

concerning form and amplitude of speed change). An exemplary result on a 400 m section of a straight road with a lead vehicle changing speed according to a sinus wave with an amplitude of 2.76 m/s and a period of 3 s resulted in an energy consumption of 68.6 Wh using low values of damping and stiffness (kd 0.1, kv 0.1) and 72.3 Wh with higher values (kd 1.0, kv 1.0). Again these results are implemented in the parameterization of the ECC system.

3.5.2 Preliminary Results

Within a pilot study the effects of an ECC system versus traditional ACC and manual driving on energy consumption are analysed. This is done by using a fixed-base single-driver simulator. Manual driving was done by using a combined pedal solution (CPS). This means that releasing the accelerator pedal leads to an electric braking of the car. The brake pedal is just used for hydraulic braking.

Two drivers drove a route of 13.9 km with rural and urban sections, different speed limits, car following, road intersections, and red traffic lights. Figure 28 shows the overall energy consumption for the three different conditions. The results indicate that an ECC system has the potential to reduce energy consumption and by doing so increases the range of an electric vehicle.

3.5.3 Discussion

Besides testing the effects of new ADAS driving simulation can also be used for the development of new driver assistance system. In the example reported an enhanced ACC system is developed and preliminary findings suggest that such a system actually reduces the energy consumption of a fully electric vehicle.

Nevertheless, such a development depends very much on the validity of the used vehicle model. Therefore, much effort should be invested in the development of the vehicle model and its correct implementation into the driving simulator.

In a next step, the effects of the ECC on a group of drivers will be analysed. The main research question will be, if a vehicle equipped with ECC will also reduce the energy consumption of drivers following this lead vehicle and controlling speed manually.

4 Discussion

The chapter presented several examples for emerging phenomena during driving interactions studied by using driving simulation. Especially the innovative approach of multi-driver simulation proved being suitable for studying emerging phenomena in road traffic. This could be lane-to-lane effects (see study on braking convoy), driver-to-driver effects (see study on group driving), or effects that modern ADAS have on drivers and their interactions.

Concerning ADAS, three systems were under study: Hazard Warning, Merging Assistant and Efficient Cruise Control. All three have the potential to improve driving on an individual, group, and system level. In order to structure future efforts on studying ADAS, it is recommended to focus on a 3 by 3 table spread by the dimensions ‘level of investigation’ (individual, group, system) and ‘evaluation criterion’ (safety, emotional climate, stress, and driver comfort, efficiency).

A systematic analysis of the effects and implications of such systems needs an interdisciplinary approach involving traffic engineering and driving psychology. Just by integrating diverse methodologies like experimental runs in the driving simulator (depending on the specific research question using single-driver and multi-driver simulators with different levels of fidelity), studies in real traffic (e.g. pilot tests on test tracks, field-operational tests), and traffic simulations (e.g. microscopic simulations modelling individual driver-vehicle entities) a comprehensive picture can be devised.

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Effective Assessment of AmI Intervention in Traffic Through Quantitative Measures

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1 Introduction and Related Work

In this chapter, we seek to quantify the benefit of Ambient Intelligence (AmI) within a complex system, specifically a motorway traffic system made up of agents with or without an AmI system. In addition to the potential autonomy of the individual AmI systems, the overall system of traffic is autonomous in general, because no external control is needed for the interaction between the devices. It is completely decentralized: although the rules are pre-installed in the vehicles, the decisions about when to activate them are induced by the local interactions, so no central instance is needed for controlling or for the configuration of the system. Such systems can be adaptive with respect to changes in the environment (e.g. presence of an accident or not) and to changes in the system itself, (e.g. a change in car density or a change in the equipment rate r, which is the percentage of all cars having the AmI device). Because of the decentralization, there is no single point of failure, so a breakdown of a device has only a small influence on the behavior of the system. Under these conditions we have a self-organizing system. For a formal definition of the self-organizing properties, see the appendix.

There are many possible approaches to establish whether a given self-organizing, AmI-driven system at work in society is having a desired or undesired effect. We could perform longitudinal studies that try to tie societal changes to new

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technologies. Or questionnaires could be used to establish users' attitudes and use of a device. In the area considered here (vehicle traffic), instrumented vehicles or video recordings can be used to try and understand traffic effects. All of these assume that the device already exists and/or is at work in traffic at large. If we only have an idea of what the device could or should do, modeling approaches come into play, and the question of what manner and level to measure needs to be answered.

One recent approach for the analysis and evaluation of such system is quantitative measures [1–3]. In the micro-level model, measures are defined for the evaluation of global properties like emergence, target orientation, adaptivity, autonomy or global state awareness. These measures are described in detail in the appendix and have the advantage that they are comparable across scenarios and systems because of normalization. In addition, some of the measures (when proposed) were novel in the sense that they quantified for the first time various qualitative properties of self-organizing systems. In this chapter, we concentrate on the measure for target orientation. In some sense this is more traditional than some of the other measures: it describes how well the system is performing, which of course is the usual goal of any system evaluation. However, due to normalization we can describe the systems success along a scale of worst possible state to best possible state with a single number. For the measure of target orientation, the goals have to be defined in advance in the form of a fitness function. The target orientation of the system is a value in the interval [0, 1] indicating how "good" the system behaves. The analysis and optimization of system parameters can then be made in accordance with predefined goals encapsulated in the target orientation measure.

The measures (including target orientation) and fitness function are generically defined for any system. The main problem considered here is how to make them domain specific. The domain at hand is vehicle traffic on a motorway, and the specific problem that of vehicle breakdowns and crashes on motorways. These have direct and indirect impacts on traffic flow (e.g. efficiency and economy) and traffic safety. The loss of a lane available to traffic can create a sudden drop in traffic flow and make driving conditions dangerous through the sudden change in traffic speed and the requirement of many braking and merging manoeuvres within a confined region. These changes often result in follow-on accidents. In recent years, a large amount of development effort has been invested in vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies which will allow incident information and driving instruction to be delivered to motorists far more rapidly than it was traditionally possible. Hence, it is now technically plausible that a vehicle-communication based system could allow even a small number of equipped and compliant drivers to rapidly improve the driving situation for others by taking appropriate action. This could happen without the aid of any infrastructure. For a longer introduction to the problem, please see [4]. We begin by giving a short overview of the system and its goals (Sect. 2) which motivates the choice of measures made in Sect. 3. The measurement process through simulation is also briefly covered in Sect. 3. Results are presented in Sect. 4 followed by a discussion and conclusions in Sects. 5 and 6 respectively. The background information on the quantitative measures themselves is contained in an appendix to the chapter.

2 System Overview

Two broad types of system are tested for the AmI devices. The first is a fine-grained speed reduction system (also known as harmonization (HAR) or speed 'funnel') where the (desired) speeds of vehicles are set individually by an on-board system according to the distance from a point of danger. This is inspired by traditional overhead, sign-based systems but differs in having the ability to communicate a speed at any place and hence with smaller increments. A similar system is investigated in [5]. In previous work, it has been shown that reducing traffic speed approaching a disturbance in traffic flow through vehicle communication improves the harmonization of the flow of traffic approaching the blockage [5]. Harmonization in this context means the reduction of sudden changes in traffic speed over time and/or space (i.e., at a macro level), that are thought to be responsible for micro changes in vehicle speed that result in accidents. Indeed, the experience of motorway operators has shown that overhead, variable message signs bring an improvement on safety (e.g. [6]). However, in these systems speed is changed (or attempted to be changed) more-or-less at the macro level directly. In a peer-to-peer AmI system, we derive these changes from many drivers changing behavior at different places and times. The danger is that one 'informed' driver may react suddenly to information that an 'uninformed' driver does not have. Hence, the macroscopic changes in traffic speed might appear similar to those obtained using an infrastructure-based system that is fixed in position (e.g. variable speed limit signs), but the microscopic interactions between the drivers may be different. This makes an evaluation based on individual agent experience more appropriate.

The second system is an adaptive cruise control (ACC) system that, when following another vehicle in range, is that of Kesting and colleagues in a special configuration for being upstream of a bottleneck [7]. Here, the acceleration is set in order to maintain a certain time headway. The ACC system when no preceding vehicle is in following range is a simple ACC that applies acceleration or deceleration within limits ($\pm$ 1.4 m/s^2) until the desired speed is reached. Both systems feature a common danger point detection algorithm that decides whether alerts are generated, forwarded, and whether a system is activated. Thereafter the control of the vehicle is governed by the HAR algorithm or ACC algorithm until the origin of the alert is passed. Full details on both systems can be found in [4].

3 Measurement Definition and Simulation Testing

To establish what measurements should be made, the target(s) of the system should be agreed upon. Derived from this, we can define which of the system states are safe or desirable and which not. These should then be assigned concrete numbers from a quantity that can be measured from the system entities. This facilitates normalization, which can either be explicit (a chosen relevant maximum and minimum) or taken from the properties of the data (both approaches are taken below).

Considering the goal of the system, i.e. reducing the risk of accidents, we want to test for the most stable possible system state, where variations in vehicle interaction states are minimized, while maintaining traffic flow. A number of possibilities exist for utilizing the vehicle data (including simply averaging measures like headway or deceleration). Specific to speed harmonization evaluation, we know of no measures applied to individual vehicle data to assess the degree of "harmonization". One recent approach applied to single-point detection data is to measure the variation coefficient of the data [8]. This normalizes the standard deviation of the data (e.g. speed) by the average, hence removing 'disharmony' that is only due to the magnitude itself. This approach is included in our application of quantitative measures to try and directly assess the success of supposed system functionality (rather than indirect benefits).

Target orientation is a time dependent measure, which describes how good the current situation is. For this purpose, a fitness function g: S → [0, 1] has to be defined on the set S of all possible states of the system. Then the level of target orientation $TO_t = E(g(s(t)))$ at time t is the mean value of the fitness of the current state s(t), where in a stochastic system s(t) is a random variable.

Based on the two properties we are seeking from the systems (traffic harmonization and safety in general), we examine three measures (expressed formally below). With measure #1, bad states are situations where velocities have a high variance coefficient, because a high variance of velocities implies that many different speeds are present in the system. Analogously, measure #2 specifies a good state by a low variance coefficient for the velocity changes that each vehicle makes from one time step to the next. These measures express the "system goals" of motorway speed management, namely to see less variance in the overall speed, and to prevent drivers from having to adjust the speed suddenly. Measure #3 attempts to examine the safety effects more directly by using a simple safety 'proxy' indicator, Time-To-Collision [9] (TTC, time until collision if one vehicle is closing in on another).

Measure #1: Link Velocity Harmonization This measure is based on the variance coefficient of velocities $\{v_i(t) | i \text{ vehicle}\}$ at each point in time t.

$TO_t^1 = 1 - K \cdot \frac{\sigma_t}{\mu_t}$ where K is a normalizing constant,

$\mu_t = \frac{1}{n_t} \sum_{i=1}^{n_t} v_i(t)$ is the mean velocity

n_t = number of cars in the system at time t,

$\sigma_t^2 = \frac{1}{n_t - 1} \sum_{i=1}^{n_t} (v_i(t) - \mu_t)^2$ is the empirical variance of velocity.

Measure #2: Acceleration Harmonization This measure is based on the variance coefficient of velocity change (acceleration) $\{v_i(t+1) - v_i(t) | i \text{ vehicle}\}$ from the current point in time t to the next time step.

$TO_t^2 = 1 - K \cdot \frac{\sigma_t}{\mu_t}$ where K is a normalizing constant,

$\mu_t = \frac{1}{n_t} \sum_{i=1}^{n_t} \Delta v_i(t)$ is the mean velocity change,

$$\Delta v_i(t) = |v_i(t+1) - v_i(t)|$$

n_t = number of cars in the system at time t,

$\sigma_t^2 = \frac{1}{n_t - 1} \sum_{i=1}^{n_t} (\Delta v_i(t) - \mu_t)^2$ is the empirical variance of velocity change.

Measure #3: Individual Safety This measure is based on the mean of all finite Time-To-Collision (TTC) values.

$TO_t^3 = 1 - K \cdot \frac{\sigma_t}{\mu_t}$ where K is a normalizing constant,

$\mu_t = \frac{1}{n_t} \sum_{i=1}^{n_t} TTC_i(t)$ is the mean TTC,

$$TTC_i(t) = \begin{cases} \frac{dist(i,succ(i))}{v_i(t) - v_{succ(i)}(t)} & \text{for } v_i(t) > v_{succ(i)}(t) \\ 3 & \text{if } v_i(t) \le v_{succ(i)}(t) \text{ or } succ(i) \text{ does not exist} \end{cases}$$

succ(i) = car driving in front of car i,

dist(i, succ(i)) = distance between car i and the car driving ahead,

n_t = number of cars in the system at time t,

$\sigma_t^2 = \frac{1}{n_t - 1} \sum_{i=1}^{n_t} (TTC_i(t) - \mu_t)^2$ is the empirical variance of TTC.

Measure #3 represents an improvement over our previous work [4] where all TTC values were considered. Here we define a threshold of 3 s [9] to represent a safe state; hence any values above 3 s are quantized to this value for the analysis.

Although the level of target orientation TO_t is defined analytically (see appendix), it is usually impossible to evaluate the level of target orientation analytically, because the set S of all global states is very large. Therefore approximation methods are needed [10]. We use the results of simulations to approximate the level of target orientation.

For such a simulation, we require the ability to model vehicles in detail (because the measures used require detailed data concerning the vehicle interactions) and the ability to simulate the system and its communication needs in an integrated fashion. For our simulations, the vehicle traffic simulation VISSIM [16] (version 5.30, PTV AG, Karlsruhe) has been used, but there are several other possibilities (e.g. ITETRIS, VSIMRTI). Generally speaking, all approaches (including ours) utilize an application programming interface (API) whereby a logic for the system and communication can be defined for when messages are sent, and what action should be taken by the driver when they are received [5]. How the communication is modeled is usually flexible depending on the level of detail required and in the event of a large amount of detail being required, the exact properties of the

Table 1 Examined system parameters

Parameter	Description	Values
thw_{f0}	Time headway desired (ACC only) (s)	{1.5, 1.8, 2.1}
f	Input traffic flow (veh/h)	{500, 1,000, 1,500}
r	Equipment rate (%)	{0, 10, 50, 100}

communication system (e.g. medium type and bandwidth). We use a specialized version of the VCOM communication model [11].

The simulation tests used a simple straight road length where one vehicle equipped with a system is stationary and broadcasts accident alerts. More details can be found in [4]. This tests the system in a generic way, but for many use-cases it may be more appropriate to use a specially calibrated simulation for a specific road stretch [12].

Table 1 specifies the values for the system parameters. Two parameters are variable for both systems: The input traffic flow f (unit: vehicles per hour) and the equipment rate r (unit: %) of the AmI device. For the ACC system, there is another variable system parameter thw_{f0} for the target time headway (unit: seconds). For all variations of f and r, the HAR and ACC systems were tested, with the ACC system in addition being subject to the three variations of thw_{f0}. All other parameters are constant. This leads to a total of $36 + 12 = 48$ configurations for the evaluation of target orientation.

Each configuration is tested for a simulation time of 1,800 s, with simulation time steps of 0.1 s (although the analysis is performed utilizing data from every tenth time step, i.e. 1 s intervals). This is both to reduce computational effort, but also to provide some aggregation of acceleration (which fluctuates highly) differences in Measure #2, as suggested in [4]. The analysis is performed over a relevant stretch of the road where communication takes place. The simulation scenario file, application/control script and evaluation scripts are available from the authors upon request.

4 Results

Although for some cases it may be useful to examine the change in Target Orientation over time, we examine here only the mean values (Fig. 1a–c). These show the target orientation measures #1–#3 (see Sect. 3) calculated from simulation results in dependency of the system variant (HAR or ACC with variable thw_{f0}, f and r). The overall level of target orientation of the system is

$$TO^i = \frac{1}{s}\sum_{i=1}^{s} TO_t^i$$

for $i \in \{1, 2, 3\}$, where s is the number of analyzed steps in a simulation run.

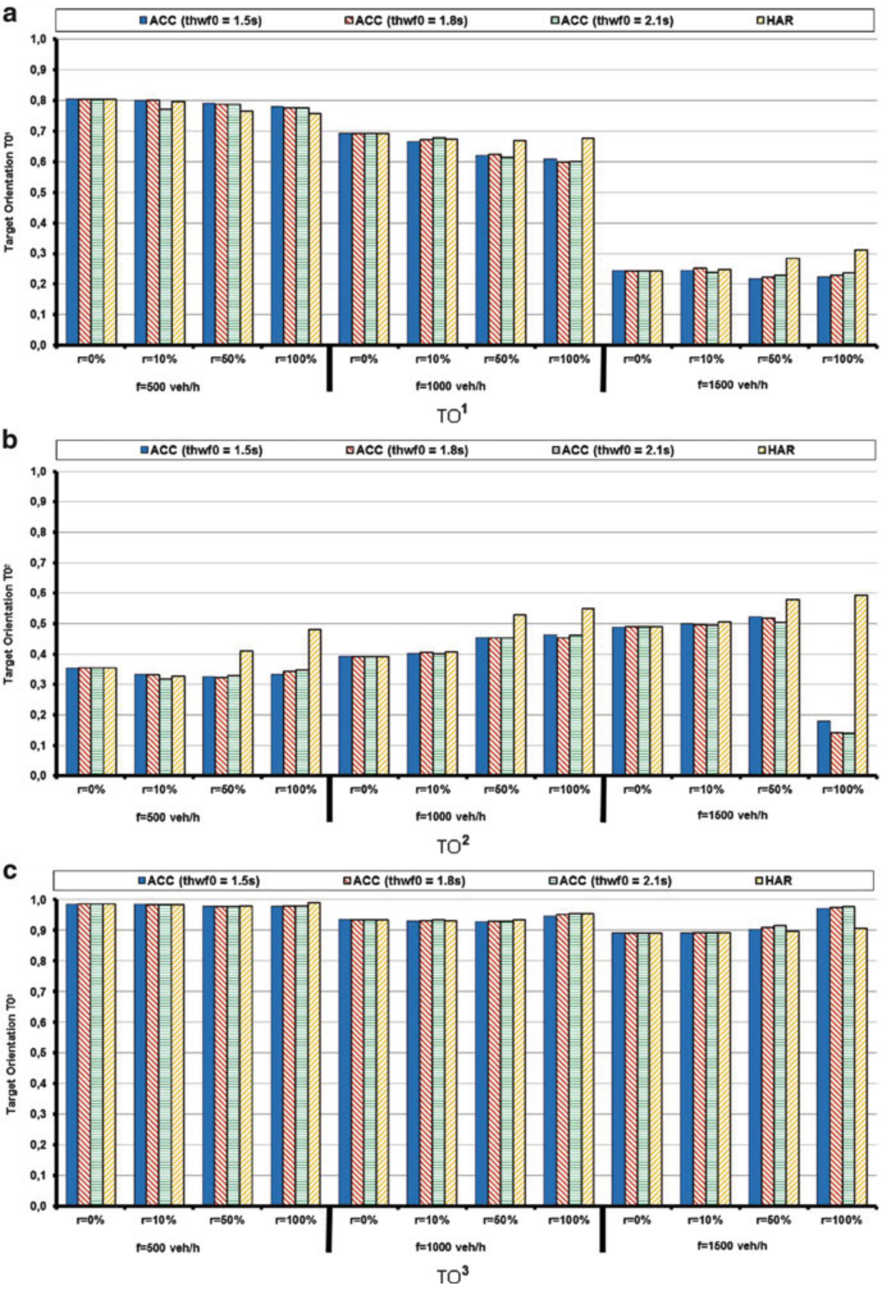

Fig. 1 Target orientation TO^1–TO^3 measured within the relevance area of the three ACC system variants ($thw_{f0} = 1.5$, 1.8 or 2.1) and HAR system separated by input traffic flow f in veh/h and equipment rate r in %, according to (**a**) the variance coefficient of the speed of all vehicles, (**b**) the variance coefficient of the speed change of all vehicles between time steps and (**c**) the mean of all

For a first analysis of these figures, we can examine the values of the measures for one variable parameter and two constant parameters:

- For fixed values thw_{f0} and f and variable values for r we observe:
  - For the ACC system measure #1 is generally decreasing as r increases. For the HAR system the picture is similar except for f = 1,500 veh/h where it is increasing
  - For the ACC and HAR systems measure #2 is generally increasing as r increases except for f = 500 veh/h and f = 1,500 veh/h with r = 100 % (outlier)
  - For the ACC and HAR systems measure #3 is generally increasing with r but values are very similar. As the base case gets worse with increasing f, these differences become bigger.
- For fixed values f and r and variable values for thw_{f0} in the ACC system the only pattern is that measure #3 slightly increases with thw_{f0}. This difference is larger with increasing f.
- For fixed values thw_{f0} and r and variable values for f we observe:
  - Measure #1 decreases as f increases
  - Measure #2 increases as f increases (except for the ACC system at f = 1,500 veh/h)
  - Measure #3 decreases as f increases (except for the ACC system at f = 1,500 veh/h and r = 100 %)

5 Discussion

The measures were tested for varying parameters, which can be freely set (under simulation conditions). Whereas the time headway thw_{f0} can be chosen for the system, the equipment rate r and the input traffic flow f cannot be controlled at the individual system level. However, the variables can still either be used to understand what system rules should be employed, or an infrastructure operator could use them to exert some control over the traffic system. For a nominally high equipment rate r, the possibility could exist to deactivate the AmI device in a certain number of vehicles (in case of undesired effects at high equipment rate). Unfortunately, the opposite problem, of too low equipment rate, can only be solved in the longer term by market take-up, and hence is only useful for market and policy-making decisions. Regarding the input traffic flow f, the variable can be somewhat

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Fig. 1 (continued) finite Time-To-Collision values of all vehicles. To assess a system benefit in a given situation, one should generally compare within the three f-value blocks against the “base case” of r = 0 %

controlled by the road operator where diversion or ramp metering facilities exist. These factors must be borne in mind when discussing the results.

