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AdaptIVe
Automated Driving Applications and Technologies for Intelligent Vehicles

Document information //

AUTHORS

This deliverable originates from the collective contribution of a group of authors participating in all the AdaptIVe subprojects.

COORDINATOR

Aria Etemad

Volkswagen Group Research

Hermann-Münch-Str. 1

38440 Wolfsburg

Germany

Phone: +49-5361-9-13654

Email: aria.etemad@volkswagen.de

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1 Executive summary

Over 42 months, ending in June 2017, 28 partners from all over Europe collaborated in the large-scale project, AdaptIVe, to advance the performance of automated driving systems for cars and trucks. Taking automation to higher levels, AdaptIVe's results support the goals of making driving safer and more comfortable, and of reducing congestion and fuel consumption. With the AdaptIVe applications, vehicles will react more effectively to external threats, will be resilient to different types of human and machine errors, and dynamically adapt the level of automation according to the current situation.

The key result from the project was the development of several automated functions offering different levels of assistance, including partial, conditional, and high automation. These systems were implemented in eight demonstrator vehicles (seven passenger cars and one truck), with a focus on three traffic scenarios: parking areas, the urban environment, and highways. In parallel, the project investigated other important domains, where new knowledge is required to support the advancement of automated driving. These areas are the legal framework, the interaction between the human being and the system, and new evaluation methods that hadn't yet been used for state-of-the-art experiments.

This deliverable first describes the AdaptIVe concept and objectives as well as the chosen methodological approach in chapters 2 and 3. Next, in chapters from 4 to 10 it illustrates the main achievements regarding all the areas just mentioned. The following part in chapter 11 highlights the perspectives of deployment for automated driving, addressing both technology and market aspects. Finally, a concluding section in chapter 12 reports about the major lessons learnt in the project and an outlook with research needs, with the aim to provide guidance for future initiatives.

A synthesis of the various parts of the present report is introduced here:

1. In the area of **legal aspects**, partners conducted an analysis on several legal topics including civil liability, regulatory law, data protection, and the rules of approval, focusing on EU member states and current activities in the US. As a result, this identified obstacles in the path towards the implementation of automated driving, with a view to possible future trends in the legal and regulatory fields. The project also discussed the appropriate terminology and classification of automation levels. A study on the technical system limitations and existing approaches for safety validation allowed the specification of further requirements for establishing a Code of Practice for automated driving.
2. The activities on **Human-Vehicle Integration** provided insights into driver behaviour in selected scenarios, establishing a set of design guidelines. The underlying rationale was the changing role of the driver, from an active controller to a more passive supervisor, such

that problems may arise related to inattention or reduced situational awareness as examples. After defining a set of use cases, the project performed several experiments, mostly based in driving simulators, addressing key research questions in the area of Human Factors. The topics under examination included: driver in and out of the loop, driver state, secondary tasks, changes between automation levels, shared control, and HMI. This research generated a structured catalogue of recommendations for the user-centred design of automated vehicles, which is now available for future studies. These conclusions were also applied to improve the solutions in the demonstrator vehicles.

3. **Application development** considered three basic situations: (i) close-distance scenarios, with a focus on precision in the reconstruction of the environment; (ii) urban scenarios, dealing with the traffic complexity; and (iii) highways scenarios, addressing a full range of continuously operating functions, up to 130 km/h. The development of the demonstrator vehicles with several implemented functions led to advances in many domains. To name just a few: a common architecture, new approaches for perception, communication protocols, fail-safe solutions, cooperative merging into a lane, a co-driver module adapting the automation level to the situation, and a minimum-risk manoeuvre able to bring the vehicle to a safe stop.

4. The **evaluation** work started by developing a framework of methodologies that took into account the new requirements for automated driving. The study considered a technical assessment, a user-related assessment, and in-traffic behaviour (regarding the interaction between vehicles, either automated or not). In the final project phase, these methods were applied to vehicle testing. Moreover, efforts were devoted to an impact analysis using simulation at a macro level, with a focus on safety and energy efficiency. The overall evaluation showed that the implemented automated systems demonstrate a control capability and variability that is very similar to human driving behaviour. There are two results that stand out: first, the time required for a lane change is much more uniform in automated driving, and, second, the automated driving function show much less variability in headway keeping. Questionnaires submitted to subjects after an extended experience with automated driving on the highway revealed that they perceived the system as useful and satisfactory. On the negative side, participants pointed out system failures, reckless behaviour in some situations, and problems while overtaking. The simulations of accident scenarios showed a good safety potential. The assessment of environmental impacts indicated that the travel time can almost be maintained while a 12.8% reduction of energy demand is feasible due to acceleration behaviour at penetration rates of 50%.