The results of Sect. 4 show that the influence of the system parameters differs according to the measure used, even though ideally all measures, which are examining desirable states, should show similar results. Intuitively, a higher equipment rate should lead to a situation, which is safer. But the simulation results show, that while this often works for measure #2, which pertains to individual driver experience, it rarely holds for measure #1, which examines the entire analyzed area. For measure #3, we observe large improvements only for the $r = 100\,\%$, $f = 1{,}500$ veh/h case. Measure #1 showed little system success except for the HAR system at higher equipment rates for the largest input traffic flow. Specific to the HAR system, this can be explained partly by noting that the velocity of the whole system is inherently unlikely to be 'harmonized' when not all vehicles are controlled and furthermore those that are controlled are not controlled in a synchronized way. Interestingly here also, when there is less congestion (lower f), higher r values do not improve the outcome. This may be because more cars can drive at their desired speeds such that the arrival of speed reduction instructions results in (relatively) more diversity of speeds in the system.

Measures #1 and #2 suggest that the HAR system is often better than the ACC system, especially for a high input traffic flow. For measure #3 there is so little improvement to be made that the use of any of the systems usually seems unnecessary.

Overall, the results are mixed. In this case they cannot be used to choose one measure as the ideal or one system is better or worse than the other. While there is evidence to show that speed harmonization based on variable message signs (VMS) improves safety (e.g. [6]), we cannot automatically assume that the same will be true of a peer-to-peer system, or show (via measure #3) that any large safety benefit is present. None of the measures bring a noticeable benefit at low equipment rates. This may serve as a warning: Systems that seem sensible for a single driver may only bring about benefits for all traffic when we ensure high equipment rates.

6 Conclusions and Future Work

In this work, we have discussed how a self-organizing AmI-based system may be evaluated in a targeted and comparable fashion using the quantitative measure of target orientation. The system was designed to increase safety on a section of highway in the event of one lane being blocked by an accident. It can be seen that quantitative measures are a useful evaluation tool, which can be used for the design, analysis and optimization of a complex decentralized system, in this case traffic. We have applied the measure for target orientation based on different fitness functions to analyze the system. The results were used to investigate the influence of system parameters on the safety in such a situation and to understand when the system performs well and when not.

There are several areas where the work can be extended upon both in terms of improving the analyses and understanding how to improve the systems themselves. The traffic situation and road network were artificial (constant input traffic flow) and hence the base driver model, while validated in general [13] is not calibrated to real data. This may have led to overly 'safe' driving demonstrated through measure #3. Obviously the examined scenario needs to be plausible and valid for the measures, no matter how suitable they may be, to be of any use. Indeed, the measures can be used to augment traditional calibration techniques whereby (if data is available) the measure from reality and an "as-is" simulation is compared. Overall, the results should not be used for the recommendation for or against the implementation of any particular system in traffic. Only one simulation per case was used for this analysis. This prohibits plotting standard error which can inform as to the likely significance of differences. We are currently performing additional simulations to make this possible. The systems are also somewhat simplistic in nature and have not been tested with real drivers.

In scenarios where there is a tradeoff between different goals that should be achieved, the corresponding measures for target orientation may be combined into a single measure. A methodology for deriving such a combination and the corresponding evaluation is left for future work. Elsewhere [4] we have considered the measure of emergence, to examine the appearance of global patterns arising from the local interactions between the entities. It is also worthwhile to investigate other quantitative measures like global state awareness [3] to answer questions like "Which system parameters can increase the global state awareness of all drivers?" Finally, we wish to stress that the evaluation methodology used in this chapter is not restricted to the special scenario of an accident on a highway, but can be used in any other context of self-organizing systems where input data can be measured. The critical steps are to define what the target(s) of the system should be, which of the states safe or desirable states are and which not, and to assign these concrete numbers from a quantity that can be measured from the system entities.

Appendix

Model of Socio-technical Systems

For modelling socio-technical systems, we use the methods of [1], which are based on the ideas of [14]: A directed graph $G = (V, K)$ describes the entities V of the system and their network topology, i.e. each node $v \in V$ in the graph corresponds to an entity and each edge $(v, w) \in K$ is used to model the interaction (e.g. transfer of data) between the entities. For modelling the external influence of the environment we use special vertices (external nodes) $E \subseteq V$ in the graph, where the edges from these vertices represent the channels for the input into the system, and the edges to these vertices represent the output of the system. All other nodes $v \in V \backslash E$

are called *internal nodes*. We distinguish between user data (data from the environment that is processed by the system) and control data (data from the environment to change the behaviour of the system).

In the real world, not all properties are known in all detail (e.g. it would be very difficult to describe a deterministic behaviour of an animal), but there are many things, that can better be described by probabilities. Therefore, a stochastic behaviour is more adequate than a deterministic one. We use stochastic automatons to describe the behaviour of the entities. These concepts allow the modelling of a wide variety of complex systems of the real world, e.g. systems that appear in biology, physics, computer science or any other field.

For an edge $k = (v, w) \in K$ the starting vertex v is denoted by $k-$ and the ending vertex w is denoted by $k+$. For a vertex $v \in V$ the set of edges ending in v is denoted by $v-$ and the set of edges starting at v is denoted by $v+$. Analogously for $T \subseteq V$ the sets $T-$ and $T+$ are defined by $T-: = \{k \in K | k + \in T\}$ and $T +: = \{k \in K | k- \in T\}$. The *input edges* are $E+$ and the *output edges* are $E-$. All other edges are called *internal edges*. For the input coming from the environment, we distinguish between control data and user data. A subset of the input edges $C \subseteq E+$, which elements are called *control edges*, are used for change the behaviour of some nodes, while the other input edges (called *user edges*) are used for the data, that should be processed by the system. For the communication between entities we need a finite set A, which is used as alphabet for communication, i.e. each value transmitted by a node to another node is in A. For modelling the behaviour of a node v, we use a stochastic automaton $a_v = (A^{v-}, A^{v+}, S_v, P_v)$, where

- $A^{v-} = \{(x_k)_{k \in v-} | x_k \in A, k \in v-\}$ are the *local input values*,
- $A^{v+} = \{(x_k)_{k \in v+} | x_k \in A, k \in v+\}$ are the *local output values*,
- S_v is the set of states,
- $P_v: S_v \times A^{v-} \times S_v \times A^{v+} \to [0,1]$ is a function, such that $P_v(q, x, \cdot, \cdot): S_v \times A^{v+} \to [0,1]$ is a probability mass function on $S_v \times A^{v+}$ for each $q \in S_v$ and $x \in A^{v-}$. The value $P_v(q, x, q', y)$ is the probability, that the automaton moves from state q into the new state q' and gives the local output y when it receives the local input x.

This model allows us to describe socio-technical systems of the real world: Assume that we would like to analyse a system, e.g. a network of AmI devices. Then each node of the network corresponds to a vertex of the graph. If one node of the network is able to communicate with another node, then we draw an edge between the vertices in the graph. The behaviour of each node is modelled by a (stochastic or deterministic) automaton, which describes, how the internal state changes for each input, which it gets from the other nodes.

If we consider the global view on the system at a point in time, then we see a current local state inside each automaton and a current value on each edge, which is transmitted from one node to another node. Such a global view is a snapshot of the system: A *configuration* $c = (c_V, c_K)$ consists of

- A tuple $c_V \in \prod_{v \in V} S_v$, which defines the current states of the automatons,
- A map $c_K: K \to A$, which defines the current symbols on the edges,

The set of all configurations is denoted as Conf. For a configuration $c = (c_V, c_K)$ and a set $T \subseteq K$ of edges the assignment $c_K|_T: T \to A$ of the edges in T is also denoted by $c|_T$. The restriction of c to the external nodes is defined by $c|_{ext} = (c_V|_E, c_K|_{E+})$. The restriction of c to the internal nodes is defined by $c|_{int} = (c_V|_{V \setminus E}, c_K|_{(V \setminus E)+})$. An *initialization* is a pair (Γ, P_Γ), where Γ is a set of configurations and $P_\Gamma : \Gamma \to [0, 1]$ is a probability mass function on Γ, which describes, with which probability the system starts in a certain configuration $c \in \Gamma$. A configuration $c' = (c_V', c_K')$ is a *successor configuration* of $c = (c_V, c_K)$ with probability p (notation: $P(c \to c') = p$) if

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$$p = \prod_{v \in V} P_v(c_V(v), (c_K(k))_{k \in v-}, c_V'(v), (c_K'(k))_{k \in v+})$$

For a configuration c let succ(c) be the corresponding random variable with the probability distribution $P(\mathrm{succ}(c) = c') = P(c \to c')$ for each successor configuration c' of c. This concept of successor can be extended in a canonical way to arbitrary sequences $(c_0, c_1, \ldots, c_j)$ of configurations to get the probability, that c' is reached from the configuration c, where the steps are considered as independent. For a given duration t let $P(c \to {}^t c')$ be the probability, that c' is active t time units after the time of c. Let $P(\Gamma \to {}^t c)$ be the probability, that c is active at time t. Define $\Gamma_t = \{c | P(\Gamma \to {}^t c) > 0\}$, i.e. Γ_t is the set of all configurations that may be active at time t, where we assume that the initialization of the system is at time $t_0 = 0$. Let Conf_t be the random variable taking values in Γ_t with the probability distribution $P(\mathrm{Conf}_t = c) = P(\Gamma \to {}^t c)$ for $c \in \Gamma_t$.

To analyze the behaviour of a system, we initialize it at time $t_0 = 0$ by choosing a start configuration $c_0 \in \Gamma$ and then the behaviour of the system, which is induced by the automatons in all nodes, is the sequence $s = (c_0, c_1, \ldots)$ of configurations during the run of the system. When we do a snapshot of the system at time t, we see a current configuration $c \in \Gamma_t$. Since the automatons and the initialization are not deterministic, the sequence s is not uniquely determined by the system, but it depends on random events. So for each time t, we have a random variable Conf_t, which describes, with which probability $P(\mathrm{Conf}_t = c)$ the system is in a given configuration c at time t.

For measuring the information in a system we use the statistical entropy: For a discrete random variable X taking values from a set W the *entropy* H(X) of X is defined by [15] $H(X) = -\sum_{w \in W} P(X = w) \log_2 P(X = w)$.

The entropy measures, how many bits are needed to encode the outcome of the random variable in an optimal way. In the following sections we use this concept to define quantitatively some properties of a system. Another concept that we need for the quantitative definitions in the following sections is the average value of a function: Let f: $\mathbf{R}^{+}{}_{0} \rightarrow \mathbf{R}$ be a real function, which is integrable on every finite interval. For points of time s > r the average value of f in the interval [r, s] is defined by $Avg_{[r,s]}(f) = \frac{1}{s-r}\int_{r}^{s} f(t)dt$. The average value of f is defined by $Avg(f) = \liminf_{t\rightarrow\infty} Avg_{[0,t]}f$.

In this micro-level model we can now specify self-organizing properties like adaptivity, emergence or autonomy by using quantitative measures. In the following, let S be a system and (Γ, P_{Γ}) be an initialization.

Autonomy

To compute the level of autonomy [1], we compare the information contained in the control data with the information of the whole system. For a point in time t, the value $H(Conf_t)$ measures the system entropy at time t, i.e. $H(Conf_t)$ is the average number of bits that are needed to encode the information of the configuration at time t in an optimal way. By restricting the configuration to a set of edges, we can analogously measure the information of the values on these edges. For example the control entropy $H(Conf_t|_C)$ is the average number of bits that are needed to encode the control information.

For a configuration c the level of autonomy of c is defined by[1] $\alpha(c) = 1 - \frac{H(succ(c)|_C)}{H(succ(c)|_K)}$.

For a point in time t, the level of autonomy at time t is defined by the weighted mean value of all these autonomy levels of configurations, which may be active at time t, i.e. [2]

$$\alpha_t(S,\Gamma) = \sum\{\ P(\Gamma \rightarrow^{t} c)\,\alpha(c)\ |\ c \in \Gamma_t\}.$$

The level of autonomy of the system S is defined by $\alpha(S,\Gamma) = Avg(t \mapsto \alpha_t(S,\Gamma))$. The system S is called autonomous if $\alpha(S,\Gamma) = 1$.

In this definition the value $\frac{H(succ(c)|_C)}{H(succ(c)|_K)}$ describes the relation between the entropy on the control edges and the entropy on all edges: A high value for this ratio means, that much control data is needed in the configuration c, and a low value for this ratio means, that the system behaves nearly autonomously in the configuration c. Therefore $\alpha(S, \Gamma)$ measures how much control data is needed relative to the data on all edges during the whole run of the system. Since $\alpha(S, \Gamma) \in [0, 1]$, a level of autonomy near 1 means, that the information contained in the control data will be

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[1] If $H(succ(c)|K) = 0$ then we define $0/0 := 0$ and $\alpha(c) = 1$.

[2] When we write a set after the sum symbol $\sum$, it should be considered as a multiset, i.e. in the following formula a value is added twice if it is contained twice in the multiset.

very low, i.e. the system behaves autonomously if we wait long enough. A level near 0 means, that it needs much control data to keep the system running, i.e. the system will not be autonomous even if we wait a very long time.

Emergence

In some systems, it may happen that some patterns or properties appear in the system as a whole, but do not appear in the single components. Such an appearance is called emergence. For a point in time t the level of emergence [1] at time t is defined by $\varepsilon_\mathrm{t}(\mathrm{S},\Gamma) = 1 - \frac{H(Conf_t|_K)}{\sum\limits_{k\in K} H(Conf_t|_{\{k\}})}$

The level of emergence of the system S is defined by $\varepsilon(\mathrm{S},\Gamma) = \mathrm{Avg}(\mathrm{t} \mapsto \varepsilon_\mathrm{t}(\mathrm{S},\Gamma))$. The system S is called emergent if $\varepsilon(\mathrm{S},\Gamma) = 1$.

For the level of emergence, the information of all edges is compared to the information contained in each single edge. Analogously to the level of autonomy, also the level of emergence is a value in the interval [0, 1]. If at the current point in time t there are large dependencies between the values on the single edges (which can be seen as patterns), the level of emergence is high: $\varepsilon_\mathrm{t}(\mathrm{S}, \Gamma) \approx 1$. If the values of nearly all edges are independent, there will be no pattern, so the level of emergence is low: $\varepsilon_\mathrm{t}(\mathrm{S}, \Gamma) \approx 0$. Therefore $\varepsilon(\mathrm{S}, \Gamma)$ measures the dependencies occurring during the whole run of the system.

Target Orientation

Before a new system is designed, we have the goal of the system in our mind: The system should fulfil a given purpose. The behaviour of each node is defined in such a way, that this goal is reached, so the design of a system needs a *target orientation*. Let b: Conf → [0, 1] be a fitness function for the configurations. For a point in time t the level of target orientation [2] of the system S at time t is defined by $\mathrm{TO}_\mathrm{t}(\mathrm{S}, \Gamma) = \mathrm{E}(\mathrm{b}(\mathrm{Conf}_\mathrm{t}))$, where E is the mean value of the random variable. The level of target orientation of the system S is defined by $\mathrm{TO}(\mathrm{S},\Gamma) = \mathrm{Avg}(\mathrm{t} \mapsto \mathrm{TO}_\mathrm{t}(\mathrm{S},\Gamma))$. The system S is called target oriented with respect to b if $\mathrm{TO}(\mathrm{S}, \Gamma) = 1$.

For the target orientation, the fitness function b describes which configurations are “good”: A high value $\mathrm{b(c)} \approx 1$ means that the configuration c is a part of our goal which we had in mind during the design of the system. The level of target orientation measures the fitness b(c) of the configurations during the whole run of a system: A high level of target orientation ($\mathrm{TO}(\mathrm{S}, \Gamma) \approx 1$) means, that the mean valuation of the configurations during a run of the system often is nearly 1.

Resilience

For socio-technical networks, there are different forms of resilience:

- Resilience with respect to malfunctioned nodes
- Resilience with respect to attacks by an intruder, who takes part in the network
- Resilience with respect to attacks by an intruder, who is outside the network
- Resilience with respect to natural disasters or other external influence, which might cause a breakdown of some nodes

Now we model these different forms of resilience: Let Θ be a set and p_Θ: $\Theta \to [0, 1]$ be a probability distribution. Let $(a_{\theta,v})_{\theta\in\Theta,v\in V}$ be a family of stochastic automatons. For $\theta \in \Theta$ let S^θ be the system S after replacing a_v by $a_{\theta,v}$ for all $v \in V$. Let $(\Gamma^{S^\theta}, P_{\Gamma^{S^\theta}})$ be an initialization of S^θ. Let Conf^θ be the set of the configurations of S^θ. Let $b = (b_\theta)_{\theta\in\Theta}$ be a family of fitness functions b_θ: $\mathrm{Conf}^\theta \to [0, 1]$ for the configurations. For a point in time t let Conf_t^Θ be the random variable, which applies the random variable Conf_t in the system S^θ after choosing $\theta \in \Theta$ randomly according to the probability p_Θ. The level of resilience [2] of S at time t is defined by $\mathrm{Res}_t(S, \Gamma) = E(b(\mathrm{Conf}_t^\Theta))$, where E is the mean value of the random variable. The level of resilience of the system S is defined by $\mathrm{Res}(S,\Gamma) = \mathrm{Avg}(t \mapsto \mathrm{Res}_t(S,\Gamma))$. The system S is called resilient with respect to b if $\mathrm{Res}(S, \Gamma) = 1$.

In this definition the automaton $a_{\theta,v}$ can be used to describe the malfunctioned behaviour of a node v. In a socio-technical network with AmI devices, this behaviour could be caused by hardware failure, it could be the behaviour of an intruder inside the network ($v \in V\backslash E$) or outside of the network ($v \in E$) or it does not send data to its successor nodes due to a breakdown. The system is resilient if despite the malfunctioned nodes the system still runs through many "good" configurations.

If there are only few malfunctioned nodes, then we can use $a_{\theta,v} = a_v$ for the other nodes. If the behaviour of a malfunctioned node v depends on the original behaviour a_v, then the automaton $a_{\theta,v}$ can be a modification of the original automaton a_v to describe the malfunctioned behaviour of v.

Adaptivity

Now we model the concept of adaptivity [2] of a system. Let Θ be a set and p_Θ: $\Theta \to [0, 1]$ be a probability distribution. Let $(a_{\theta,v})_{\theta\in\Theta,v\in C-}$ be a family of stochastic automatons. For $\theta \in \Theta$ let S^θ be the system S after replacing a_v by $a_{\theta,v}$ for all $v \in C-$. Let $(\Gamma^{S^\theta}, P_{\Gamma^{S^\theta}})$ be an initialization of S^θ. Let Conf^θ be the set of the configurations of S^θ. Let $b = (b_\theta)_{\theta\in\Theta}$ be a family of fitness functions b_θ: $\mathrm{Conf}^\theta|_{\mathrm{int}} \to [0, 1]$ for the configurations of internal nodes. For a point in time t let Conf_t^Θ be the random variable, which applies the random variable Conf_t in the system S^θ after choosing $\theta \in \Theta$ randomly according to the probability p_Θ. The level of adaptivity of S at time t is defined by $Ad_t(S, \Gamma) = E(b(Conf_t^{\Theta}|_{int}))$, where E is the mean value of the random variable. The level of adaptivity of the system S is defined by $Ad(S, \Gamma) = Avg(t \mapsto Ad_t(S, \Gamma))$. The system S is called adaptive with respect to b if $Ad(S, \Gamma) = 1$.