5. The project derived a perspective for the **deployment of Automated Driving** with surveys on the legal and technical aspects, workshops, and discussions with experts and market specialists. Key challenges and corresponding market drivers were identified in the domains of

system reliability, validation, legal aspects, mixed traffic, and Human Factors. The study allowed the defining of roadmaps covering the technical functions developed in the project, with a time horizon through 2030. Despite the challenges, the European automotive community expects a broader market introduction for automated driving over the medium term, starting with parking and progressing with applications for the highway.

In conclusion, automated driving remains a field open to further developments, and a complete, more coherent picture will come into focus over the coming years, including applications for freight delivery. The results obtained in AdaptIVe provide an industrially oriented point of view, with relevant clues in all the key areas. A suitable route towards automation will require close cooperation between all the stakeholders, as well as greater public understanding of the potentials and limitations of automated vehicles. The project partners believe that legal issues will remain on the international scene over the coming years, especially as regards liability, type approval, and data security/privacy.

Specific research is required for the subsequent steps to be taken. These include a more complete validation of the solutions, using pilots and Field Operational Tests with potential users. The roadmap for reaching higher levels of automation should be enhanced, figuring out what the optimal functions are. In this context it will be important to consider on-road vehicle interactions at different automation levels as well as the role of infrastructure. From the technology point of view, one remaining key topic is perception improvement, possibly strengthened by new sensors able to handle a wide variety of more complex situations. Communication techniques will also require additional efforts, including standards and interoperable solutions. In the domain of Human Factors, further studies are certainly needed as regards effective approaches for human-vehicle interaction. As new developments become available, a study of automated driving's long-term effects will become crucial for understanding the influence of both positive and negative factors.

2 The Project and Its Context

2.1 What Is Automated Driving

Automated driving is seen as a major breakthrough in automotive technology, with the potential to modify mobility models for vehicle users, and even to shape our lifestyles in some ways.

Over the past years, all major car and truck manufacturers have been seriously investigating automated driving technologies, with an aim to introduce self-regulating systems able to partially or totally replace the human driver for longer periods of time and in a larger range of situations.

The main drivers for these implementations are:

- Safety: the system is able to assist or replace drivers, especially in demanding or repetitive tasks, avoiding errors and reducing the occurrence of accidents.
- Traffic efficiency and environmental benefits: automated driving improves traffic flows and reduces energy consumption and CO_2 emissions.
- Social aspects: this technology significantly enhances mobility access for everyone, particularly with respect to unconfident drivers and present trends towards an ageing society.

In this context, automated driving can be considered a key aspect for future global transport, well in line with the policies of the European Union and its member states as regards social and environmental challenges.

Automated driving has also received a great deal of attention from the media and the general public in recent years, apparently being met with a mixture of fascination and scepticism. Fascination comes from the technological advances already demonstrated by several manufacturers, and from a kind of dream as regards the possibility of reducing workload when driving and gaining more time for oneself. At the same time, scepticism arises from a lack of trust in the technology, such that general confidence in it will be enhanced when people see more examples of it in action.

In terms of enabling technologies, automated driving is an evolution from the advanced driver assistance systems (ADAS) for active safety, which were developed over the past decades and are still being continuously improved. The key elements of the technology are therefore as follows:

- A reliable sensing system is required to perceive the environment and nearby obstacles, in many cases addressing complex and highly dynamic scenarios. Sensors can be supported by digital maps, and by communication with the infrastructure or between vehicles. A perception system analyses the data and provides a real-time reconstruction of the dynamic scenario.

- The next important element is the on-board intelligence, which must work out suitable and safe driving strategies. A fundamental point in this respect is the system operation in close connection with the driver, understanding their intentions, but also acting autonomously when necessary. It is clear that automated driving involves several new situations that have not yet been experienced in ordinary vehicles. With the increase of automation, the role of the human being will gradually be changing from that of an active driver to a passenger, at least for some parts of the trip.
- The final key element concerns the actuators, which impact the precise controlling of vehicle dynamics, and the Human-Machine Interface (HMI). This latter point remains a required aspect, since the driver maintains a supervisory role, and in specific circumstances must re-engage in the driving task when the system is unable to manage the situation.

Europe has established technological and industrial leadership in these areas derived from a long history of collaborative research, investments, and product development.

Nevertheless, the automotive community is facing important challenges when aiming for higher levels of automated driving that can operate in varying traffic conditions. These challenges include improving the technology – for instance where reliability and fault-tolerance become fundamental – but other aspects must also be considered. One obvious point is that legislation and the regulatory framework must be adapted to the technological advancements. The path to industrialisation is another basic aspect that must be considered in order to meet customers' expectations and to obtain economic benefits. Many of these challenges have been addressed in the AdaptIVe project, and the corresponding considerations are treated in the subsequent chapters of this report.

Having briefly outlined some key aspects of the on-going evolution towards automated driving, it is important to have a clear understanding about automation levels and their classification. A definition of these levels is presented in Table 2.1 showing how the role of the automated system increases from Level 0 to Level 5. The logic behind these definitions is easy to understand: the driving task is composed of different subtasks such as speed keeping, distance keeping to the vehicle in front, lane keeping, and obstacle avoidance (to name but a few). As the automation level increases, more and more of those subtasks are transferred from the human driver to the technical system. The classification in the table was formulated by the SAE International Organisation [SAE 2014] and selected by AdaptIVe after a comprehensive analysis. The focus of current developments by car manufacturers is in the range from Level 1 to Level 4. An important transition is between partial automation (Level 2) and conditional automation (Level 3), since in the latter case the driver is allowed to be out of the loop.

Table 2.1: Terms and categorisation of automated driving according to SAE

SAE Level	SAE name	SAE narrative definition	Execute steering and acceler./ brake	Monitor driving environment	Fall-back performance of dynamic driving task	System capability (driving mode)
Human driver monitors the driving environment						
0	No Automation	The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n.a.
1	Driver Assisted	The driving mode-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial Automation	The driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task	System	Human driver	Human driver	Some driving modes
Automated driving system ("system") monitors the driving environment						
3	Conditional Automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task with the expectation that the human driver will respond appropriately to a request to intervene	System	System	Human driver	Some driving modes
4	High Automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if a human driver does not respond appropriately to a request to intervene	System	System	System	Some driving modes
5	Full Automation	The full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver	System	System	System	All driving modes

2.2 Overview of the State of the Art in ADAS

This section of background information briefly provides an overview of industrial and research activities as regards driver assistance systems and automated driving for understanding the available solutions, some technological limitations, and the areas requiring new advancements. The focus is on technical aspects, since the regulatory issues are addressed in a subsequent chapter.

Market products: The automotive industry is focusing its efforts on developing products and solutions to support drivers. Until a few years ago, the majority of such systems only provided information or warning to the driver, and few could actually intervene or automate parts of the driving task. Examples of warning-based systems on the market include forward collision warning, blind-spot detection, lane departure warning and lane change assistant. More recently, car manufacturers are proposing active intervention systems that can be considered precursors to automated driving. Among them are collision mitigation and brake assist.

A more advanced system with automated operation that has already entered the market is the parking assistant. However, these applications have several technical limitations that restrict their operation to well-structured spaces or controlled environments.

Finally, advanced emergency braking can be considered a significant example that automates a part of the driving task, at least in specific situations when a collision is imminent and it is inferred from sensor data that the driver has no possibility to intervene. This system is rapidly gaining penetration on the European market.

While driver assistance systems have mainly targeted highway or parking scenarios in the past, their use in inner-city traffic is increasingly coming into focus nowadays. The latest generation of systems will accelerate the trend of automation in more complex driving situations. This will require innovation in environmental perception, the vehicle state, and the corresponding capacity for planning suitable manoeuvres while taking into account infrastructure and the behaviour of other road users. Future systems will therefore have greater requirements for sensor coverage, particularly in urban scenarios, where it will be necessary to perceive the entire surroundings.

One of the reasons why such systems have not yet been deployed on a wide scale is the high cost of the sensors required for full environmental perception. In order to overcome certain physical limitations of sensor-based systems, solutions related to wireless communication have been investigated. However, there are a number of obstacles for exploiting this approach: currently ongoing standardization activities, the critical mass in the market needed for proper operation, combined with the investments required for infrastructure. For these reasons “talking” vehicles have not yet reached the market. Other technical reasons hindering the development of automated driving are related to the limitations in the systems’ intelligence. It remains difficult for a computer-based system to understand traffic situations in all cases, even unexpected ones, and act accordingly. Finally, system intentions and actions should be aligned with drivers' expectations and their own preferred actions. Failing to do so might result in new safety-related issues and in a low uptake in the market.