The level of adaptivity measures the influence of the change of control data: A high value of $Ad(S, \Gamma)$ means that the mean valuation of the configurations during each run of the system with the new control data is nearly 1, so many "good" configurations are reached. If the system has no external nodes ($E = \emptyset$), then no automaton in replaced. In this case, the concept of target orientation can be seen as a special case of the concept of adaptivity: By choosing a one element set $\Theta = \{\theta\}$ we get $TO(S, \Gamma) = Ad(S, \Gamma)$. For $E = \emptyset$ with $|\Theta| > 1$ the level $Ad(S, \Gamma)$ is the weighted mean level of target orientation $TO(S, \Gamma)$ with respect to $\theta \in \Theta$: $Ad(S,\Gamma) = \sum_{\theta \in \Theta} p_\Theta(\theta) TO_\theta(S,\Gamma)$, where $TO_\theta(S, \Gamma)$ is the level of target orientation with respect to b_θ.

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Part IV
City Scale

City Scale Evacuation: A High-Performance Multi-agent Simulation Framework

Kashif Zia and Alois Ferscha

1 Introduction

In addition to its importance due to ever-increasing urban populations and disasters probability, a city evacuation is an interesting scenario in many respects. It provides us with a scale in terms of individual and functional diversity which results in behavioural patterns more unpredictable and susceptible to emerge into a co-evolution as a result of macro-to-micro feedback loop. At the same time, there are many challenges while modelling and simulating at this scale. The main focus of this chapter is to present generalization techniques to address these challenges. Firstly, the simulation should not be specific to one city and its features, so that as soon as we intend to go for a different city, the whole system would not work. To encounter this problem, we have investigated on main typological features of cities, typically in European context. We settles with 5–6 main city types and features related to these types. A city type represent many cities of the same genre, hence eliminating the need to model each city separately. A thorough account of this study is given in Sect. 3.

Modelling based on city type is just one feature of high performance urban simulation framework presented in Sect. 4. This chapter is written based on building blocks of the framework having one of the city type chosen for the study, namely instance of a city type. An instance of a city is a conceptual type. Populated with related data, it defines a city and makes it available for modelling subsequently. The Sect. 4.2 describes how an instance of a city type can be created based on its typological features integrated with required data sources. Even if a high performance software and hardware platform is available, the scale and complexity of a city is extensive, thus necessitating abstraction of the physical, functional and individual features. Section 4.3 describes motivation based on visual

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perception of a city dweller to simplify the map, demographic features and functional modalities often found in a city. High level agent formalism (Sect. 4.4) describes agent's capabilities, such as local interactions (networking, modalities, connectivity), models of adaptations, decision-making, and multi-scaling (layering, clustering) etc. It serve as a core of the framework, integrating modelling aspects and data-driven instance of the city to extend the classical agent formalism. In addition to elaborate the formalism for a city scale scenario, in Sect. 4.5, we have annotated it with aspects of interest categorized under formalism of agents' heterogeneity, interaction, adaptation and action.

The Aspect oriented Modelling (AoM) paradigm considers technology invasion as an important ingredient for mobility, justifying a case of agents' interactions at different scales. Simulation is performed at a real physical and demographic scale after converting a high resolution city map into grids of cells. The Cellular Automata (CA) describing the space lets the mobile agents on the top be maneuvered. It also provides a natural way to link an agent with the real space. However, a city-scale simulation of this scale in terms of space and number of agents cannot be handled without explicitly employing a Parallel and Distributed Simulation (PDS) hardware and software platform.

In this paper, we have taken up a system which can be categorized as a socio-technical system for urban mobility with geo(graphic)-simulation capabilities, which we refer to as geo-socio-technical-urban-mobility simulation. The simulation software (Sect. 5) supports distribution of space for parallel execution and handles a large population of agents. We consider an city-scale emergency scenario for applying the framework. The urban evacuation simulation is performed on a shared-memory multi-process hardware platform using a really fine-grained ($1.25\ \mathrm{m}^2$) grid based space incorporated from a real map. The software platform is a full multi-agent system compatible with grid based space. The AoM paradigm (Sect. 4.5) provides design principles for the agent model. Section 6 gives a detailed account of agent model. The hardware and software platforms used to perform the simulation are presented in Sect. 7. Section 8 is devoted to the simulated scenario and a discussion on the simulation outcome, focusing both on agents' behaviour and performance of the parallel and distributed simulation.

2 Relationship of Urbanization and Disasters

A city or an urban area is constituted by a specifically designed infrastructure, other supporting structures, and buildings that create an environment to serve a population living in a relatively small and confined geographical area. There is a high interrelationship of systems within a city supporting the living of its population. "Capital stocks makes up much of the infrastructure that includes business fixed-capital machinery and equipment, structural capital (plant, infrastructure, overheads, offices, and social-physical capital), and residential capital (dwellings).

A disaster can directly affect people and capital stock and, as a consequence, the systemic functioning of both." [1]

An urban hazard is a risk that threatens a city, its population and its socio-economic activities. As indicated by editors in [2], even though the urban areas are particularly vulnerable to disruptions from extreme events, the evaluation and management of disaster is the most underestimated issues in urban development. Where, "Disaster impacts are increasing in severity. Annual direct losses for weather-related events have increased from $3.9 billion in the 1950s to $63 billion in the 1990s. Moreover, a number of ongoing trends have the potential to cause even more severe and broader disaster impacts than ever before. These include increased environmental degradation, the impacts of climate change, population growth in cities, and globalization." [2]

The experts, disaster management researchers, and development practitioners participated in World Bank report "Building Safer Cities The Future of Disaster Risk" [2] have categorized the impacts at four levels: Globalization and the Economic Impacts of Disasters; Environment, Climate Variability, and Adaptation; Social Vulnerability to Disaster Impacts; and Vulnerability of Critical Infrastructure to Disasters.

Globalization and Economic Impacts of Disasters: Globalization has economic and social impacts which in turn affects the intensity of disaster and capabilities of authorities to handle it. For example, Charlotte Benson and Edward Clay e Benson [3] have identified that increased economic activity in a city results in environmental degradation increasing the frequency and intensity of natural disasters. Torben Andersen [4] focuses on economic consideration of disaster relief, particularly focusing on developing and poor countries. He coins a term "moral hazard" which results due to unwillingness of a country to mitigate potential hazards of larger intensity, hoping that the international community would bail them out in such a situation. Andersen identifies the importance of experts in political and bureaucratic spheres who can influence the policies towards adoption of diversified economic bases and self-reliance in disaster management.

Although, reliance on outside assistance in larger disaster is a natural action, it cannot be guaranteed. As indicated by Albala-Bertrand [1], in case of recession at world level, disaster recovery contributions may take longer, or may never come in. Hence, it is mandatory for governments to have a programme of handling with such a situation of their own, which may not be setting aside money to handle such a situation. Albala-Bertrand focuses on urban disasters and argues that "their effect on the macroeconomy is often negligible because reconstruction and business opportunities brought by a disaster provide opportunities and economic stimulation. Disaster management activities, therefore, should focus on communities and their resilience since the economy will either recover on its own or be subject to greater forces that cannot be controlled." [1]

Hence, the disaster management activities should focus on resilience and preparation of communities and populations. In this case, the involvement of communities, organizations, businesses and private sector would play a vital role. For example, Howard Kunreuther [5] discusses whether individuals and businesses have enough economic incentives to carry out socially appropriate levels of mitigation for reducing future disaster losses. Kunreuther concludes that "such interdependent risks serve as a disincentive for undertaking mitigation measures since one or a handful of families will not invest in mitigation measures if their home will still be at risk due to an unprotected neighbour's home." To encourage mitigation measures, therefore, he suggests greater public-private partnerships that encourage individuals to undertake loss reduction measures and governments to enforce regulations and building codes. [5]

Environment, Climate Variability, and Adaptation: The twentieth century turned out to be disastrous for environment and natural equilibrium. "The industrial revolution, ever-increasing technological innovations, rapid urbanization resulting from the mechanization of agricultural production, and the birth of megacities have put pressure on natural resources and contributed to climate change." [5]

The key changes in the environment affected by climate change identified by Anthony Bigio [6] are sea-level, wildfires and storms. He desires adaptation mechanisms (particularly in the form of global awareness and regulations) to improve infrastructure and strengthen defences. In particular, climate change in the context of coastal megacities is discussed by Richard Klein et al. [7], who are convinced that much of the projected growth in large cities is expected to take place in such locations which are naturally more susceptible to earth-related hazards, for example, tsunamis, coastal erosion, storm and wind damage, flooding, and salinization of surface waters. They have presented a framework "linking the analysis of present and future hazardous conditions and enhancing the capacity for disaster prevention and preparedness with disaster recovery."

Social Vulnerability to Disaster Impacts: At short term, the most important goal of disaster management is the protection of human life, whereas at much longer terms, the post-disaster recovery is of more importance allowing individuals and communities to resume dignified lives. "Industrialized countries often have the resources and the advance warning systems to evacuate thousands of people and build disaster-resistant structures, all of which save lives. Most developing countries are not as fortunate. Disasters still claim tens of thousands of lives each year and destroy livelihoods in an instant." [5]

Diversity in culture and perception about risk plays an important role in disaster prevention and management. There are several factors forming culture including religion, traditions, and norms. Ben Wisner [8] in his study finds out that even in cities that might share similarities, there are vast differences in perceptions of vulnerability and risk. "In Mexico City, for example, squatters and children were thought by other city dwellers to be the most vulnerable to disasters. In Los Angeles, by contrast, the elderly and disabled were perceived to be the most vulnerable."

Vulnerability of Critical Infrastructure to Disasters: The implications of vulnerability of critical infrastructure (e.g. hospitals, fire departments, and emergency service stations, specifically designed to manage a disaster) to disaster is an important issue. Benoit Robert and colleagues [9] while discussing the essential services, point out that the failure of one system can cause several other critical systems to fail, resulting in a domino effect. “Realization of the interlinkages and possible multisystem failures should be taken into account when identifying risks and attempting to mitigate them in the disaster management process.”

According to the World Bank report, “Building Safer Cities The Future of Disaster Risk” [5], there is a need to manage the urban hazards at two levels: developing innovative approaches to disaster risk reduction and changing people’s perception of risk. In addition to recognizing the importance of new and innovative approaches, several risk management techniques are recommended, including: investing in improved data and indicators on disaster risk, developing community participation programs, creating new risk transfer and risk reduction mechanisms, and reinforcing partnerships among stakeholders to reduce communities’ vulnerability to risk.

Unfortunately, city development contributes itself to its vulnerability to disasters. Wenzel [10] highlights these factors as:

- Poor housing quality due to below standard construction
- Complexity and age of infrastructure
- Presence of extensive lifeline systems to support citizens (water, electricity, transportation, and communication)
- Inadequate critical facilities (public health, safety, education)
- Insufficient capabilities with respect to disaster preparedness, response, and relief

The above are consequences of more generic problems faced by cities and hence playing negatively for Urban disaster vulnerability [11]. Mitchell [12] discussed these problems under six distinct categories:

- **Population Density:** In most of the mega-cities, the concentration of people and activities is confined to a limited space. This not only increases the vulnerability of natural (if originating in the concentrated region) as well as man-made (usually proportional to the population density) disaster, but also, facilitates the exploitation of synergy between primary and secondary disaster.
- **Hazardous Zones:** Many of the larger cities of the world are located or have grown into hazardous zones. For example, 20 % of the global population is currently living in “near-coastal zone.”
- **Nature and Climate:** Cities, by their nature, make some hazards worse; for example destroying flora to pave paths and housings reduces infiltration, increases run-off, and results in greater flood volumes. Climate Change is another self-destroying speciality of human-being. Metropolitan regions, particularly those in developed countries, are important contributors to the greenhouse gas, where the sufferers would mostly be urban agglomerations in Asia and Africa, being affected by consequences of global warming. “The projected increase in the frequency and severity of meteorological disturbances (such as cyclones, storm surges, and heat waves) accompanying global warming is also likely to disproportionately affect coastal areas [6]”

- **Insufficient and Obsolete Infrastructure:** This mostly corresponds to the Wenzel [10] deliberations.
- **Population Vulnerability:** Many cities have really vulnerable populations, such as urban poor, homeless crowd, and ignorant immigrants. It is a fact that the most hazardous locations in the world's rapidly growing cities are occupied by an even faster growing under-resourced population living in some of the most poorly constructed housing without access to many basic infrastructure services [13]. The informal settlements also seldom benefit from mitigation interventions. The urban poor are thus not surprisingly the group most often killed and injured in both natural and technological disasters [1].
- **Financial Incapability:** Many cities, particularly in developing countries, operate on the edge of their financial capacity and have not devoted adequate resources to hazard or vulnerability reduction activities. A disaster at an unprecedented scale would be problematic for even a developed country.

It is evident from the discussion here that a city (or a city type in particular) itself defines its vulnerability towards a disaster. It also defines its capability to encounter a disaster. Hence it is necessary to understand the city types in more details, particularly along the lines of the factors describing city's vulnerability towards disasters or its capability to face it.

3 City Typologies

"Typology (in urban planning and architecture) is the taxonomic classification of (usually physical) characteristics commonly found in buildings and urban places, according to their association with different categories, such as intensity of development (from natural or rural to highly urban), degrees of formality, and school of thought (for example, modernist or traditional) [14]". We enhance this definition also including other dimensions of taxonomic classifications relating with social, cultural, functional, technological and co-operational features in addition to physical, more specifically, regional, geographical, structural and architectural and mobility-based classifications. Relating a category from one class to a category in another class helps us understand the "nature" of a city. Cities with similar nature can be classified as same "type" of cities where investigations performed for one can easily be applied to the other. Additionally, instead of treating each city as a separate entity, a more abstract definition of a city can be taken from its type. In the following, we describe the typologies of cities categorized under *general* and *qualitative*.

The types described based on **general** features are as under.

Purpose: Historically cities were built around its utility, typically trade, religion, protection, knowledge or state centres [15]. More recently, cities were especially built for education, industry, shopping, tourism etc. Most of the large cities are a mix of most of these features. For example, Rome is a well known tourist city, but at the same time, it is capital of Italy. Additionally it has many other prominences in relation with shopping, universities etc. So we cannot consider it having a single or two prominent functions. It would have "multiple" prominent feature, and cannot be categorized as specifically purposed.

Architecture and History: Construction of a city over time is referred to as Architecture of a city [16]. We can also think of architecture as design of building blocks of a city, i.e. building and houses. But we refrain from it due to the fact that the granularity at this scale is not required. It is very difficult to extract distinct architecture specific features for cities because with the passage of time most of the cities were reconstructed to current state with little or no relation with the history. However it remains a well established typological aspect with diversity for more keen observers.

Topography and Culture: Most prominent aspects along which cities are categorized are Demography describing the characteristics of the people living in city, and Geography describing the geographic characteristics of a city. The Culture of a city is a by product of both demography (ethnicity, gender, groups, quality of life etc.) as well as geography (historical settlements, climate, strategic location etc.). The geography is also related with a city's "susceptibility to disaster" such as earthquake, tsunami, flood etc. [17], and weather and climate. Topography can roughly encapsulate the overall shape of the city, i.e., the Structure, such as linear, orthogonal, radial etc. However, most of the cities does not present any structure due to organic growth typical to large cities. The Land related features such as buildings, vegetation and transportation can be considered as a topographic as well as geographic feature.

The types described based on **qualitative** features are as under.

Knowledge based Economy: Focusing on European zone, the categorization of cities based on Knowledge based Economy serves as a useful typology due to recent importance. The study in [18] presents an analysis framework featuring demography (population, students, education level, economic sectors, knowledge based industries), geography (accessibility), and culture (quality of life, social equity, foreign population, human capital). A city ranked higher in this framework means that it qualifies successfully for most of the indicators described above. Additionally it provides a mechanism to distinguish between cities otherwise apparently very close to each other. This study does not include global cities; such as London and Paris.

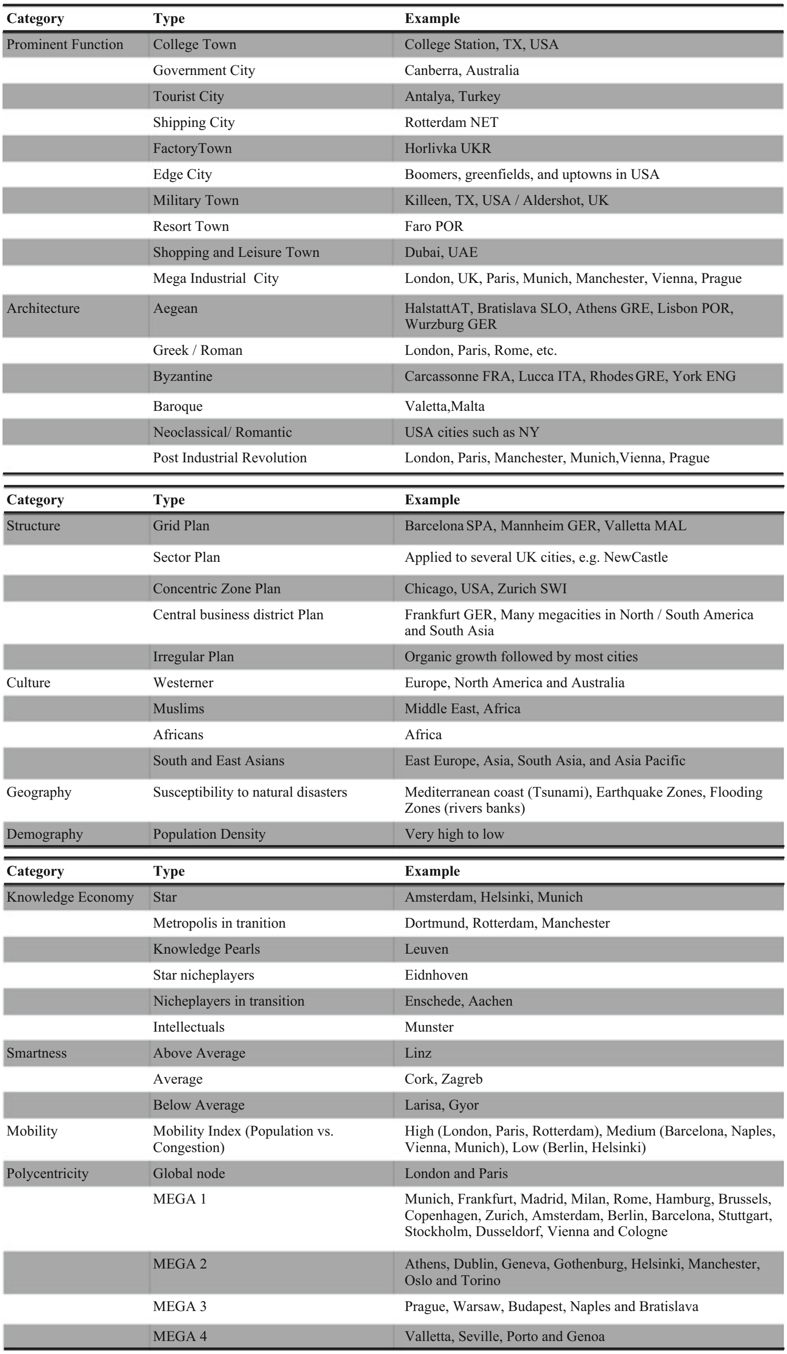
Smartness: Similar to above, analysis of cities based on its Smartness [19] has broader agenda, also including factors related to governance, mobility, environment and living in addition to economy and people. The project in focus deals with medium-sized cities and their perspectives for development [19]. Even though the vast majority of the urban population lives in such cities, the main focus of urban research tends to be on the 'global' metropolises. As a result, the challenges of medium-sized cities, which can be rather different, remain unexplored to a certain degree. Smartness of cities is analysed against six characteristics, each having several factors (see original report for details [19]).

Urban Mobility: Urban Mobility is another related area in which European researchers has been focusing on. The knowledge based economy as well as smartness of a city is highly dependent on extent of urban mobility in the city. The apparent challenges of urban mobility are dealing with overcrowding and congestion, reduction in emission and pollution, removing constraints of vehicle usage (rising fuel prices, shortage of parking places and anti-congestion tolls), political and economic constraints and demographic changes (e.g. increasing age). Authors in [20] has exhaustively studied the approaches to address these challenges. In doing so they have compiled European cities into size versus congestion relation which is a main requirement in urban planning.

Polycentricity: Finally, Polycentricity is the study of attractiveness of a city when seen in regional context, hence it is obviously a superset of knowledge-based economy, mobility and smartness of a city with additional features of tourism, manufacturing and regional/global decision making. Polycentricity has two complementary aspects [21]. The first relates to morphology, i.e. the distribution of urban areas in a given territory (number of cities, hierarchy, distribution). The second concerns the relations between urban areas, i.e. the networks of flows and cooperation. These flows are generally related to proximity, though networks can also be independent of distance. According to the report, polycentricity at different levels (macro, meso and micro) is seen as a useful alternative model to enhance regional development more evenly across the European territory. A polycentric Europe is thus seen as an attractive alternative to a European space dominated by the Pentagon, the area delimited by London, Hamburg, Munich, Milan and Paris, i.e. the European core with approximately 14 % of the EU27 area, 32 % of its population and 43 % of its GDP. This situation is often contrasted with that of the USA, where there are several global integration zones. A European wide application of polycentricity is designed to promote several larger zones of global economic integration in the EU in addition to the Pentagon.

The building blocks of polycentricity are the functional urban areas (FUAs). A FUA consists of an urban core and the area around it that is economically integrated with the centre, e.g. the local labour market. The analysis was conducted based on population, transport, tourism, manufacturing, knowledge, and decision-making in public and private sector. All variables except Tourism and Administration have been combined to give an overall ranking of the FUAs into three groups. The 76 FUAs with the highest average score have been labelled Metropolitan European Growth Areas (MEGAs). The strengths of the strongest FUAs, the 76 MEGAs, are analysed further in a discussion of where the most likely counterweights to the Pentagon are to be found. The analysis here is based on indicators for each of the four qualities; mass, competitiveness, connectivity and knowledge basis. The MEGAs are compared with each other for each quality, ranked and divided into five groups: Global node, MEGA1, MEGA2, MEGA3, and MEGA4.

City Types: The urban types discussed above are tabulated with relevant examples in Fig. 1. Figure 2 shows the conceptual mechanism to perform the



Category	Type	Example
Prominent Function	College Town	College Station, TX, USA
	Government City	Canberra, Australia
	Tourist City	Antalya, Turkey
	Shipping City	Rotterdam NET
	FactoryTown	Horlivka UKR
	Edge City	Boomers, greenfields, and uptowns in USA
	Military Town	Killeen, TX, USA / Aldershot, UK
	Resort Town	Faro POR
	Shopping and Leisure Town	Dubai, UAE
	Mega Industrial City	London, UK, Paris, Munich, Manchester, Vienna, Prague
Architecture	Aegean	HalstattAT, Bratislava SLO, Athens GRE, Lisbon POR, Wurzburg GER
	Greek / Roman	London, Paris, Rome, etc.
	Byzantine	Carcassonne FRA, Lucca ITA, Rhodes GRE, York ENG
	Baroque	Valetta,Malta
	Neoclassical/ Romantic	USA cities such as NY
	Post Industrial Revolution	London, Paris, Manchester, Munich,Vienna, Prague

Category	Type	Example
Structure	Grid Plan	Barcelona SPA, Mannheim GER, Valletta MAL
	Sector Plan	Applied to several UK cities, e.g. NewCastle
	Concentric Zone Plan	Chicago, USA, Zurich SWI
	Central business district Plan	Frankfurt GER, Many megacities in North / South America and South Asia
	Irregular Plan	Organic growth followed by most cities
Culture	Westerner	Europe, North America and Australia
	Muslims	Middle East, Africa
	Africans	Africa
	South and East Asians	East Europe, Asia, South Asia, and Asia Pacific
Geography	Susceptibility to natural disasters	Mediterranean coast (Tsunami), Earthquake Zones, Flooding Zones (rivers banks)
Demography	Population Density	Very high to low

Category	Type	Example
Knowledge Economy	Star	Amsterdam, Helsinki, Munich
	Metropolis in tranition	Dortmund, Rotterdam, Manchester
	Knowledge Pearls	Leuven
	Star nicheplayers	Eidnhoven
	Nicheplayers in transition	Enschede, Aachen
	Intellectuals	Munster
Smartness	Above Average	Linz
	Average	Cork, Zagreb
	Below Average	Larisa, Gyor
Mobility	Mobility Index (Population vs. Congestion)	High (London, Paris, Rotterdam), Medium (Barcelona, Naples, Vienna, Munich), Low (Berlin, Helsinki)
Polycentricity	Global node	London and Paris
	MEGA 1	Munich, Frankfurt, Madrid, Milan, Rome, Hamburg, Brussels, Copenhagen, Zurich, Amsterdam, Berlin, Barcelona, Stuttgart, Stockholm, Dusseldorf, Vienna and Cologne
	MEGA 2	Athens, Dublin, Geneva, Gothenburg, Helsinki, Manchester, Oslo and Torino
	MEGA 3	Prague, Warsaw, Budapest, Naples and Bratislava
	MEGA 4	Valletta, Seville, Porto and Genoa

Fig. 1 Typology of cities based on general and qualitative features

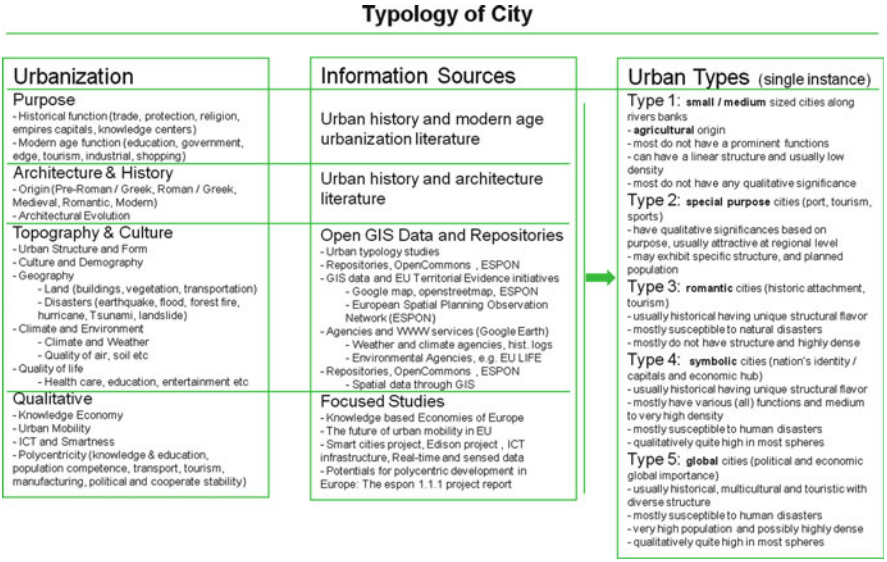
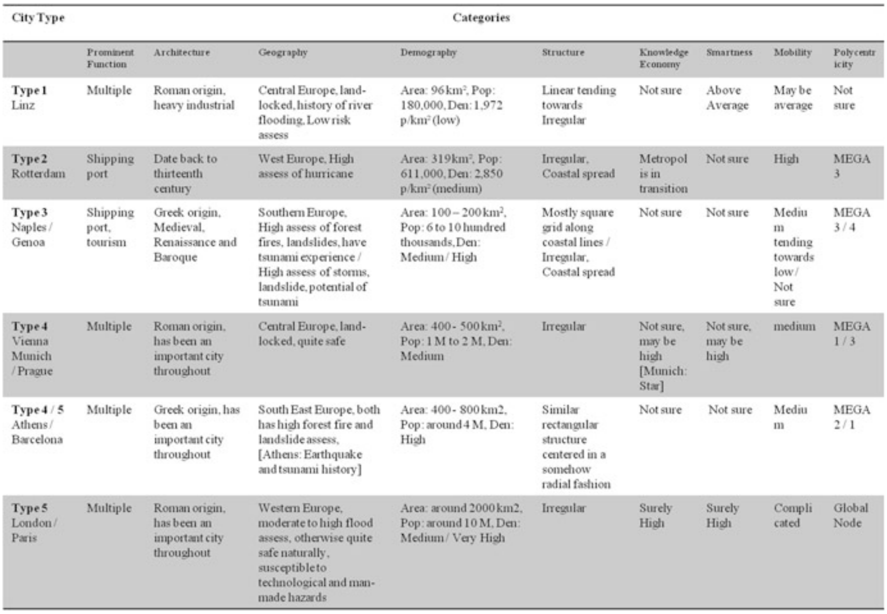


Fig. 2 Conceptual framework of typologies of cities

study. The components of the framework are straight-forward. Urban types are extracted from literature review in four basic categories; purpose, architecture and history, topography and demography, and qualitative studies. There are remarkable differences between these cities thus qualifying each for a type (see Fig. 3) with similar cities considered as sister cities. There may be more, but we have settled with five types:

1. **Small/medium sized cities of agrarian origin:** are historical cities developed in agricultural background. Due to reliance on water for agriculture, these cities are usually found along river banks, and hence can grow linearly. Unless designated specifically to have some prominent function (e.g. culture, industry, education, sports etc.) recently, these cities remain relatively isolated and qualitatively insignificant.
2. **Special purpose cities with a prominent function:** are specifically maintained and hence may have qualitative significance of certain nature. These cities may have a structure specifically designed and a planned population.
3. **Romantic cities due to historical attachment:** These cities usually have unique structural features attractive to tourists. Most of these cities have organic spread and are highly dense. Incidentally, most of these cities are susceptible to natural disasters.
4. **Symbolic cities due to importance for the country:** The importance of these cities may be due to their economic or identity significance or both. Mostly, these cities are historical, have unique architectural flavour, and have multiple functions. These cities have medium to high population density, high population, and qualitatively significant.



City Type	Categories								
	Prominent Function	Architecture	Geography	Demography	Structure	Knowledge Economy	Smartness	Mobility	Polycentricity
Type 1 Linz	Multiple	Roman origin, heavy industrial	Central Europe, land-locked, history of river flooding, Low risk assess	Area: 96 km^2, Pop: 180,000, Den: 1,972 p/km^2 (low)	Linear tending towards Irregular	Not sure	Above Average	May be average	Not sure
Type 2 Rotterdam	Shipping port	Date back to thirteenth century	West Europe, High assess of hurricane	Area: 319 km^2, Pop: 611,000, Den: 2,850 p/km^2 (medium)	Irregular, Coastal spread	Metropol is in transition	Not sure	High	MEGA 3
Type 3 Naples / Genoa	Shipping port, tourism	Greek origin, Medieval, Renaissance and Baroque	Southern Europe, High assess of forest fires, landslides, have tsunami experience / High assess of storms, landslide, potential of tsunami	Area: 100 – 200 km^2, Pop: 6 to 10 hundred thousands, Den: Medium / High	Mostly square grid along coastal lines / Irregular, Coastal spread	Not sure	Not sure	Medium tending towards low / Not sure	MEGA 3 / 4
Type 4 Vienna Munich / Prague	Multiple	Roman origin, has been an important city throughout	Central Europe, land-locked, quite safe	Area: 400 - 500 km^2, Pop: 1 M to 2 M, Den: Medium	Irregular	Not sure, may be high [Munich: Star]	Not sure, may be high	medium	MEGA 1 / 3
Type 4 / 5 Athens / Barcelona	Multiple	Greek origin, has been an important city throughout	South East Europe, both has high forest fire and landslide assess, [Athens: Earthquake and tsunami history]	Area: 400 - 800 km2, Pop: around 4 M, Den: High	Similar rectangular structure centered in a somehow radial fashion	Not sure	Not sure	Medium	MEGA 2 / 1
Type 5 London / Paris	Multiple	Roman origin, has been an important city throughout	Western Europe, moderate to high flood assess, otherwise quite safe naturally, susceptible to technological and man-made hazards	Area: around 2000 km2, Pop: around 10 M, Den: Medium / Very High	Irregular	Surely High	Surely High	Complicated	Global Node

Fig. 3 European cities categorized in six types

5. **Global cities:** are cities with economic and political importance at global scale. Mostly, these cities are historical, have unique architectural flavour, multi-cultural, tourism-friendly and have multiple functions. These cities have high population density, high population, and qualitatively very significant. Obviously these cities are more susceptible to human disaster.

4 High Performance Computing Urban Simulation Framework

4.1 Overview

Due to advancements in high performance computing, both at hardware and software level, it is now possible to model the urban situations at almost atomic level. Considering, a human individual as one of the entities at atomic level, modelling may focus on them. There are at least two reasons of considering humans as model entities; (1) humans are ultimate beneficiary of any advancements in the systems in most of the cases, and (2) it is now possible to sense and impact people at individual level due to advancements and availability of body worn and hand-held devices.

While simulating an urban situation, well explored paradigm of Agent-Based Modelling (ABM) is well equipped to address the challenge of describing a societal

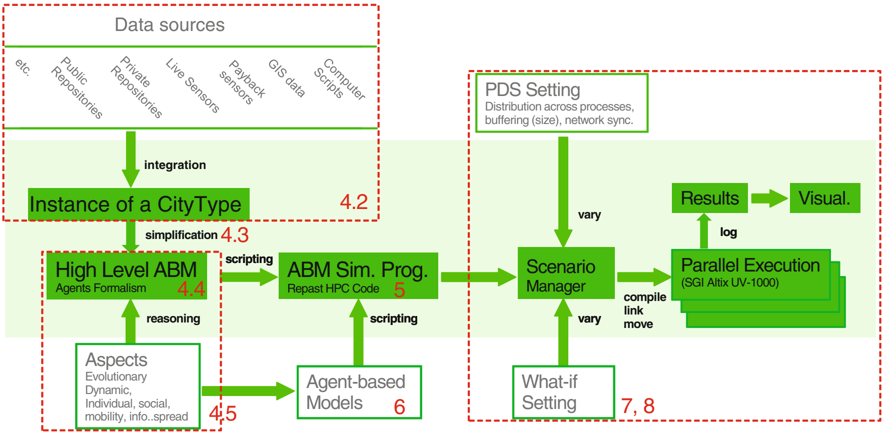


Fig. 4 High performance computing simulation framework

actor [22]. Parallel to it, the advancement in Parallel and Distributed Simulations (PDS) are coming up to the mark to simulate billions of complex agents [23]. However, the complexity in modelling and conducting parallel simulation (in this context) is still a new research venue and is a challenging task.

Coupled to it is difficulty in access of useful data which is vital for realistic models. There is a variety of data that is there, however access to it is mostly inhibited or restricted due to business concerns and privacy issues. For example, most of the individual data of the people resides with Internet, mobile and other service providers. Demographic and population data often is with districts governments and can be provided anonymous. The most promising progress in this direction which probably provided the impetus towards urban simulation in the last decade is open GIS data which is increasingly becoming ubiquitous and easy to use.

The main components (as annotated in Fig. 4) of the framework are the topic of sections to follow. The components of the agent-based parallel simulation software are described in Sect. 5. The software framework actually incorporates varieties of models described in Sect. 6. Sections 7 and 8 are devoted to simulation.

4.2 Creating a City Type with Integrated Data Sources

The city data consists of spatial data, demographic data, urban form data, transportation data and environmental data. In recent years, the complexity and extend of spatial data available to be used has increased at an exponential pace. The GIS maps themselves are regularly being updated on participatory fashion, now including every minute details of the space. This includes information about points of interests (healthcare, education, tourism and entertainment facilities etc.), distances, directions, and weather. In parallel, the population related data is also being made available either through newer GIS features or through open data initiatives from countries and regions. This include data related to city/regional demographics, urban forms, and transportation routines and modalities. The third set of data is related with climate and environment which is particularly useful for evacuation scenario. All of these data sets are related and complement each other. So there is a requirement of *Integration* of data from disparate sources, each with its own sampling frequency, latency characteristics, and semantics.

An instance of a city is a conceptual type along with related data defining a city and available for modelling subsequently. For example, many historical cities lying at the bank of river Danube passing through the centre of the Europe are of similar nature. They have low density populations, land-locked and have been assessed as low risk. However, most of them experienced heavy flooding a decade ago. In evacuation situations this poses a realistic threat for the future. This enhances the need to integrate the flooding data when preparing the city for modelling.

The more important demographic features that should be integrated with spatial model are related with population. Some examples are:

- Region/district wise population
- Demographic features such as district wise age, gender and profession distribution
- Time based activities of people and travelling modes

The most important features related to the type of the city let us include flooding scenario as cause of a possible evacuation. This would require elevation data to integrated with the city map. The statistics of flood rise in the city from the history is another set of useful data that would possibly alleviate the need to simulate the flooding. The city type also tells an irregularly dispersed city form that does not need a specific treatment (e.g. in case of circular or rectangular grid typology).

4.3 Image of a City as a Simplification Strategy

It is important to know that how a dweller looks at a city. Modelling for urban activity should emphasize more on user perspective rather than other conceptual categorizations. This should serve as a driving force inter-linked with other aspects of a city. From perspective of visual perceptions, the seminal work of Kevin Lynch [24] describe an environmental image as having three components: the image should have an *identity*; after being identified, it might be categorized as a specific *structure*; and the image should have a purpose or *meaning* attached to it. According to [24], if such an image is identified, it will fall into one of the following elements.

- **Paths:** Paths are the channels along which the observer move, e.g., street, walkways, transit lines, walking tunnels, canals and railroad etc. For many people these are the prominent elements in their image as they relates the other environmental images in reference to paths.
- **Edges:** Edges are the boundaries between two phases, linear breaks in continuity. For example, shores, railroad cuts, edges of buildings, walls, and turns on the streets. For people the edges serve as important organizational images.
- **Districts:** Districts are the medium to large sections of the city, conceived of as having two-dimensional extent, which the observer mentally enters “inside of,” and which are recognizable as having some common, identifying character. Districts along with Paths are most important elements of a city for an observer.
- **Nodes:** Nodes are points in the imagery of an observer at which an observer can be or want to be. They may be primary junctions, places of breaks in transportation, a crossing or convergence of paths or moments of shift from one structure to the other. Away from its access based imagery which simply focus on convergence of paths, events or people are also related with nodes. For example, a node may relate to a simple concentration, which gain its importance from being the condensation of some use of physical character, as a street-corner or an enclosed square. Some of these concentration nodes are centre or focus of a district, called as *cores*.
- **Landmarks:** Landmarks are another type of point-reference, but in this case the observer does not enter within them, they are external. For example, a special building, a market (store), a sign (monument), or a mountain.

None of the element types, practically exists in isolation. Districts are structures with nodes, defined by edges, penetrated by paths, and sprinkled with landmarks. This can be an advantage or disadvantage depending on the way we look at it.

Motivated by above, we have simplified the description of the city extracted from GIS and other data sources. We have used CA for spatial modelling where a unit of space can be considered as a static agent. The mobile agents occupy the space as an overlay. As a feasible enabling methodology for such a scenario (city scale evacuation), neither does it reduce the complexity of agents themselves nor the complexity due to interactions between them, however. One of the contribution of our research is a generic methodology simplifying the urban mobility scenario as shown in Fig. 5. The real physical space is very complex. Instead of considering space supporting numerous mobility modes (e.g. pedestrians, bikers, vehicles and water vessels) we have reduced it into two logical modes; *space* is where an *agent* (or a mobile agent) can be and an *obstacle* is where it cannot be. A bunch of space elements constitute a “Point of Attraction” (*PoA*) having a significance for decision making and mobility (e.g. city airport, railway station or an entrance for a highway). On this simplified logical space, different type of agents can be created and moved. Similar to the logical space model with two states, in terms of mobility modes, the agents simply are particles in motion without any particular mobility modes such as pedestrian, bus, car or biker. However, the agents are of two types: (1) “informed” agents having some form of Ambient Intelligence making them more

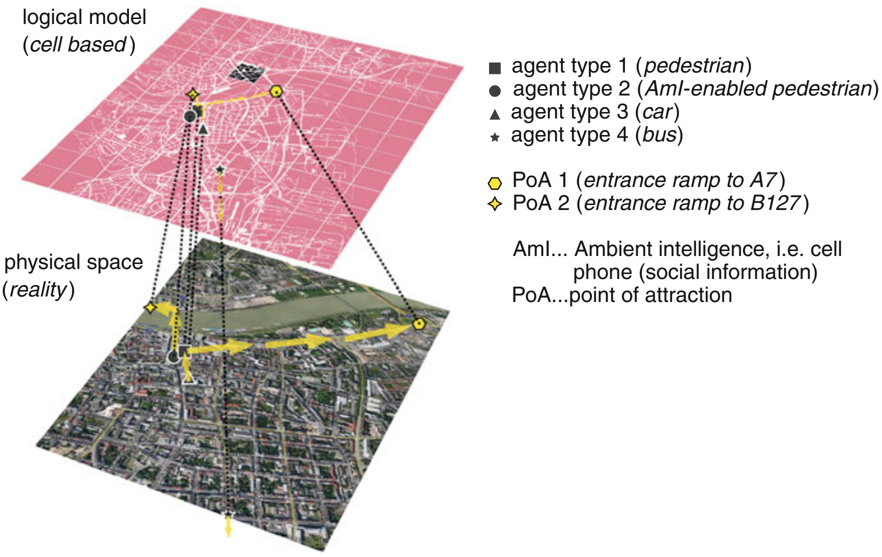


Fig. 5 Simplifying urban mobility scenario: from physical to logical

knowledgeable about how to make decisions and (2) the "regular" agents, lacking such an intelligence.