Research prototypes: The growing interest in automated driving is also shown by the numerous research activities that have taken place in the last decade, both in Europe and the rest of the world, related to automated or semi-automated driving functions and cooperative systems. EU-funded projects are among some examples of the large number of activities. For instance, HAVEit indicated the routes for highly automated functions based on shared control, CityMobil2 addressed new concepts for personal rapid transit using automated shuttle services, and SARTRE investigated the platooning of several vehicles. InteractIVe is another project that studied active intervention by means of integrated driver assistance functions, while DRIVE-C2X, SAFESPOT, CVIS, and COOPERS investigated cooperative technologies.

These projects, together with several other initiatives at the national level, have developed and successfully demonstrated prototypes and have gained interest from policy makers at the European level. It can also be noted that there is widespread attention being paid to automated driving in the US, and relevant activities have been undertaken, starting with the DARPA challenges in 2004, and recently including an ambitious five-year national programme on vehicle automation. The Google initiative based on a concept of completely driverless operations is another specific example, with cars now tested across almost 5 million km.

Research activities are providing a solid basis for further developments, covering several areas such as vehicle technologies, perception, communication, legal aspects, HMI, and including standardisation work and evaluation methods. However, in most cases the developed prototypes and the functions considered segregated or constrained traffic environments, or referred to specific manoeuvres. This implies that advancements are needed for operating in a broad range of conditions in ordinary traffic.

European research on automated driving is even more focused than in the past with the current Horizon 2020 programme. The research community recognized that research work is needed in order to properly integrate automation in our vehicles and introduce them to the roads. The key topics under investigation refer especially to the system intelligence (where issues remain for understanding the traffic situation in real time), planning and executing manoeuvres in a sensible manner, recovering from critical situations, and interacting with other vehicles (either automated or not) as well as interacting with other road users and the infrastructure.

2.3 AdaptIVe Vision

Ageing populations, reducing CO_2 emissions, and improving road safety are the main drivers for developing new driver assistance systems. After the introduction of these solutions to the market in recent years, AdaptIVe took the next step toward developing automated driving applications for daily traffic while considering the needs of a new generations of drivers.

AdaptIVe's vision is the widespread application of automated driving to improve road safety and address inefficiencies in traffic flow whilst mitigating the environmental impact of road traffic. Performance is enhanced because drivers are supported in demanding or repetitive tasks. Vehicles can dynamically adapt the level of automation according to the current situation, can react more effectively to external threats, and are resilient to different types of system and human failure.

Today automated driving is an established field of research and development, in which industries are investing, and has reached the level of the first driving tests on public roads. The continuing evolution of this technology will expand its application across a large range of situations and driving conditions.

In this context, the AdaptIVe project aimed to contribute with breakthrough advances leading to more effective and viable automated driving. Although good and continual progress in the field is being reported, it is clear that the project's vision towards zero-accident and sustainable mobility remains an ambitious target, requiring considerable effort and the tackling of difficult challenges. Some of the basic aspects of the vision are summarized here:

- AdaptIVe cars are capable of resolving authority issues between the driver and the vehicle. The automatic system understands the driver and vice versa, so that together they work in a symbiotic way.
- Automated vehicles can flexibly adapt their operation and the automation level to the current situation. In particular, they can assure the basic functionalities, possibly at a reduced level, in case of failures in one subsystem. A Minimum Risk Manoeuvre can bring the vehicle to a safe stop.
- The high performances of the sensor system and decision-making allow reliable operation under uncertain conditions. Robustness of the perception and on-board intelligence ensure a proper matching between the representations of the world used by the system and by the driver. This is especially important in complex environments or in adverse weather situations.
- Integration of data sources allows the capability of on-board sensors to be extended by exploiting information from traffic-control centres and digital maps. This makes better navigation possible based on a predictive automated driving style. V2V communication protocols are

also able to enable dialog and negotiations during specific manoeuvres such as a lane change or a filter-in.

- Trust in automated vehicles is improving, based upon their performance and especially on the good cooperation between the driver and the system. This is not just an engineering issue, it involves cultural, sociological, and interpersonal perspectives [Lee and See 2004]. A fault-tolerant and resilient architecture is a key element in this context.