4.4 High Level Agent Formalism

As a analytical method for social systems, the Agent-Based Modelling (ABM) is rapidly gaining popularity, due to its capability of directly representing individual entities (and behaviour) and their interactions [22]. Traditionally the sociologist has been modelling the social processes as interaction among variables. With popularity of Agent-Based Modelling (ABM), the simulation is now focusing on actors rather than factors [25]. The notion of actor describes a paradigm shift of modelling social life focussing on adaptive agents rather than aggregation of variables. The agents are behaviourally adaptive in a sense that they influence others in response to the influence they receive. This is contrary to the sociologists' earlier understanding of social life as a hierarchical system of norms and influences from the top down. In fact the social behaviour is mostly very complex and usually not governed by a global system. ABM provides a possibility to model such a system as emergent properties of local interactions among adaptive agents. This can serve us two purposes: (1) saves us from extremely complex task of precisely modelling a non-linear system of such kind, (2) modelling in manner which is more closer to the reality and for which an evidence can be collected.

An agent based model provides appropriate agent level features that could define a social entity. These features are:

- Autonomy (ability to make its own decisions without a central controller): The global behaviour emerges in a bottom up fashion without central coordination solely by local interactions among autonomous decision-makers. This process is also known as “self-organization” [26].
- Social Ability (ability to interact with other agents): Agents interact and depend on each other. The influence of one agent onto the other can also be indirect following the laws of transitivity.
- Reactivity (ability to react to a stimuli quickly with simple rules): In spite of human cognitive processes seemingly complex at a global level, human beings are quite simple [27]. Human beings follow rules in the forms of norms, moral and social habits, culture, and heuristics. In many situations, the rules are very simple, however, they can produce patterns that may not be all that obvious and difficult to comprehend. This does not stop human beings to be reflexive and reactive and make decisions quickly.
- Adaptivity (ability to adapt according to the situation): Agents describing a social behaviour often generate a “complex adaptive system” [28]. Agents adapt locally by moving, imitating, replicating or learning without being aware of global consequences.

In addition to the above features, an agent based model allows multiple scales of social structures culminating naturally at a macro or societal level. In this way, ABM can be used to design a complex system which exhibits self-organization, adaptation and emergence.

The main focus of agents based models is theoretical development and explanation rather than precise prediction [29]. To do so, the agents’ behaviour must be abstracted to explore possible explanations that can describe observed phenomena. This means that we are not much concerned about realistic assumptions. In fact, if the goal is to understand the fundamentals of a process, “then simplicity of the assumptions is important and realistic representation of all the details of a particular setting is not.” [30] If the agents are more behaviourally sound, a situation often occurs where we are not able to explain the results of a model thus undermining the usefulness of the modelling technique.

ABM are most suitable to systems that do not require central coordination imposing an order in a top down order. The systems that can be described by bottom up simple and predictable local interactions generating “familiar but highly intricate and global patterns, such as the diffusion of information, emergence of norms, coordination of conventions, or participating in collective action.” [25] It is possible that unexpected patterns emerges and then vanish quickly, such as market crashes and panic in crowd. The most suitable system for ABM can be categorised as system exhibiting emergence of social order and systems presenting social self-organization.

4.4.1 Formalism of ABM for Social Design

Model design plays an important role in producing results which can potentially be conflicting. It is important to conceptually understand the varieties in the design that influence the outcome of the model. We formalise and extend the "series of interrogations" introduced by Macy in [25] in following:

Networking of Interactions: How the agents are connected with each other? We can easily distinguish between "spatial" and "social" connections. The spatial connections can be global as well as local. Agents which are connected with other agents irrespective of spatial considerations can be considered as globally connected; such as global telecommunication connectivity and Internet users. There can be other agents who are constraint by spatial connectivity constraints; such as users of a local area network or Bluetooth based connectivity. The social connections may act as an overlay on top of locally or globally connected agents. For example, not all the Internet users are connected with an agent on a social networking facility. A social connection can also be purely spatial, e.g. attendees of a meeting. Additionally a social connection can be a cognitive connection without spatial considerations, e.g. kinship.

Modalities of Interactions: With whom and how often the interactions happen? Even when an agent is networked with an other agent, the interactions cannot be guaranteed. The ties can be elective, forced or probabilistic. For example an agent can decide to send a message to a single person or a group or choosing probabilistically. There can be other situations in which the interactions are forced e.g. announcements. The frequency of interactions is also a related issue. It can be forced by technological capabilities (e.g. network delays) or human capabilities who is always overwhelmed by parallel tasks and interests.

Persistence of Connections: How the connections persist once established? Do the social and spatial constraints break the ties during a course of activity. The answer to this question is complicated. For example, movement can break auditory and visual ties between members of a family. However, they can decide to keep a connection through phone conversation due to social desire.

Modalities of Adaptation: What are the mechanism of adaptation in behaviour? "Learning" and "Evolution" are two basic adaptation mechanism. Social learning can be categorized as *observational* or *pedagogical*. Observational learning (also known as vicarious learning, social learning, imitation or modelling) is a type of learning that changes the concepts or behaviour of a person as a result of observing the behaviour of others. According to Bandura, there is a conflict between observational learning with desire to persist with the behaviour by noting that "social imitation may hasten or short-cut the acquisition of new behaviors without the necessity of reinforcing successive approximations as suggested by Skinner (1953)." [31] This is a simplistic theory favouring an abrupt adaptation due to observational learning. Social pedagogy is learning that takes place at a wider scale than individual or group learning and has potential of changing the behaviour at societal level [32]. Of course the atomic component exhibiting a behaviour is a single human being influenced as a result of social interaction between peers. This certainly changes the behaviour through observational learning. But it may or may not lead to a change in attitudes and behaviour at societal level. Social pedagogy happens when the affects of change start appearing on societal level which explodes the change afterwards. More specifically, to be considered social pedagogy, a process must: "(1) demonstrate that a change in understanding has taken place in the individuals involved; (2) demonstrate that this change goes beyond the individual and becomes situated within wider social units or communities of practice; and (3) occur through social interactions and processes between actors within a social network."

From evolutionary biology view point, "evolution is a process of selective reproduction and substitution based on the existence of a geographically-distributed population of individuals displaying some variability." [33] Social evolution is a branch of evolutionary biology that is concerned with social behaviours that have fitness consequences. The following classifications were proposed by Hamilton in his novel contribution [34]:

- "Mutually beneficial – a behaviour that increases the direct fitness of both the actor and the recipient
- Selfish – a behaviour that increases the direct fitness of the actor, but the recipient suffers a loss
- Altruistic – a behaviour that increases the direct fitness of the recipient, but the actor suffers a loss
- Spiteful – a behaviour that decreases the direct fitness of both the actor and the recipient"

Social reproduction is a sociological term referring to processes which sustain or perpetuate characteristics of a given social structure or tradition over a period of time.

The learning modifies the probability distribution of the behaviours encoded in an agent in certain situations. More advanced learning mechanisms also modify the behaviour itself. The evolution modifies the frequency distribution of the behaviours across the population of the agents.

Mechanism of Decision-making: During selective reproduction and substitution, fitness consequences signify the decision making mechanisms of an agent. Whatever the social influence forces an agent to decide what fits best in a situation while interacting with peers (for example being mutually beneficial, being selfish, being altruistic or being spiteful), the decision-making is influenced by two factor:

- Visibility of decision parameters: Is the visibility of the parameters is limited to external states of the agents (e.g. observable behaviour), or do agents have access to internals of agents as well?

- Decision Criterion: What is important for decision making; attainment towards a goal (success, fitness, payoffs or status), or familiarity (proximity, frequency)?

Individual behavioural fitness during interaction and decision parameters (hence decision) may conflict each other. For example if an agent is selfish, it can expect same behaviour from its peer. In this case, how the peer agent would provide a correct view of internal parameters to calculate the state of achievement.

Multi-scale Modelling: There are at least two ways in which the scale of a multi-agent model can be described. Both these concepts overlap and should carefully be modelled.

Modelling Scale: The microscopic models are concerned with manipulations of agent level parameters which have implications at global level. The macroscopic models are concerned with system-level parameters to test a macro theory about the dynamical implications of environmental assumptions. Combining these two level at a functional level can be termed as a hybrid scale to have adaptation at local as well as global scale. In this way an ABM can act as a theoretical bridge between micro- and macro-scopic model.

Correspondence to the Reality: There is usually a one-to-one correspondence between real world actors and virtual agents which makes it easier and natural to design an agent and also to interpret the simulation results. However, the correspondence can vary in scale based on the notion of atomicity of a real world object. Most of the times, a human being is considered as an atomic agents, but a bus on a road is an atomic entity in its own right which is practically a composition of several travellers. In many situations agents composed of fine grained agents has behavioural consequence and need to be modelled in an hierarchical and integrated manner. Using ABM, agents can interact with each other at different granularities thus introducing the core social building blocks of communication and grouping etc.

Heterogeneity: Possible heterogeneity in agents behaviour advocate the usage of ABM in social systems. Different types of agents representing different behaviours is another concept of heterogeneity classed as "intra-agent heterogeneity" and "inter-agent heterogeneity". In first case, it is almost impossible to generate each agent as a unique entity, however some simplifications techniques can be applied to automate a related but unique behaviour. Second case in obvious, for example, space, vehicles and pedestrians etc. One example of such heterogeneity is modelling moving human being on a static space.

Bounded Rationality: This is a concept describing how far the agents are rational. Many models simply assume that the individuals whom they model are rational. Herbert Simon [35], criticized this and suggested that people should be modelled as "boundedly rational", i.e., as limited in their cognitive abilities and thus in the degree to which they are able to optimize their utility [36]. ABM makes it easy to create boundedly rational agents. *In fact, the challenge is usually not to limit the rationality of agents but to extend their intelligence to the point where they could* *make decisions of the same sophistication as is commonplace among people* [22]. This goes back to the argument by Axelrod in [30].

4.4.2 Application Domains

ABM are not suitable to systems that require top-down central coordination but can be described by bottom up simple and predictable local interactions. The most suitable system for ABM can be categorised as system selectable to emergence of social structure and order [25].

In the models of *Emergent Structure*, the population differentiates into structures (clusters) segregating, dispersing, diffusing or converging (spread of innovation, coordination of conventions, emergent norms and cultural diffusion) by following simple rule at the level of local interaction. These models often study clustering within spatial networks.

In human societies, the social adaptation occurs through imitation of the fittest where agents are not replaced by better performers (as that of ecological survival) but simply copy the behaviour of the agents. The agents are normally influenced by space-dependent population exhibiting a density, familiarity, and popularity. This may lead to the assumption that agents would ultimately converge to a single profile termed as "mimetic convergence." However several studies show exactly opposite of it. For example, in Social Impact Model [37], agents mimic their neighbours in a two-dimensional space. Contrary to the expected outcome of convergence, it was noted that the system ended in a stable diversity, in which "The minority was able to survive, contrary to the belief that social influence leads to uniformity" [37].

Models of *Social order* focus on consequence of emerging (emergent) structures; in particular, the ways in which network structures affect the viability of prosocial order [38]. Four network properties have been shown to promote or inhibit participation and cooperation in collective action, namely, Relational Stability (Ongoing or continuous relationship differs from abrupt and occasional relationship), Network Density, Homophily (being influenced due to similarity), and Transitivity (of interactions).

4.4.3 How the Simulation Design Corresponds to ABM Requirements

The basic bottom-up modelling approach is the core of simulation design where each agent has a unique and independent existence. However, it is also possible to investigate on micro–macro links at several levels that is a key factor to ensure usefulness of the "feedback" loop [39]. The agents are able to adapt totally based on local interaction. The agents can be generated as different "breeds" representing different types and hence different behaviour. The breeds differentiate between behavioural uniqueness between agent types including microscopic interaction patterns and access to the macroscopic trends.

An agent can have as many features as desired. However, it is not desirable to overload the agent with behaviour and interactions too complex to comprehend. It is an established fact in ABM community that even very simple model of local interaction often generates quite complex global patterns. The interrelationship of behaviours is still a challenge to be addressed in ABM research. However, the fact that “everything is related with everything in the world” cannot and should not be modelled, similar to all rational disciplines of human existence.

Also not all the problems of the world can be solved by using ABM. The idea is that the system should have an explanation to be categorized as bottom-up system and some observed and acceptable reasons (rules) should be there to have a predictable local interaction. The broad categories of such domains are diffusion of information, emergence of norms, coordination of conventions and collective action.

The consequence of modelling a problem within these domains results in collective structures mostly based on local interactions. These structures can be of diverging nature such as cultural differentiation, stratification and homophilous clustering, or of converging nature such as diffusion, crowding, and sudden collapse of norms. These emergent structures are consequence of an emergent social order facilitating of restricting participation and cooperation of a population of agents, where the decision about cooperate or to defect is dependent on traits like trust, reputation, biases, and physical and cognitive capabilities. In this context, relating a “phase transition” of collectives of structures with social order is an interesting problem, called as “co-evolutionary dynamics.”

In conjunction with the data sets available within SOCIONICAL to formalize local behaviours, the scenarios of “Evacuation” and “Transportation” provide excellent opportunity to investigate on emerging structures as a consequence of emerging social order and how a structure and an order co-evolve. Many of the ABM domains are relevant to the scenarios and present interesting “aspects” to investigate on. Section 4.5 present a thorough discussion of how these aspects are compatible with ABM formalism.

4.5 Aspect-Oriented Modelling Paradigm Influence on ABM Formalism

When comparing with the simplistic scenario of evacuating from a building [40, 41], simulating a geo-socio-technical-urban-mobility system has many additional challenges. There are many types (each considered as a different **population**) of interacting entities, where each entity can have its own character and behaviour. The social and technological interaction may have different modalities as well, resulting in varying **information dispersion** based on extend and periodicity of interaction. Essentially, each such entity/agent has its **individuality** which would be reflected in **social** relations (both technological and humanistic). Additionally, inclusion of geographical information as an underpinning **space** to which each such agent is attached to adds a new dimension to the level of complexity. In addition to space being a direct influence to the **mobility** of agents, the fact that space may **change** its state has consequences on every possible behaviour including mobility. The Aspect Oriented Modelling Paradigm (AoM) presented in Sect. 4.5 not only captures the social-technical dimensions of a crowd mobility based phenomena in its entirety, but also focuses on the ultimate embodiment of space at which this phenomena may occur; i.e. the scale of a city. The modelling framework (see Sect. 5) describes a formalism where model variety would be integrated into an agent-based PDS.

A socio-technical system is a complex system with a number of related modelling aspects possibly in an overlapping fashion. From here on, we will be using aspect(s) and model(s) as having the same meaning because a model is governed by one or more of these aspects.

In above, the aspects important for a geo-socio-technical-urban-mobility system were introduced, namely, individual, social, population, information dispersion, space, mobility and dynamics of evolution. Here we discuss these categories under three headings adhering to the usual practice of how an ABM is formalized, namely, Heterogeneity, Interaction and Adaptation, and Space and Mobility. The discussion given below covers the most important dimensions of the system required to simulate the city-scale agent-based model for evacuation scenarios described in this paper.

4.5.1 Heterogeneity

Agent Behavior

The heterogeneity is related with **individual** aspect. These aspects range from *physical* dimensions of a human being (e.g. body, age, gender, agility etc.) to *personal* attributes which can be “biological” and “cognitive”. The biological aspects include human perceptions (sense of vision and hearing), whereas, the cognitive aspects include emotions (e.g. models addressing trust and belief of the agents).

The physical characteristics of individual humans have significant effect on individual and crowd behavior, thus mobility. For example, elderly individuals are generally less agile than younger individuals [42]. However, the most important are personal biological characteristic of an agent. The sensory perception are the perceptions of an individual to sense the environment. These may include sense of vision, hearing or touch. In a technologically equipped urban environment, technology plays a vital role in decision-making [43–46]. That is why we also consider a shared/public (e.g. an exit sign or a public display) or a private/personal (e.g. a smart phone) device as an agent. The interaction capabilities of such a device is considered a conceptual equivalent of human sensory perceptions.

The personal cognitive characteristics are as important as the biological ones. Some examples of individual cognitive characteristics are:

Instinct: Instinct refers to internal patterns of behavior in response to specific stimuli. Executing an instinct does not require a conscious thought process. Examples of human instincts are fear (hope), survival, smiling. When there is a need to make decisions under high stress, following one's instincts is the most intuitive way [47].

Experience/Knowledge: An individual often relies heavily on personal experiences in decision making. Many life events are highly repetitive. An individual usually develops a set of relatively standard routines over time and then applies them to similar situations in the future.

Trust and Belief: Belief is individual's judgment against an option. Trust is an attitude of an agent towards an information source that determines the extent to which information received by the agent from the source influences agent's beliefs. The trust to a source builds up over time based on the agent's experience with the source. In particular, when the agent has a positive (negative) experience with the source, the agent's trust to the source increases (decreases). Trust and belief have an umbrella effect on all the behavioral pattern an individual may have.

Collections and Containers

The fact that ABM provides the capability to create one-to-one correspondence of real world actors with virtual agents, defining an agent itself describes an individual. However, the granularity of atomicity of an individual is an issue to settle for. For example, taking space description also as an agent, should we represent a building as an agent or a square cell constituting a building as an agent? We opted for the second option. The minimally resolvable description, if opted as an agent would not hinder representing a collection of these as a collective structure. For example, in many simulations that we have conducted, we represented functionally collective structures (e.g. an exit) as a collection of space agents of type *exit* having assigned the same *exit ID*.

Many simulation environments define a **population** as a special agent group which falls into some class. A population describes a group of individual related spatially, temporally, socially or behaviourally. For example, in a morning rush hour, there would be a high population of school going youngsters in a train or during a cultural event, a high population of tourists is expected in a street. On the behavioural side, a population has a common goal and movement pattern which distinguishes it from other populations. This means that members of such a population are likely to follow the same social models and may have similar individual attributes. We have used concept of *breeds* to represent behaviourally-similar populations.

The fact that a notion of “containment” may exist between two breeds of agents, the solution is implemented using pointers. For example, dozens of people (contained agents) travelling in a bus (container agent) are contained within the container through connections. In this case, the contained agents do not loose their existence or identity. However, the certain attributes of the contained agents would be overtaken by the container agent. For example, in the above example, the travellers would not have any control over their speed and direction which would be the speed and the direction of the bus.

Behavioural Abstraction

Due to existence of agents as entities at minimal possible atomicity, we faced no difficulty in managing heterogeneity of the agents and hence their individualism. However, the interrelation of model and complexity of the features described above could be problematic to comprehend if more rationality is required. As discussed above, the main idea of ABM is to explain the phenomena, not to predict precisely. To this end, the agents’ behavior must be abstracted just focusing on the core features.

4.5.2 Interactions and Adaptation

Social Structures

Interactions between individuals constitute a society, hence a **social** behaviour. In a socio-technical system, the interactions between agents can be humanistic and technological. The social aspects are divided into two broad categories: (1) models which address the influence of social attributes of an individual which affect the interaction among individuals, and (2) models which describe an information flow or mechanism as a result of these socially influenced interactions.

By viewing a crowd or a group within a crowd as an emergent structure, we can identify many significant factors that may contribute to such an emergence. A group within a crowd is related with localized interactions where people may behave synchronously or may differentiate themselves from others. In either case, such a social influence defines behaviour of a group of related people either moving together, or forming a queue [48], or transforming into a herd or a jam. It also describes the movement pattern and decision making in case of agents following an agent with more knowledge (e.g. leader-followers behaviour). Mostly emergence of such a group within a crowd cannot be programmed and it evolves due to localized agents’ interactions where different types of agents have different social rules, norms and values.

Information Dispersion

How an agent is “connected” with others influences the **information dispersion** and collection mechanisms [49, 50]. We have categorized information spread into two broad categories: (1) Explicit: where information is transferred explicitly, e.g. speaking, announcing, or communicating; and (2) Implicit: where information is implicitly perceived, e.g. seeing or being influenced. Due to exceedingly high proliferation of digital devices which can interact with each other without human intervention, the interaction capabilities (range and mode) of these devices is an aspect worthwhile to explore.

The connectivity can be spatial and/or social. With the proliferation of personal technologies in the society, an agent can interact with others overwriting the spatial constraints. However, technologies are also spatially influenced and have limitations of their own. We use the terms “extent” and “periodicity” of interactions to harness variations in connectivity. The variations can be in spatial extent; i.e., global connectivity, local network based connectivity, group connectivity and proximity based connectivity. The variations in extent of social connectivity can be locality, relational or social networking. The extent also focus on probabilistic connectivity in spatial as well as social domain. This primarily affects the information dispersion mechanism as not all agents are humanistically/technologically feasible to interact with. The interaction is also concerned with how often it happens or should happen, addressed by the concept of periodicity.

Different possibilities of information spread related with real life situation can be explored. For example, one mode of information spread can be observation or vocal dispersion. In this case the senses are purely humanistic and individual differences can result in different behaviour. On the technological side, the possibilities of agents having various modes of interaction capabilities would play an important role in deciding about dispersion level and freshness of transmitted information. Social networking is yet another paradigm highlighting the importance of connectivity extent.

Adaptation

Interactions result in change in behaviour of agents. The obvious way of realizing the adaptation is to model the change in behaviour within agent’s description where an agent would be influenced by the information it receives from different channels; proximity, group or global. For example, an agent can opt to move towards the least dense region in its surrounding based on its visual range. Or an agent can delete a destination from it list knowing that the destination is no more accessible. The first example is related with reacting to the situation at the local level and does not require information dispersion. The second example is related with reacting to the **change dynamics** happening at the societal level and requires information dispersion.

4.5.3 Space and Mobility

Related Work

The representation of the physical space plays a central role in simulation. In the domain of **crowd simulation**, there are many ways to deal with the space and consequently the mobility. The CA model in [51], for example, uses a discrete structure of space. Helbing et al. [52], in their social force mobility model, use the equation of motion to describe the change of location of the pedestrians, assuming a continuous treatment of space, similar to the multi-layer utility maximization approach proposed by Hoogendoorn et al. [53]. In all of these models, the pedestrian is seen as a point or a particle in a 2D environment. In the agent-based approaches, the agent moves through a virtual environment where the movements can be discrete or continuous [54]. A completely different approach is proposed by Borgers and Timmermans [55]. They use a network representation, where each node corresponds to a city-centre entry point or a departure point and each link denotes a different shopping street. In this case, the network topology represents the walk-able space and the movement occurs along the links between two consecutive nodes.

One of the earliest agent-based models used CA as representation of space [56]. In fact, cells of CA were actually agents with different states. There are other recent examples in which a cell acts not only as a space but also as an agent iteYassemi [67]. For more complex ABM, CA was used as an underlying space with mobile agent on top of it [57–59]. Many software programs also adopted this as one of the design principle realizing its usability and consistency with most of the real life systems, for example, NetLogo [60], Repast [61] and Mason [62]. To implement the local mobility decision, these approaches adopted interaction topologies mostly based on von Neuman and Moore neighbourhood [63]. However, other interaction topologies are also important and continuously being included into simulation systems. These are Euclidean 2D/2D space, Network topology, GIS or Aspatial [64].

The most promising progress which probably provided the impetus to the urban simulation in the last decade is open Geographic Information Systems (GIS) data, which is increasingly becoming ubiquitous and easy to use. Several examples of integration of the GIS data in the environment modelling at a city or broader scale are already there. These simulations are categorized as **geo-simulations** due to use of GIS data for space modelling. For example GIS data has been used to simulate the land-use [65], urban growth [66], fire propagation [67] and traffic flow [68]. However the static nature of GIS data does not allow an easy integration with dynamic processes [67]. Cellular Automata (CA) gives us a simplistic way of performing dynamic integrated GIS modelling. CA is inherently spatial and can readily be used with available GIS sources [69]. Raster based GIS is a simplistic way to get a CA based space when modelling is spatial and discrete-time. It does not require complex vector manipulators and conversions.

For mobility, raster-CA provides necessary flexibility and behavioural sophistication. Most of the (raster) GIS based CA models concerning with land and region oriented simulations use cells as agents where change in the states of the cells brings in the dynamics on top of the static map. However, there can be layers of agents on top of cell space. For example, in traffic flow simulation [68], the vehicles reside on top of static space agents (cells) and are mobile. This increases the complexity in modelling and execution time of the simulation.

In the case of city scale crowd simulation, there can be multiple layers of agent groups arranged in a hierarchical order. For example, a road segment (collection of cells) can be assigned to a moving agent representing a vehicle which may further contain many mobile human agents (travellers). There are other mobility modalities that can also be imagined, either independently or in a mixed mode. There are research efforts which consider combining two or more of these modalities [70]. However, most of them are conceptual studies. To the best of our knowledge, the complex task of actually performing a mixed-mode simulation on a large and real scale has never been achieved. Our simulation framework is capable of achieving it due to its very fine-grained spatial distribution after applying a suitable mechanism of augmenting the space with necessary semantics. This successfully extends the current spatial abstraction in which the agents can either be static or mobile, where one of the mobile agents may occupy a static agent partially or fully, even not exclusively.

Space

Agents usually have simple behaviour which is influenced by their interaction with other agents. The guiding principles of agents' behaviour is its autonomy of making decisions. However, an agent's decision-making depends on the agents it is (has been or will be) interacting with, which many a times has spatial consideration. Particularly in urban domain, the position of an agent is very important and it is related to a certain geography. We consider a cell as a unit of space, which is treated as a static agent. The mobile agents occupy the **space** as an overlay, thus adhering to the approach suggested by [57–59]. Our CA-based interaction topology is based on Moore neighbourhood [63], but with possible variation of radial scale.

Technically for a space, obstacles and attractors must also be modelled. Fixed obstacles are represented by regions that no pedestrian can access. Moving obstacles are groups of pedestrians occupying space which is consequently not available any more. Attractors are useful areas with particular meanings for the individuals. Finally, origin and destination areas, where pedestrians originate and end up in a system, must be defined.

The concept of space has two meanings; semantic and physical. In the semantic case, we take space as a room, or a specific corridor connecting two rooms. The conceptual definition of space in this way guarantees a more convenient behavioural analysis granularity focusing on a conceptual basis of analysis rather than unnecessary physical (coordinates etc.) details of a space. In the physical case, we describe the space in physical domain which is necessary to generate CA. While modelling a space based on GIS raster map, we took the physical concept of space for implementation.

Mobility

The **mobility** models address how individuals move within a locality and make decisions about route choice. The combination of CA with agents as an overlay makes it easy to manage the mobility. The locomotion (small scale movement) has two basic features [42].

Speed: Speed is the most important feature of locomotion. In an empty space, the destination and the path are almost sufficient to reproduce the trajectory of a given pedestrian. When the environment is crowded and contains obstacles, the direction and the speed of the pedestrian may be significantly affected [71].

Collision avoidance: The collision avoidance patterns stem automatically from a combination of the velocity vector of the other pedestrians and the density parameter. In microscopic models, an individual tries to keep a minimum distance from the others. In the social force model, this pattern is described by repulsive social forces.

The route choice is choosing a destination at a coarser level of interaction [55]. An example of route is the Google map description of route plan given a source and destination. In CA based models, the route is chosen based on very limited information in the cells, unless we augment it with macroscopic information about the decision parameters such as densities at possible destinations.

5 Agent-Based Parallel Simulation Software

5.1 The Framework Components

The software framework for agent based parallel simulation consists of three main components, illustrated as three large blocks in Fig. 6a: the image processing unit, the agent-based PDS unit, and the output data processing and visualization unit.

5.1.1 Image Processing

The massive city map, initially a raster image, is incorporated into the model by first reducing it to the relevant areas (Fig. 7a). The focused area was then segmented into partitions depending on the processing resources and inter-process synchronization overhead; i.e. 200 equal sized squares regions of 20 rows and 10 columns (Fig. 7b).

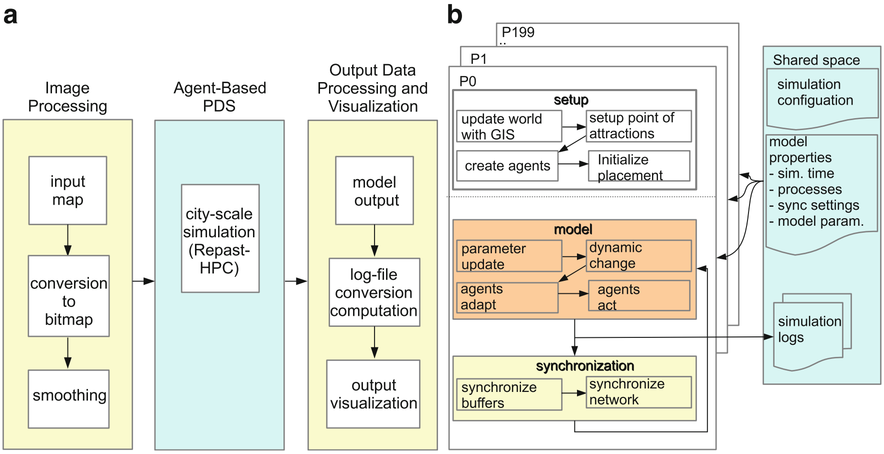


Fig. 6 (**a**) Overview of agent-based parallel simulation framework and the major sub-components. (**b**) Agent-based city-scale PDS using Repast HPC

These regions were first converted to a binary grid. The streets are selected to be walkable areas (agents can move here), and all other areas are considered to be non-walkable (agents cannot move here). Secondly, a smoothing algorithm is run, first horizontally, then vertically, to counter inconsistencies in raster. The smoothing function is a low-pass filter, with filter coefficients equal to the reciprocal of the span. The 200 files are saved to ASCII format to be used as GIS based space.

5.1.2 Agent-Based PDS

The simulation space is divided between two conceptual memory distributions; the local memory and the shared memory. The **local memory** is the memory place of each of the processor p_x (or process) out of total P. The **shared memory** is the memory place shared by all the processes. The physical sharing of data is mostly managed by high performance software platform designed for shared memory multiprocessor architectures, i.e. Repast for High Performance Computing (Repast HPC) [72]. The shared memory is used for synchronization of processes, simulation configuration files and disk space for files IO (e.g. simulation log).

The simulation setup at each of the processes can be guided by simulation and model configuration files. In Repast HPC, any process, synchronization and model related parameters that need announcements at shared data level can be written in these configuration files. The most important are the boundaries of the space in terms of x- and y-coordinates (in CA mode), the number of processors and their vertical/horizontal distribution, the simulation time in terms of number of iterations, and synchronization information. An *ID* is automatically assigned to each of the process based on vertical/horizontal distribution of the processes which

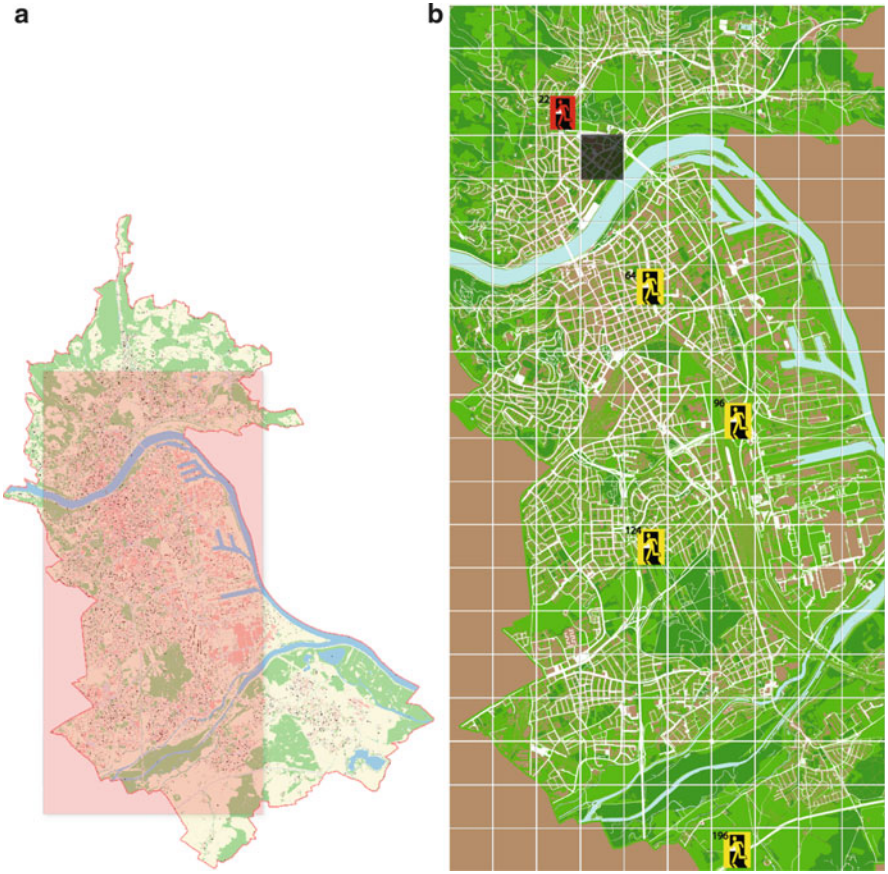


Fig. 7 (**a**) Original raster map of a city. Our agent-based model is simulated for the highlighted area. (**b**)The simulated city map, showing the 200 sectors as *squares*. Each sector was simulated by one processor. For the city-scale evacuation simulations, the exits (PoAs) are highlighted in *yellow* and *red*

starts at 0 and ends with $N - 1$. It is clear that on the left hand side of the Fig. 6b, there are 200 processes with *IDs* from 0 to 199.

A process model can be divided into three components: Setup, Model and Synchronization.

Setup

The following steps are part of simulation setup:

- Update world with GIS: Initially the Repast HPC creates an inert grid of cells with default setting. This space should be updated with the GIS information provided in ASCII files.

- Setup point of attractions: Another GIS information which is not currently part of the ASCII files; i.e. the location of Point of Attractions or possible destinations on the map, provided through model properties files; should also be incorporated into the space.
- Create agents: In this step the space is populated with moving agents; i.e. *n* numbers of agents of *t* types are created mentioned in properties files.
- Initialize placement: Moving agents are placed in the space based on required density and mutual distance.

The setup module is executed once before the start of the simulation.

Model

The following procedures are part of our agent model:

- Parameter update: The global variables (e.g. processes densities) are shared and updated.
- Dynamic change: In this logical step, the space dynamic is updated. This includes the floor field spread and spreading of information about change in dynamics of the space.
- Agents adapt: Each of the moving agent updates what it knows about the agents in the proximity as well as update in information at the global level parameters. This may result in adaptation of agent's behaviour.
- Agents act: Finally, based on possibly adapted behaviour, an agent performs the required action.

Synchronization

The basic purpose of these procedures is to synchronize the buffer and network space. The buffer space is set from model properties files so it is same for all processors. The buffers are managed on all sides of the adjacent processes and can be synchronized at i_{th} iteration where i can be 1 if required. The network space shares the information between connected nodes. Each pair of such agents is synchronized at i_{th} iteration where i can be 1 if required, if peer agents reside in the adjacent processes.

This interaction range (proximity) along with the periodicity of executing a step (update/change/adapt/act), synchronization and writing log files should be carefully managed keeping in view the trade-off between simulation efficiency and information.

5.1.3 Output Data Processing and Visualization

The output of our system consists of a series of log files which are processed by a computer script to obtain the necessary format both for evaluation and for visualization. All of the visualizations of the city model are created by NetLogo [60].

5.2 Efficiency Parameters

Scalability is defined as the performance of a system as the size increases. If we wish to decide whether a simulation model will scale or not, we have to consider the architectural as well as the algorithmic side of the system. The following interrelated factors influence the efficiency of a parallel and distributed agent based simulation setup:

- Agents' Interaction: The extent (the range of interaction) and periodicity (how often the agents interact with each other).
- Agents' Behaviour: The complexity of agent's models and types of agents present in the system.
- Space Distribution across the Processors: How the space can be distributed across the processors; the size and shape of the space.
- PDS Essentials: How the synchronization mechanism between the processors is implemented and how often the synchronization takes place.

5.2.1 Agents' Interaction

The extent (the range of interaction) and periodicity (how often the agents interact with each other) are two basic parameters affecting the PDS efficiency. In our previous study [73], we have focused on simulation efficiency of a large scale agent population. We designed and simulated a framework of large scale social agent (an abstract definition of a social entity) simulation with essential social features namely cluster size (interaction range) and connectivity extent where each agent had to execute a hypothetical workload. It was concluded that while using a cluster machine, an acceleration of a factor of up to 727 is possible in one of the realistic variation in cluster size, connectivity and workload, when compared with a single CPU.

5.2.2 Agents' Behaviour

The complexity of agent's models and types of agents present in the system establish the requirement of processing time and memory utilization. In our study [73], we realized that increase in work load decreases the efficiency of PDS. Some models are really computationally intensive in terms of process cycles and memory requirements, e.g. unconditional trust on an leader agent (as used in this paper) is far less computationally intensive then a cognitive trust evaluation model we used earlier [74–76]. The model described in [75] also requires recent cognitive state of the neighbourhood agents, thus demanding frequent agent interactions.

5.2.3 Space Distribution Across the Processors

As stated by the authors in [77], CA provides a natural mechanism of space distribution across the processors in a regular grid style. However, the decision about size and shape of the space chunks is important. It depends on the available resources on the PDS hardware. It also depends on the average population of mobile agents attached to one of those chunks.

5.2.4 PDS Essentials

The processes can be synchronized at various levels; adjacent buffers, network of connected nodes and space itself [78]. For CA based map, buffer synchronization is essential. The modelling requirements advocate the sync periodicity and buffer size. The extent of effort required in synchronization is linked with space distribution. The space should not be distributed at a very fine level. It would cost a lot of resources on synchronization alone. Contrarily, it should not be very coarse either resulting in utilization of only a few of the available processors thus degrading the efficiency.

The optimization of these factors to guarantee the best efficiency is a challenging task. In this paper (in Sect. 8), we have reported the important aspects we learned from our experience.

6 Models

6.1 Map Distribution

The space is an extract of a raster map of the city of Linz with dimension roughly equal to $10,000 \times 15,000$ cells. Each of these cells is a square and equal to 1 m a side (1.25 m to be exact). We cropped sides of the map and focused on more interesting central region of the city (see Fig. 7a). This reduced us with a space equal to $5,000 \times 10,000$ cells. We divided this space into 200 sectors where a *sector* is the space distribution unit of parallel execution. The 200 sectors were distributed as $m \times n$ along horizontal and vertical axis respectively where m is equal to 10 and n is equal to 20. Each of these 200 sectors was executed on a single processor as a process p_i, where i is process ID from 0 to 199 (see Fig. 6). Each process is responsible for a space equal to $x \times y$ cells (a sector) where x and y are equal to 500 cells each. It is important to note that x and y are equal whereas it is not mandatory. Figure 7b shows a compact visualization of the city space which is simulated. Figure 7b also highlights one sector (in black color) used for small scale debugging and test runs before conducting a full scale simulation.

6.1.1 Repast Patch

A patch is a single unit of space. In CA it is equivalent to a cell. Each patch/cell is represented by a integer coordinate anchored at the center of the patch. The most important GIS information each patch has is the "structure-type", i.e. type of the structure the patch is constituted of. At a city scale, the examples are street, motorway, building, green areas, water etc. The type thus can be mapped onto functionality, e.g. along with vehicles, a street is where a pedestrian can walk whereas a motorway is where she cannot.

Functionally, we have started with pedestrians only. However, traffic can also be incorporated in a CA based space [68]. To achieve a mixed mobility, the inter-model behavior should also be modeled [70]. For now, We have simplified the space of having only binary states (as structure); walkable (1) and non-walkable (0). Except for streets, the other walkable areas (e.g. greens, open space etc.) are ignored. Further a walkable patch may be a "Point of Attraction (PoA)" having a significance for decision making and mobility.

6.2 Floor Field: Modeling for Information Dispersion Through Space

Using floor field concept of CA, the information which relates to the space can be propagated and stored as a field. For example space should know the navigation information relating to PoA(s). The (movable) agents knowledge and memory is another layer of navigational information which can overlay the space information. In this paper, we do not present results of information sharing between moving agent (the aspect of information dispersion between agents).