In line with the above long-term vision, the partners specified a number of objectives for the project, which are synthetically presented in the next section.

2.4 AdaptIVe Objectives

AdaptIVe's main objective was to develop and demonstrate new functionalities provided by partially-automated and highly-automated vehicles. These applications aim at improving safety, energy efficiency, dependability, and user-acceptance of automated driving.

In order to meet this general objective, AdaptIVe's focussed on the design, implementation, and evaluation of several integrated functions, suitable for different traffic environments and speed regimes. In particular, three traffic conditions were addressed: parking areas, highways with only motor vehicles, and urban traffic with several road users. Therefore, a wide range of speed regimes was covered, from low values up to 130 km/h. Mixed traffic with non-automated vehicles was addressed in all the cases.

The project also dealt with different automation levels (2,3 and 4) for system interventions: partial automation, conditional automation, and high automation. The focus was on Level 3, with some applications, such as an automated manoeuvre to a safe stop, attaining Level 4.

The developed functions were introduced on dedicated demonstrator vehicles, namely seven passenger cars and one truck, taken from production vehicles representing a wide range of uses and classes. Besides providing physical prototypes to prove all the aspects of the developed design, the purpose of the demonstrators was to allow a comprehensive evaluation of technical and user-related aspects as well as to disseminate the project ideas and results to the target audience, showing the system operation. An overview of the developed demonstrators with examples of the respective functions is shown in Figure 2.1.

Figure 2.1: Demonstrators and examples of the respective functions

The development of the planned applications requires addressing a number of scientific and technological objectives, outlined in Figure 2.2.

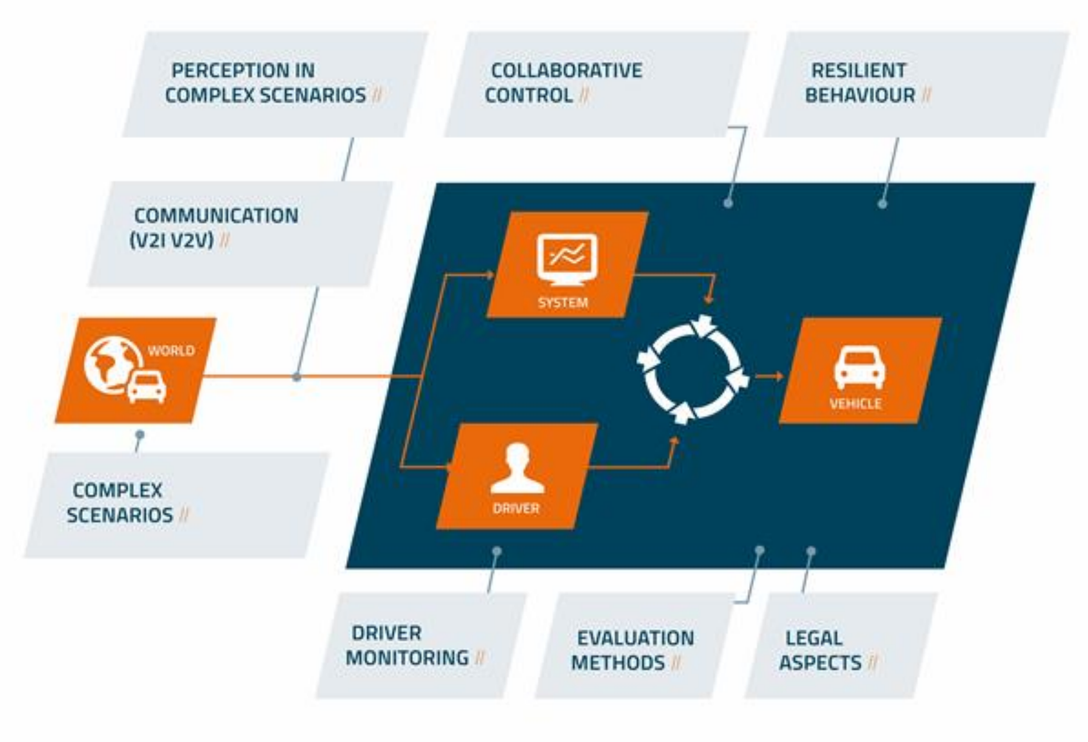


Figure 2.2: Scheme of scientific and technological objectives

The specific AdaptIVe project goals and the corresponding implementation approaches were defined as follows:

Extend the range of possible circumstances for the application of automated driving

Consider very different driving situations: highway, urban traffic, close-distance manoeuvres. Address unstructured urban environment with complex dynamics, including pedestrians, other cars, and obstacles.