The processes and coordinates of the PoAs are provided manually, but these can be purely random. Each patch has three variables for decision making:

- Direction: Directions of PoA(s) from current patch – DOM
- Distance: Distances of PoA(s) from current patch – HOPC
- Route: The sequence of processes towards PoA(s) – ROUTE

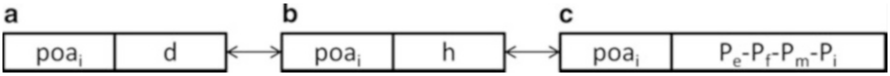


Fig. 8 Structure of patch's floor field: the information in all three cases is indexed by PoA's ID. (**a**) Direction: d ranges from 0 to 355.99 calculated as relative angle between sender and receiver patch. (**b**) Distance: h is number of hops the information has traveled before it reached to the patch. (**c**) Route: the sequence of processes taking part in propagating the information

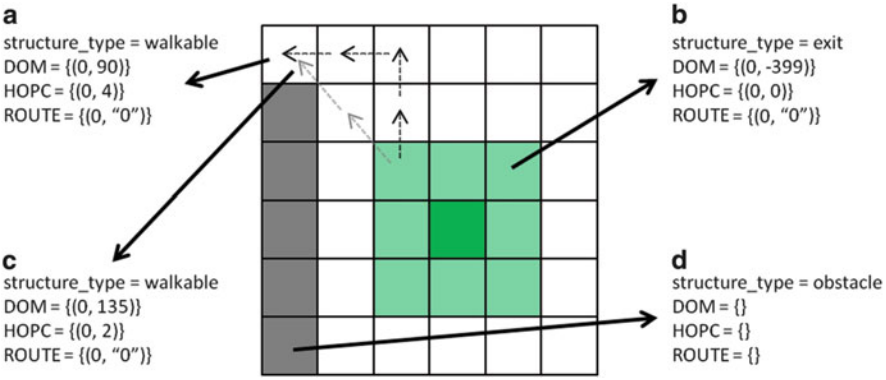


Fig. 9 An example Point o Attraction (PoA) – in *green* – on a process

A typical structure of the variables at a patch level is shown in Fig. 8.

Note that initially these variables assume the role of an obstacle representation (see Fig. 9d) with no value assigned. A PoA is the originator of the floor field (see Fig. 9b). A PoA is represented by assigning impossible values to DOM (−399) and HOPC (0). Each walkable patch **p** other than PoA itself iterates through its Moore's neighborhood to update its knowledge about PoAs. If a neighboring patch (source) has information about a new PoA in its DOM collection or is reporting lesser hop count for an existing PoA, **p** creates/updates the PoA information of its own with reference to the source. This involves calculating the relative angle towards the source, incrementing the hop count of source by 1 and concatenating (represented by ".") the process ID (if different from process ID of **p**) in ROUTE process sequence. For a more frequent case (when a PoA does not resides on the same process as that of the patch), the route may have the following formation: $\{(15, 2.12.13.14.15)(0, 2.1.0)\}$ where the patch is residing on process 2 and there are two possible PoAs at process 15 and 0.

The information flow and decision making is integrated; i.e. we do not run the floor field generation prior to actual simulation run. This is possible but does not correspond to real world situations. During the simulation run, a patch may have no or partial information which is as valuable as full information as agents represent humans who perform some action in any situation. Each patch would ultimately have information about all the PoAs if there is no disconnection (a series of non-walkable patches disrupting the information flow) after some time which can be considered as rate of flow of information and can be controlled.

6.3 *Interaction Modalities and Modeling for Multi-resolution*

6.3.1 Synchronization

Since each sector is executed by a unique process, the information synchronization mechanism must be invoked across the processes wherever it is needed. This applies both to space and mobile agents.

Thinking about propagation of patch fields (both floor field and change dynamics) is simplistic in a single process scenario. But special attention is needed in multiple processors. Same is true for mobile agents when having proximity spread across the processes or having to "migrate" to new process due to mobility. Two modes of synchronizations are supported by Repast HPC; buffer and network. Both modes work with space (patch) and mobile (turtle) agent.

Buffer Synchronization: In a grid space (CA), the processes may be synchronized across the boundaries with specification of buffers of a certain size. The buffered would be shared between the processes as a read-only copy (both patch and turtle). In Fig. 10a, the buffer synchronization of size 1 for process 64 is shown. Process 64 synchronizes the patch and turtle data with process 54 (shared space in orange), 63 (shared space in green), 74 (shared space in blue), and 65 (shared space in violet). The processes at the diagonals are also synchronized which are not shown. Some patches of process 64 are shared between more than one processes (shown with gray color).

Network Synchronization: The network space shares the information between connected nodes (both patch and turtle), if peer agents reside in the adjacent processes. An example is shown in Fig. 10a where two patches (in red) are networked with each other residing on adjacent processes 64 and 74.

Patch and Turtle classes, both are treated as an Agent and inherit the same field of "agent id", "process id" and "agent type". These three fields are essential to synchronize the buffer of networked space of adjacent processes both in case of reading or migrating. The other fields are specific to the functionalities of agents. For example, Table 1 lists the variables that are synchronized.

6.3.2 Process Parameters

There can be situations in which information at process level must be shared. For example, the "density per unit walkable area" (Eq. 1) is stored at process level and accessed by all the agents to calculate the speed (see Fig. 10b).

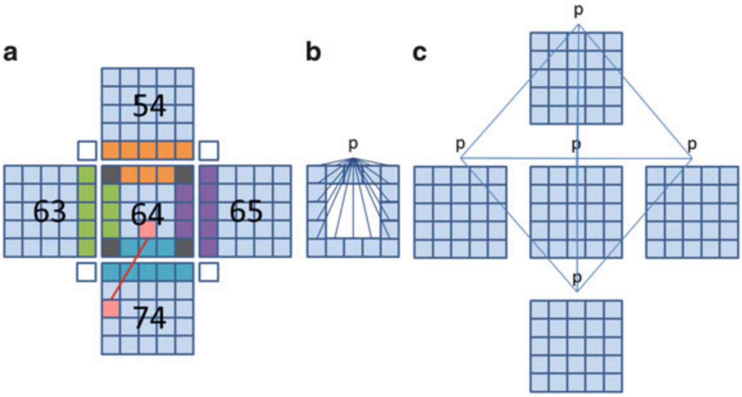


Fig. 10 Data sharing across the processes. (**a**) Buffer and network synchronization, (**b**) process level parameters, (**c**) inter-process parameters sharing

Table 1 Variables synchronized across buffers

Variable name	Agent type	Description
Agent_id	Both	Unique ID of the agent
Process_id	Both	Process ID where agent is currently residing
Agent_type	Both	Type or class of the agent
Structure_type	Patch	Type of the GIS space
DOM	Patch	Floor field
HOPC	Patch	Floor field
ROUTE	Patch	Floor field
Orientation	Turtle	The current angle of direction which is a value for a PoA from patch's DOM
Curr_exit	Turtle	The current PoA the agent is destined to
Wait	Turtle	For how long an agent has been waiting to move (in terms of iterations)
Speed	Turtle	The speed at which the agent would make the current move
Following?	Turtle	Ts the agent following some agent with better information than itself?
Confidence	Turtle	How confidence the agent is about his current move

$$process - unit - density = pop/wal \tag{1}$$

where "pop" is equal to count of moving agents on the process and "wal" is count of walkable patches at the process.

6.3.3 Global Parameters

The inter-process parameters sharing is an expensive task but cannot be replaced by local/process level data. For example, the density at each process is an absolute requirement for route decision during mobility (see Fig. 10c). However it cannot be executed in each iteration of the simulation due to high cost of execution.

6.4 Modelling for Agents Behaviour and Adaptation

All agents are of type pedestrians. There are two types of pedestrians:

- AmI-assisted: The agents who have access to all the information; process level as well as across the process.
- Non-AmI-assisted: The agents who have access to only local information (process level).

All agents can recognize the type of any other. All agents can access any information available at process and in the buffer zone.

At a very high level, randomly placed agents are destined towards one of the PoA as soon as they are able to do it. Agents use information present in the patch underneath, information available at process level and information synchronized at global level.

6.4.1 Agents Creation and Random Placement

Agents are created based on fractions where each process gets a fraction equal to its walkable count as shown in Eq. 2. Each agent is initialized with following variables values: orientation(-999), current-exit(-1), speed(0), wait(-1), confidence(-1) and following(false), irrespective of agent type. An agent is generated on patch not already occupied by another agents and is of type walkable.

$$count_{Type} = (Perc_{Type}/100) * ((ProccessW/TotalW) * TotalP) \tag{2}$$

where $Perc_{Type}$ is percentage of agents of a particular type, $ProccessW$ is count of walkable patches on current process, $TotalW$ is sum of all walkable patches in the simulation space and $TotalP$ is total population of movable agents.

6.4.2 Next Step Decision: Locomotion and Collision Avoidance

There are two general purpose procedures common to mobility strategies:

- Before proceeding with an actual move, an agent if already residing on a PoA would destroy itself with an increment of 1 in save count at process level.
- For an actual move, a neighborhood based "next step decision" would be made selecting the appropriate direction with a certain speed (step distance).

6.4.3 Speed of Agents

One aspect of proximic influence is the "next step decision" seeking availability of one of the neighbours as described before. The strategy is based on evidence and described in [79, 80]. The speed of the agents is density based where local observation range of density is that of local process (this depends on individual characteristics of range of possible observation, e.g. visibility, noise level etc.). The formulation for speed is based on free flow speed and is given in following equations:

$$\begin{aligned} speed\_on\_density = v_o * (1 - count(agents)/ \\ count(walkables)/max\_density\_per\_patch) \end{aligned} \tag{3}$$

$$speed = max\{v_{min}, speed\_on\_density\} \tag{4}$$

where $v_o = 1.36$, max_density_per_patch is maximum allowed pedestrians per patch $(= 1)$ and $v_{min} = 0.0136$.

6.5 *Modelling for Social Influence*

The true influence of social awareness on agents' decision making is described as following behaviour of agents (Non-AmI-assisted) due to presence of some of the agents which are more informed (AmI-assisted). Different possibilities can be considered starting from very basic where AmI-assisted agents are informed about densities of all the sections of the city so that they make an *optimal* route decision and adhere to it. Any Non-AmI-assisted agent in the interaction range of an AmI-assisted agent can then follow the AmI-assisted agents overwriting its own understanding about PoAs. The other possibilities are related with dispersion mechanism which can be varied in terms of how the information spreads or extent of connectivity between AmI-assisted agents.

The effects of availability and freshness of information to AmI-assisted agents on crowd behaviour is important. However, there is another question that is equally important: Why a Non-AmI-assisted agent should follow an AmI-assisted agent. Currently we have only implemented "unconditional following" which is essentially very simple and without any social consideration. However, in our earlier papers [75, 81] we investigated the role of emotions in social decision making particularly following a leader or formation of group. The computational cognitive agent model anchored on trust and belief was proposed which integrates existing neurological and cognitive theories of affective decision making. Based on this model several variants of a large scale crowd evacuation scenario with technically assisted agents were simulated. By analysis of the simulation results it was established that spread of emotions in a crowd increases resistance of agent groups to opinion changes and supports continuity of decision making in a group with technically assisted agents. The general outcome is that in a system with scarce and uncertain information, AmI technology can be used to stimulate emergence of leaders and groups to increase the efficiency of evacuation.

6.6 Modelling for Mobility

In mobility we are considering the route selection strategies based on agents types, information extent (full, partial or none) available as floor field, information update rate/pattern and principle of unconditional following of AmI-assisted agents. Numerous variation can be applied such as controlling information dispersion mechanism, varying interaction ranges and population sizes and introducing more sophisticated social behaviour models. Currently we are taking nearest measure to populate the DOM, HOPC and ROUTE collections of the patches. We are not considering multiple routes for one PoA yet. There are two possibilities though in which nearest can be inferred. One where we do nothing after a PoA x has a value in DOM, i.e. based on the information which is received first. Due to typical behaviour of instruction sequence in Repast HPC, this may not be exactly the nearest. However this can be a good approximate. In the other we explicitly compare the hop count of PoA information and update the PoAif fresh information has hop count less than what a patch already had.

6.6.1 Mobility Factors

In the mobility strategies there are three factors which are important: (1) Population Type, (2) Information Granularity, and (3) Approximation Considerations.

Population Type

Mobility strategies are dependent on population (agent type/breed). We have considered three variations:

- With all agents having Non-AmI-assisted type: Strategy 1 and Strategy 4
- With all agents having AmI-assisted type: Strategy 2
- With agents with a %age of Non-AmI-assisted as well as AmI-assisted type: Strategy 3 and Strategy 5

Information Granularity

Integrated with all mobility strategies, this is an assisting feature helpful in deciding the extent of information (full, partial and none) an agent has while choosing one of the PoA.

Approximation Consideration

While using approximate information, the only motivation here is to save processing time if there is not much difference in quality. The approximations are realized using Strategy 4 instead of Strategy 1 and Strategy 5 instead of Strategy 3.

6.6.2 Mobility Strategies

Strategy 1: If all the agents are of type Non-AmI-assisted, only the local movement strategy would work where the selected PoA would be PoA with minimum hop count. The strategy would direct the agents towards the nearest PoA. The notion of nearest is exact here which means that we make sure that hop count in minimum irrespective of the when the information is received.

Strategy 2 (Move_to_Best_Available): If all the agents are of type AmI-assisted, a decision would be made between available options by all the agents. If we define a point of attraction, *poA*, as a series of process identifiers forming a route (*R*), we can formalize this as $R = \{ID_{j_1}, ID_{j_2}, \ldots ID_{j_N}\}$ where ID_{j_i} is the identifier for the process j_i. The subscript of j denotes the index of the process in the route j. We assume N processes form a given route. We compute the average density for each route as

$$\rho(poA_j) = \sum_{e=1}^{N} \rho(ID_{j_e})/N. \tag{5}$$

The point of attraction selected, poA^*, is chosen to be the one with the minimum average density over the route. Formally,

$$poA^* = poA_j \text{ with } min(\rho(poA_j)). \tag{6}$$

Strategy 3: In case of a hybrid population of agents of type AmI-assisted and Non-AmI-assisted, a mix of Move_to_Best_Available (AmI-assisted agents) and Move_to_Nearest_with_Follow (Non-AmI-assisted agents) would be executed. Move_to_Nearest_with_Follow: A Non-AmI-assisted agent would always seek for an AmI-assisted agent in the proximity and follow. The following principle is unconditional and random chosen (in case of more than 1 AmI-assisted agent in the surroundings).

Strategy 4: When compared with Strategy 1, this strategy considers the first information about a PoA as optimal in terms of hop count.

Strategy 5: While Non-AmI-assisted agents are performing lookup for AmI-assisted agents within interaction range, the procedure Move_to_Nearest_with_Follow would not be executed in each iteration but after a specific gap.

6.7 Dynamics over Time

A trademark of a complex social system is evolving dynamics. An ABM should be able to handle unpredictability in agents' behavior and environmental conditions. We have handled change in states of the environment and updated mobility strategies to handle it; in particular, the situation in which the availability of PoA varies with time. Based on the possible real world situations, we have take three cases:

- Case 1: One of the PoA x abruptly becomes unavailable but readily becomes available again. The information about its nonavailability reaches everywhere instantly. Information about its re-availability disperses as the PoA x is new and have no history.
- Case 2: One of the PoA x abruptly becomes unavailable and remains as it is. The information about its nonavailability reaches everywhere instantly.
- Case 3: One of the PoA x abruptly becomes unavailable and remains as it is. The information about its nonavailability disperses in step-by-step fashion.

We used strategy 5 of mobility to incorporate these changes. Taking i as simulation iteration when floor field across the map has been populated with all possible PoAs, we described following strategies according to the three cases given above.

Strategy 6: At iteration i, the contents against PoA x are erased from DOM, HOPC and ROUTE collections of all the patches. At iteration $i + 1$, the information dispersion mechanism starts again for PoA x.

Strategy 7: At iteration i, the contents against PoA x are erased from DOM, HOPC and ROUTE collections of all the patches.

Strategy 8: At iteration $i + 1$, the information about non-availability of PoA x start to disperse initiated from PoA x itself. This means that unless the patches receive this information, they would consider PoA x valid.

7 Software and Hardware Considerations

To change over from a single CPU system to a shared memory multiprocessor (SMP) environment not only allows to perform simulations on larger models (space geometry, number of agents) within reasonable time, but also, allows to simulate more complex behaviour. For example, it would enable to simulate behavioural aspects of agents, such as trust, belief, decision making, etc. and with all its mutual influences on a city-scale level. It has to be pointed out, that the factor of speed-up actually achievable with a model executed on a SMP system highly is depends on inter-agent interactions. While execution time scales almost linearly with the number of cores for mainly independent agents, it gets extremely complex and difficult to model for highly interdependent agents [82]. Furthermore, parallel processing, in contrast to execution on single CPU systems, requires to deal with issues such as synchronization (between spatially adjacent processes) and mutual influence (e. g., density of agents in one space fragment (=process) have an influence on other space fragment). Where most SMP frameworks are able to provide built-in mechanism to achieve synchronization, the global parameters exchange across all the processes has to be explicitly managed by the programmer.

7.1 Repast HPC

Repast for High Performance Computing (Repast HPC) [72] is an agent-based modeling and simulation framework for high performance distributed computing platforms written in C++ and using MPI[1] for parallel operations. It is designed for parallel environments where many processes are running in parallel and where the agents themselves are distributed across processes. Shared, synchronized spaces are used for passing an agent from one process over to another, or to gather information such as agent density, blocked exits, etc. from the neighbouring processes. Beside writing “pure” C++ applications, Repast HPC also allows to develop simulation models in a Logo-like language very similar to the commands used by NetLogo framework.

7.2 Systems

To discover variety in the different modelling approaches and to gain experience in potentials, problems, etc. the different platforms might have, the full range of environments, starting with a single CPU system, continuing with a fine grained parallel processor (GPU), a shared memory multiprocessor (SMP) system with 768 cores (SGI Altix 4700), and finally a SMP with 2,048 cores (SGI Altix UV) was utilized to challenge different evacuation (i. e., agent movement enriched with individual and group behaviour) models. Subsequently, we give a brief overview of hardware/software systems used so far.

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[1] Message Passing Interface, URL: http://www.dmoz.org/Computers/Parallel_Computing/Programming/Libraries/MPI/, Retrieved February 1st, 2012.

- GPU: NVidia GeForce 9700M GT, G96 PU (625 MHz), 32 stream processors, 512 MB GDDR3, DirectX 10, Shader 4.0;
- ‘SMP768’: SMP, SGI Altix ICE 8200, 768 cores, type Intel Xeon 2.5 GHz, 1.45 TB shared memory;
- ‘SMP2048’: SMP, SGI Altix UltraViolet 1000, MIMD, 2,048 cores (256 Intel Xeon E78837 (WestmereEX) CPUs, 2.66 GHz, 24 MB L3 Cache); 16 TB shared memory (ccNUMA), 21.3TFlops, 192 TB SAS HDD;

Both test and real scale simulation use ‘SMP2048’.

8 Evacuation Simulation and Selected Results

8.1 Scenario

The simulation is performed at two scales; the small-scale and the city-scale. The small scale simulation serves to evaluate the methodologies and models, connecting the simulation efficiency with that of agents’ behaviour. Based on the small scale simulation results, the most suitable mobility strategy in each category of behaviourally “similar” strategies is chosen based on simulation efficiency and tolerance to functional equality. Only these chosen strategies are then simulated at the scale of the city. This provides us opportunity to utilize the hardware resources without incurring an endless wait and overburdening the shared processing capability.

In both scales, the raster map based space is distributed across multiple processes. Each patch of the space is either walkable or not. The space is also augmented with PoAs where agents need to move to based on the strategy they are following. The agents can be of two types; AmI-assisted and Non-AmI-assisted.

The exit strategies can be categorized into three; (i) nearest (strategy 1 and 4), (ii) following (strategy 3 and 5) and (iii) following with evolving space (strategy 6, 7 and 8). In category (i), there is no AmI assistance and all the agents move to “nearest” PoA based on the floor field at time. In category (ii), there is hybrid population of AmI-assisted (5 %) and Non-AmI-assisted (95 %) agents. The AmI-assisted agents calculate the “optimal” PoA based on: (a) the floor field at time, (b) distances to available PoAs, and (c) accumulated regional densities along ROUTE of available PoAs. The Non-AmI-assisted agents, if possible, just follow one of the AmI-assisted agent in the proximity. In category (iii), one of the variation in (ii) acts as base case (strategy 5). Additionally, after a specified time, one of the PoA becomes unavailable which affect the agents’ choices subsequently. Strategies 6, 7 and 8 explore different possibilities of change is state of PoAs with respect to how the information about non-availability of one of the PoA is dispersed throughout the floor field (Figs. 11 and 12).

It is important to note that floor field is evolving with time. It would predominantly not affect strategy 1 or 4 where it can safely be assumed that the CA based

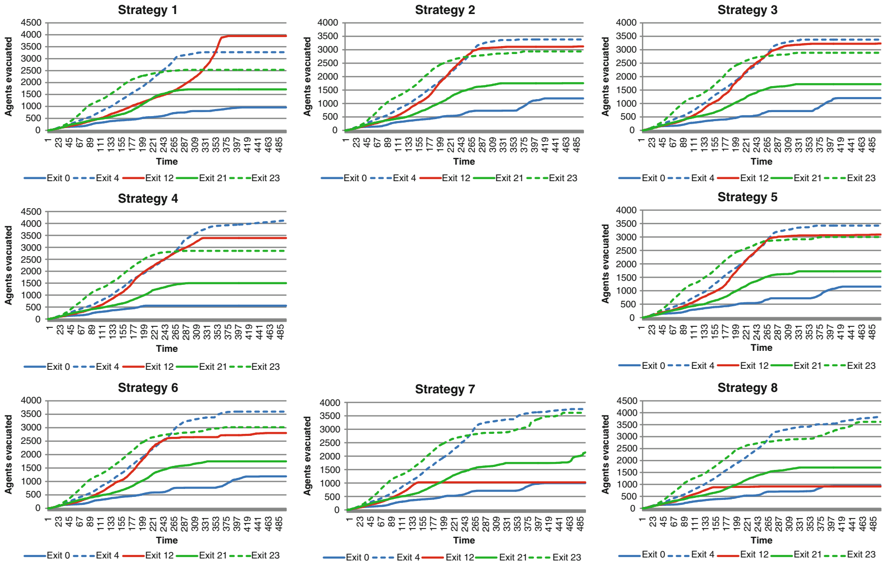


Fig. 11 Small scale results: individual PoAs plots. The graphs show time-series of evacuating agents through PoA or Exit 0, 4, 12, 21 and 23 for strategies 1–8

field spreading mechanism would guarantee that a patch receiving the information about the first PoA would generally be the "nearest" PoA. However, it can affect the relative behaviour of strategies in categories (ii) and (iii). It is because, the (AmI-assisted) agents would choose an "optimal" PoA out of available few (starting with 1) at the start of the simulation. Obviously, at that time, and optimal PoA would be more "nearest" than "optimal".

8.2 Small Scale Evaluation Study

The test space consisted of $5 \times 5(= 25)$ processes and equal to a dimension of 500×500 cells. This space represents one of the section of the city which is roughly $1/500th$ of the city map (highlighted in Fig. 7b). Each process (out of 25) is equal to 100×100 cells. The small-scale simulated space can be seen in Fig. 13. At this scale, the PoAs are not realistic and are intuitively chosen. The PoAs are labelled with ID of the process they reside in and PoA 12 (coloured red) represents the exit which changes its state from "available" to "unavailable" after specified time.

The space in Fig. 13 also shows the density of agents at the start of the simulation, which is 12,500 agents distributed across 25 processes based on availability of walkable space. The absence of red (AmI-assisted) agents shows that the simulation snapshot is taken when starting a strategy in category (i). All eight

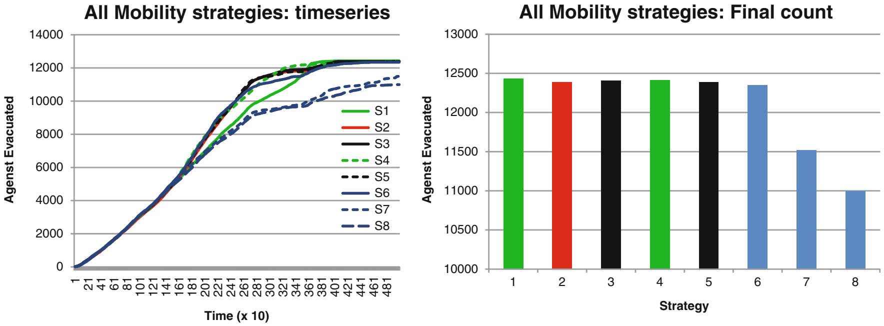


Fig. 12 Small scale results: comparing strategies irrespective of PoAs usage. Strategies 1–8 are shown with name "Sn" where n represents the strategy number

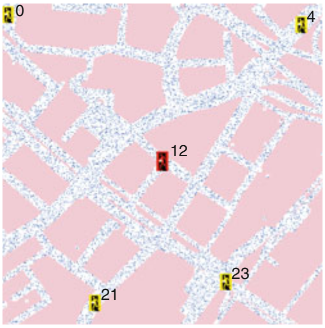
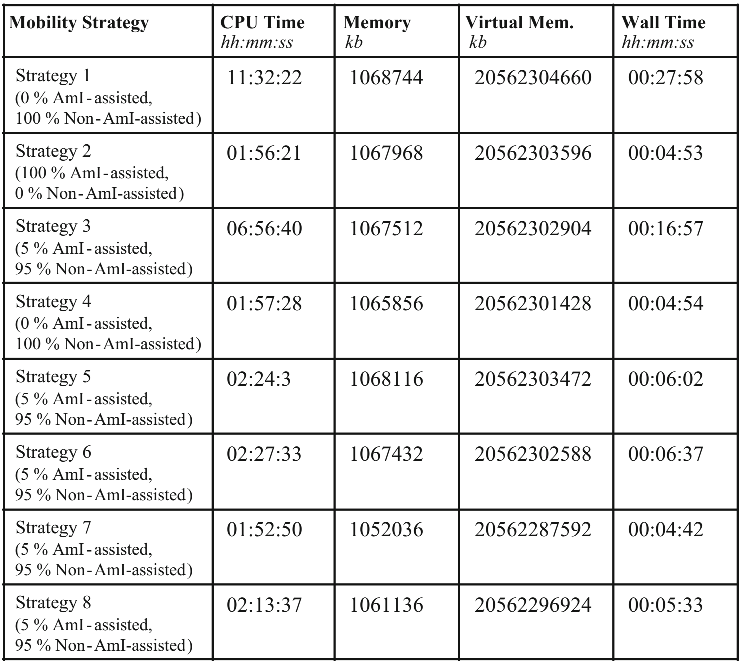


Fig. 13 The small scale scenario distributed across 25 (5 × 5) sectors. Each sector was simulated by one processor. The exits (PoAs) are highlighted in *yellow* and *red*

mobility strategies were simulated for time equal to 500 iterations. The PoA 12 changes its state from "available" to "unavailable" at time 150.

Discussion: Since basic purpose of the simulation is evacuation, the analysis of the results is anchored at evacuation patterns and efficiency. The purpose of the small scale simulation was to evaluate the execution time of the strategies with the behavioural difference. We noted that there was a significant difference in execution time when comparing strategy 1 with strategy 4 and that of strategy 5 with strategy 2 (see Table in Fig. 14), whereas the behavioural difference is acceptable.

While comparing strategy 1 and 4 based on graphs shown in Fig. 11 and Table 2, it is evident that the notion of "nearest" is affected by floor field spreading mechanism due to spatial features of PoAs. PoA 0 and 21 have narrow scope when compared with PoA 4 and 23 (see Fig. 13). That is the reason the % of agents reaching to PoA 0 and 21 has dropped when comparing strategy 4 with 1. Exactly opposite of that has happened with PoA 4 and 23 where PoA 4 is most broader in spatial sense and receives the best rise. Although PoA is almost in the centre, it does not mean that it also at the feasible place w.r.t. spread of CA based information.



Mobility Strategy	**CPU Time** *hh:mm:ss*	**Memory** *kb*	**Virtual Mem.** *kb*	**Wall Time** *hh:mm:ss*
Strategy 1 (0 % AmI - assisted, 100 % Non - AmI-assisted)	11:32:22	1068744	20562304660	00:27:58
Strategy 2 (100 % AmI - assisted, 0 % Non - AmI-assisted)	01:56:21	1067968	20562303596	00:04:53
Strategy 3 (5 % AmI - assisted, 95 % Non - AmI-assisted)	06:56:40	1067512	20562302904	00:16:57
Strategy 4 (0 % AmI - assisted, 100 % Non - AmI-assisted)	01:57:28	1065856	20562301428	00:04:54
Strategy 5 (5 % AmI - assisted, 95 % Non - AmI-assisted)	02:24:3	1068116	20562303472	00:06:02
Strategy 6 (5 % AmI - assisted, 95 % Non - AmI-assisted)	02:27:33	1067432	20562302588	00:06:37
Strategy 7 (5 % AmI - assisted, 95 % Non - AmI-assisted)	01:52:50	1052036	20562287592	00:04:42
Strategy 8 (5 % AmI - assisted, 95 % Non - AmI-assisted)	02:13:37	1061136	20562296924	00:05:33

Fig. 14 Small-scale evaluation setup: comparative PDS performance between mobility strategies

Table 2 Small-scale simulation: comparison between (%) of agents evacuating from PoAs

Strategy	PoA 0	PoA 4	PoA 12	PoA 21	PoA 23
1	8	26	32	14	20
4	4	33	27	12	22
3	10	27	26	14	23
5	9	27	25	14	24
7	9	33	10	19	31
8	8	35	8	16	33

That is the reason, the % of agents reaching to PoA 12 has dropped when compared with strategy 1 (representing more realistic nearest). Another important factor is to consider the overall efficiency of the two strategies. It is evident from Fig. 12 due to agents moving towards "real" nearest almost all the time, strategy 1 is able to evacuate much faster than strategy 4; 20 % more efficient to be exact. However, there is no difference in total number of agents evacuated in 500 iterations. Additionally, the execution time of strategy 1 is nearly 7 times that of strategy 4 (see Fig. 14). Hence for full scale simulation, instead of strategy 1 we opted for strategy 4.

Strategy 3 (and 5) disperses the agents more evenly across the PoAs when compared with strategy 1 where load is shed from PoA 12 towards PoA 0, 4 and 23. It means that even a small % of AmI-assisted agents are able to make an impact.

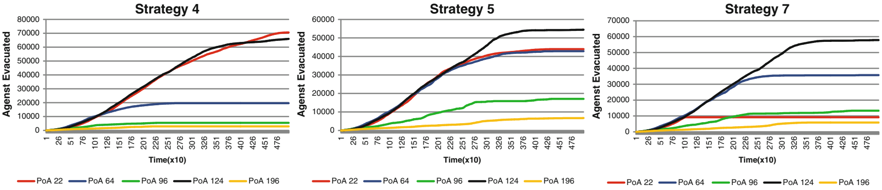


Fig. 15 City scale results: individual PoAs plots. The graphs show time-series of evacuating agents through PoA 22, 64, 96, 124 and 196 for strategies 4, 5 and 7

While comparing strategy 3 and 5 based on graphs shown in Fig. 11 and Table 2, it is evident that there is not much difference in PoA utilization and evacuation speed. Whereas, the execution time of strategy 5 is nearly three times that of strategy 3 (see Fig. 14). Hence for full scale simulation, instead of strategy 3 we opted for strategy 5 (Fig. 15).

Both strategy 2 and 6 are not a realistic settings at the scale of the city. That is why we have not considered these for city scale simulation.

Strategy 7 (and 8) are able to reroute the agents towards new destination if PoA 12 becomes unavailable during the simulation. It can be seen in Fig. 11 and Table 2 that the agents previously destined for PoA 12 are rerouted towards PoA 4, 21 and 23. This "transfer" is dependent on location of the PoAs where PoA 23 and 4 get more attention than PoA 21, whereas, PoA 0 remains unaffected. Strategy 6 and 7 look very similar in terms of PoAs usage and execution time. However, strategy 7 has much better speed of evacuation than strategy 8 due to abrupt knowledge being spread about unavailability of PoA 12. This diminishes the possibility of unproductive moves towards PoA 12. We chose strategy 7 upon strategy 8 based on these benefits.

8.3 City Scale Evacuation Simulation

For city-scale simulation, the map was divided into 200 sectors (see Fig. 7b) distributed as $m \times n$ along horizontal and vertical axis respectively where m is equal to 10 and n is equal to 20. Each of these 200 sectors (or processors) consisted of a space equal to $x \times y$ cells where x and y are equal to 500 cells each. A total of 200,000 agents were simulated which corresponded to population of the city. Each sector got its share of agents based on fraction of walkable space it has. At this scale, the PoAs are realistic and represent crowd attractions such as city center (PoA 64), industrial area (PoA 96), city stadium (PoA 124), sub-urban center (PoA 22) and motorway exit (PoA 196). The simulation was run for 5,000 iterations. The PoA 22 changes its state from "available" to "unavailable" at time 1,000.

Discussion: We present the simulation results by computing the total number of agents exited over time, shown in terms of iterations for strategies 4, 5 and 7. In Fig. 16, we plot the total number of exited agents over time, irrespective of PoAs.

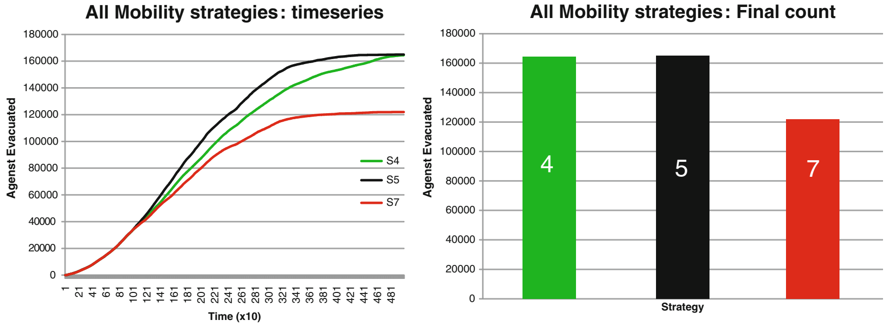


Fig. 16 City scale results: comparing strategies irrespective of PoAs usage. Strategies 1–3 are shown with name "Sn" where n represents the strategy number

Table 3 City-scale simulation: comparison between (%) of agents evacuating from PoAs

Strategy	PoA 22	PoA 64	PoA 96	PoA 124	PoA 196
1	43	12	3	40	18
4	27	26	10	33	4
7	8	29	11	47	5

We can see that with strategy 5, more agents exit at an earlier time; 80 % of the agents exited by iteration 3,690 in strategy 5 whereas 80 % of the agents exited by iteration 4,540 in strategy 4. Obviously strategy 7 cannot compete with strategy 5 as transfer of agents from PoA 22 towards other PoAs would require more time. That is the reason strategy 7 was only able to evacuate 60 % of the agents in given time.

Next we look more closely into the results by considering the number of exited agents per PoA (see Fig. 15 and Table 3). Overall, we can see that in strategy 5 the exits are more evenly used; i.e. the least used exits from strategy 4 have more usage in strategy 5, and the highest used exits from strategy 4 have less usage in strategy 5. This results in a delayed flattening-out of many of the curves in strategy 5, which results in the sooner exiting by agents. In strategy 4, only 2 out of 5 PoAs remain active where others flattens out in first half of the simulation.

The actual positions of the agents in the five processes containing exits are shown in Fig. 17. Plots (a) to (e) show the configuration at iteration 2,500, exactly half way through the simulation for strategy 4. Exactly the same frames at iteration 2,500 are shown for strategy 5 in (f) to (j) below. The agents are the small blue dots, often lined up at the exiting points, which are the slightly larger green dots. The largest noticeable difference can be seen for exit 2 ((b) vs. (g)), where several paths are developed towards the exit in (g), though only one is taken in (b). This clearly shows the difference in the process densities resulting in more diverse paths towards the exit for strategy 5. Also, at exit 3 ((c) vs. (h)), in strategy 4 the exit is no longer used half way through the process, however, it is still used in strategy 5. This reiterates the effective spreading based on density cause more even exit usage in strategy 5. A similar conclusion can be made for exit 5 ((e) vs. (j)), where this exit is quite distant and non-central, however, it is made to better use in strategy 5 by the agents.

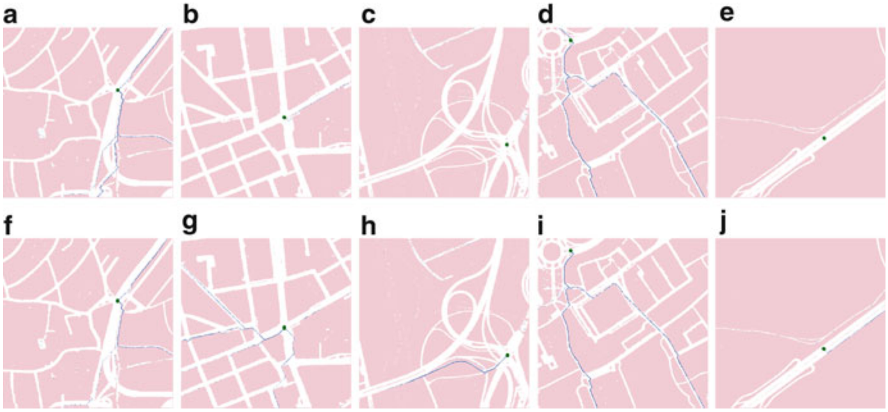


Fig. 17 Visualization of the five exits half-way through the simulation (iteration 2,500) for Strategy 4 (**a**–**e**) and Strategy 5 (**f**–**j**). Agents are demonstrated as *blue dots*. The *green dot* in each figure visualizes the exit. We can see the more even distribution of exit usage in strategy 5, especially in (**b** vs. **g**), where more paths are created towards the exit. Additionally (**c** vs. **h**) and (**e** vs. **j**) illustrate the less central exits continue to be used in strategy 5, though not in strategy 4

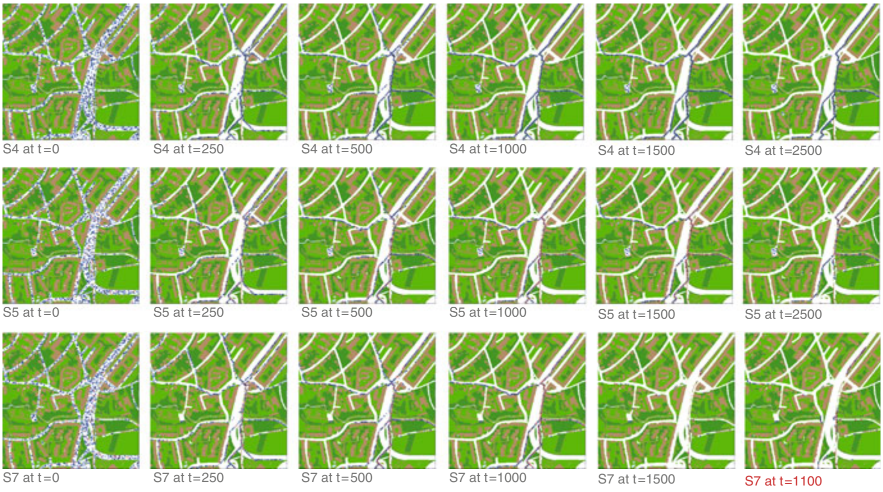


Fig. 18 Visualization of the agents around PoA 22 for Strategy 4 (*uppermost*), Strategy 5 (*middle*), and Strategy 7 (*lowermost*). Strategies 1–3 are shown with name "Sn" where n represents the strategy number and t represents the iteration number

Visual comparison of strategy 4, 5 and 7 is given in Fig. 18. It is evident that agents start to disperse away from PoA 22 towards others PoAs around iteration 2,500 when comparing strategy 4 with 5. When comparing strategy 5 with 7, it can be concluded that both are similar before iteration 1,000. When PoA 22 becomes unavailable, we can see migration of agents from PoA 22 to other PoAs (at t = 1,100). Later, there are no agents around PoA 22 at iteration 1,500.

9 Conclusion

The potential of parallel and distributed simulation for an agent based geo-simulation can only be materialized if in addition to an efficient hardware architecture, the algorithmic optimization is also taken care of in order to fully utilize the agent based modelling strength in which each agent may potentially have a unique behaviour. The scale becomes a real issue if the focus is an urban space with billions of space agents in addition to millions of mobile agents. Fortunately the space agents (e.g. cells space in CA) are usually not as diverse in function as moving agents can be, mainly representing spatial features of the environment which can be as basic as a bitmap representing walkable and non-walkable space in a map. However a space like that simple would require to have a smart information dispersion mechanism to be incorporated, so that mobile agents are able to make mobility decisions. In addition to an efficient floor field spread, the interaction of moving agents with others should also be minimized within tolerable limits.

For example, while running a simulation at the scale of a medium size city, one of the mobility strategy (strategy 1) can be that agents always move towards nearest point. But this requires update based on the neighbourhood field in each of the simulation iteration. This is a choice clearly not practical as we observed that we had to abort the simulation run after 278 h in which only the 4 % of the simulation was complete [83]. By modifying the strategy 1 into strategy 4, which considers the first information received about a PoA as the final information, a full simulation run was possible in around 12 h. The change is strategy does not incur much difference in mobility pattern due to the large scale. Similarly we were able to run the simulation with strategy 5 in 98 h which was not feasible at all with strategy 3 [83]. The strategy 5 and 3 differ only in terms of moving agents interaction periodicity.

Simulation of urban mobility is a complex task with respect to variety of aspects that are important. We have tried to conceptualize these aspects into categories and designed an agent-based PDS framework to simulate. This is an ongoing research where we intend to enrich the agents' models with more data, information and behavioural rules.

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