Enhance the perception and communication capabilities

Implement features regarding the sensor platform, communication to other vehicles or to infrastructure. Improve safety in potentially dangerous situations via cooperative manoeuvres.

Develop solutions for Human-Vehicle Integration

New models for the functions of a co-driver. Guidelines from simulator experiments addressing specific research questions focused on driver-system interactions.

Design and demonstrate resilient behaviour for the applications

Develop a fail-safe architecture and demonstrate an automatic handover to a safe situation.

Improve the safety and adaptability of automated driving

Implement logics for a dynamically adaptive level of control. Investigate solutions for the transitions between automation levels.

Develop and apply specific evaluation methods

Develop new methods for technical and user-related assessment, taking into account unprecedented situations generated by automated driving. Evolve new procedures for the analysis of safety and environmental impacts at the European level.

Provide guidelines on legal aspects

Analyse the legal framework for introducing partially and highly automated systems on the market. Establish requirements for safety validation and specify qualifications for system availability.

3 AdaptIVe Concept

This chapter provides an overview of the areas covered by AdaptIVe in the development of automated driving and outlines the related project structure, consisting of various subprojects. It also presents the timeline for all the activities leading to the final results. This presentation can be seen as an introduction to the more detailed descriptions of the work done and results obtained in the different subprojects, specifically: legal aspects, human-vehicle interactions, application developments for the three traffic domains, and, finally, the evaluation methods.

The AdaptIVe project – which stands for A*utomated Driving Applications and Technologies for Intelligent Vehicles* – built on the partners' interests and consolidated experience in the field of Intelligent Transport Systems (ITS). Over the years, the organisations in the consortium participated in a number of national, European and company-funded projects developing advanced systems for driver support, applications based on cooperative mobility, and highly efficient vehicle controls.

The consortium was composed of 28 partners (10 OEMs, 4 suppliers, 11 research institutes and 3 SMEs), from 8 European countries, with coordinated goals as follows:

- The *automotive industry* aim to provide advanced products to their customers, responding to the demands of enhanced safety and sustainable mobility. In the present phase, where it is uncertain how automated driving will evolve, manufacturers are interested in gaining experience in all the technical and methodological aspects for beneficial exploitation. Both ordinary users for the cars, and professional drivers for the trucks, were considered in the project.
- The *automotive suppliers* have similar interests, with a focus on obtaining benefits from the progress of information and communications technologies. Their main purpose is to offer performing, low-cost solutions for underlying technologies, e.g. vision systems, novel sensors for obstacle detection, advanced navigation systems, vehicle controls, and vehicle-to-infrastructure integration.

Research institutions and universities are developing basic knowledge and new methodologies. Their participation allows them to consolidate their leading positions at the forefront of research in this field, which is characterized by a high level of interest from the research community, industry, and society in general.

3.1 Towards High Automation

As outlined in chapter 2, automated driving offers the opportunity to address several important social challenges posed by road transport in the areas of safety, energy efficiency, and social inclusion. High automation has the potential to offer mobility to all users, to increase comfort when traveling, and to promote new solutions for transport that could have a significant impact on overall mobility. These considerations can be applied to both passenger and freight transport.

In this framework, AdaptIVe focused on the development path to automated driving as defined by the automotive industry, with a specific focus on users and vehicle technologies, but also keeping an eye on related aspects such as infrastructure and service offerings.

Automotive manufacturers are forging the path forward to high automation based on previous and successful experience regarding driver assistance systems, where automation at Levels 1 and 2 has been realised (according to the classification shown in Section 2.1). The rationale is to move from these intermediate levels to automation at higher levels. But this progress is combined with a fundamental choice, i.e. to consider ordinary traffic conditions and standard roads with mixed traffic. This approach is different than other on-going developments with respect to driverless vehicles (such as a robot taxi, which could even eliminate the driving controls): these systems are based on more or less segregated environments, with an ambition of course for gradually moving towards less constrained situations.

Reaching the automation Level 3 and beyond, where a driver can be out of the loop at least for some time, poses challenging questions. An overview of these challenges is outlined here, together with a short description of the areas where AdaptIVe is contributing.

Environmental detection and reconstruction: High precision and perception reliability are needed to enable automatic driving functions. A related concern is the difficulty to foresee all the situations that a vehicle could encounter. AdaptIVe integrated different sensor types and used data-fusion approaches, including other sources of information besides the on-board sensors, to improve overall perception. Redundancy was used in some applications to improve overall performance and reliability. In the project, new approaches were also studied, including simultaneous localisation and mapping (SLAM) and the enhancement of digital maps. Advanced communication methods were developed for cooperative manoeuvres on highways involving vehicle-to-vehicle data exchange. The cost reduction for the sensor system remains an open issue, but in the project, efforts were made to use less sophisticated devices while improving data processing techniques.

Legal and regulatory aspects: Legal issues are currently considered as one of the main obstacles to the deployment of highly automated driving. Different stakeholders are engaged with this topic, such as authorities, manufacturers, technology suppliers, drivers and road users, insurance companies, etc. A common position must be achieved on aspects including responsibility and liability of all involved persons and organisations. One key point here is reaching a harmonised regulatory policy at the EU level to avoid a fragmented approach. Very recently, the legal framework for testing automated vehicles was addressed by the authorities, and first steps to allow such experiments have been accomplished. Over the longer term, it will be necessary to fully adapt legislation at the European level (without forgetting other initiatives in the world) to allow the commercialisation and use of automated vehicles. AdaptIVe was deeply involved in analysing legal issues. The project investigated existing approaches for safety validation and the technical system limitations in order to provide guidelines for a Code of Practice on automated driving. An analysis was conducted on several legal topics such as civil liability, regulatory law, data protection and the rules of approval. This work aimed to identify legal obstacles to implementation, with a view to possible future trends.

User acceptance and trust: The acceptance of automated driving at a social level should be improved to overcome several concerns users have. Affordability is an important customer expectation. Other issues regard privacy and security, especially in the case of connected vehicles. AdaptIVe contributed to the study of many aspects in this area. Large efforts were dedicated to the Human-Vehicle Integration, both theoretically and experimentally, thus providing design guidelines and solutions which are usable and well accepted. New approaches were studied for human-like driving that mirrors human behaviour in sensing and acting. The specific concerns of professional drivers travelling for long distances were investigated for the truck applications. Arguments on data privacy were also studied in the framework of legal aspects. The issues related to trust were not specifically addressed, but the project's dissemination activities were intended to show the benefits of the developed applications, not only to researchers, but also to the public.

Validation and testing methods: Right now it is unclear what the suitable validation procedures for automated vehicles are, as well as the key performance indicators. There are also concerns regarding possible misuse during driving. A first AdaptIVe contribution in this area was a functional safety analysis. A second area concerns the definition of a comprehensive evaluation methodology, which was validated for several representative cases using the developed demonstrator vehicles. This work was covered by the technical assessment, the user-related assessment, and a specific in-traffic evaluation addressing the effect of surrounding traffic on the automated vehicle and vice versa. In addition, the existing procedures for type approval were considered in order to identify additional needs related to automated driving.

3.2 Project Structure and Work Areas

AdaptIVe was a complex project involving a high number of partners and closely interrelated activities. In order to properly manage the cooperative work, it was structured into seven subprojects reflecting the different tasks to be carried out (see Figure 3.1).

Three subprojects (SP4-Automation in close distance scenarios, SP5-Automation in urban scenarios, SP6-Automation in highway scenarios) were devoted to application-oriented work, aiming at designing, developing, and validating the intended functions in the three traffic domains.

These subprojects (so-called “verticals”) were supported by cross-functional activities (“horizontals”) investigating technical and methodological aspects common to all the applications. The three subprojects of this type were: SP2-Response-4 (on legal aspects), SP3-Human-Vehicle Integration, and SP7-Evaluation. The strong liaisons between the subprojects implemented during the work are reflected, at least in part, by the interactions shown in Figure 3.1. An additional subproject, SP1-IP Management, was included for handling project coordination, links to external activities, dissemination, and general administration.

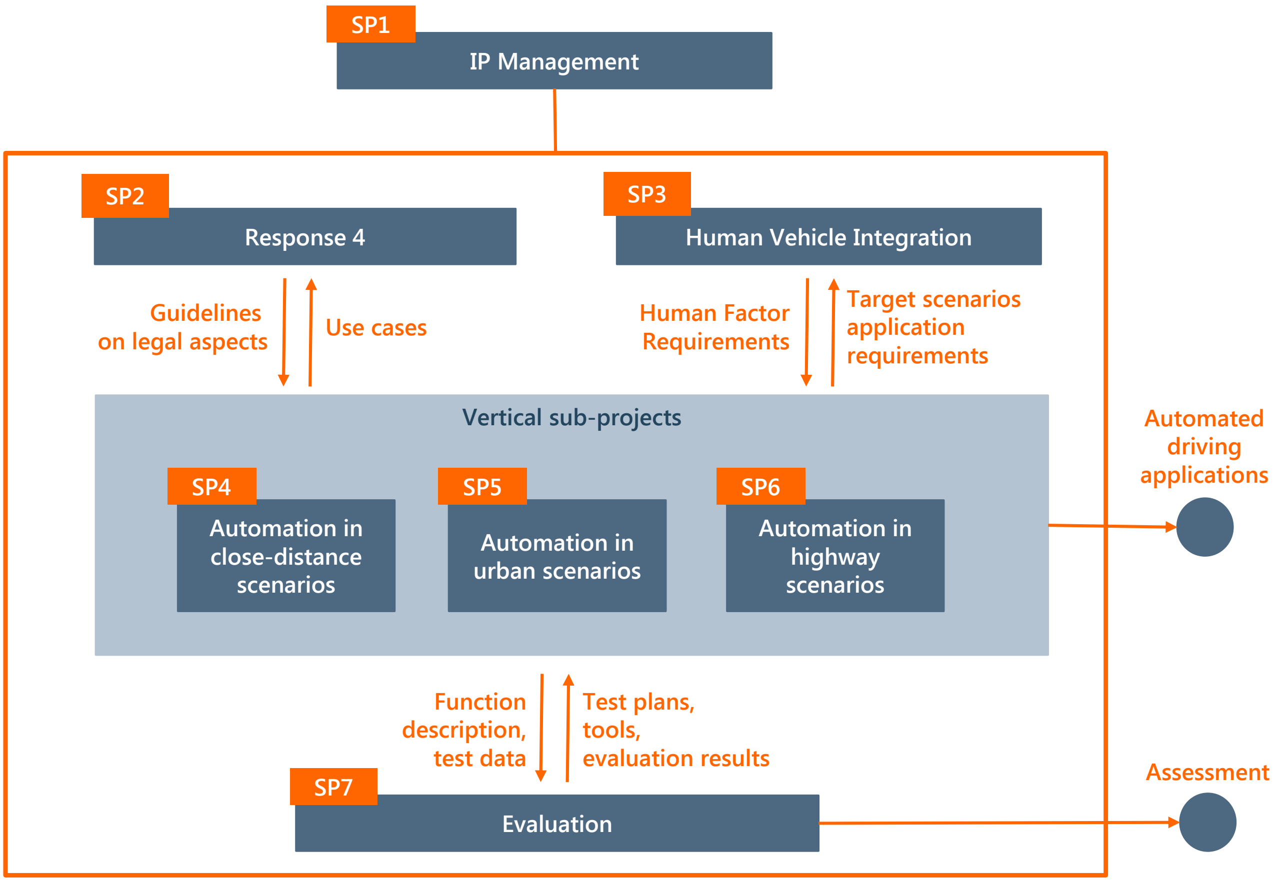


Figure 3.1: Interaction of AdaptIVe subprojects

3.3 AdaptIVe's Methodological Approach

The development path throughout the project followed a consolidated approach (see Figure 3.3). Three major phases were addressed, described in the following:

Analysis: The project started with an analysis phase. Having identified a-priori the traffic scenarios, the first key point was the definition of detailed use cases as a means to clarify how drivers interact with the applications. Use cases are typically connected to a driving manoeuvre such as for instance parking, lane change, or merging onto a highway. Activation and de-activation were also considered. Each use case was developed by describing a sequence of interventions by the user and the technical system to achieve a specific goal, thus constituting a basis for precisely describing the applications and for specifying their functional requirements. The next part of the analysis involved the finalisation of requirements and the definition of detailed sets of specifications. This work was done with parallel and linked activities in all the application subprojects, with support from the cross-functional subprojects. The specifications were iteratively defined with two major releases. In parallel, the production of a legal glossary allowed constraints related to some non-functional requirements to be taken into account. In order to have a major concept for the design, a generic high-level architecture was defined for the project (Figure 3.3). This approach was common to all the applications, but specific aspects and detailed architectures were finalised for each particular vehicle taking into account its objectives and characteristics.

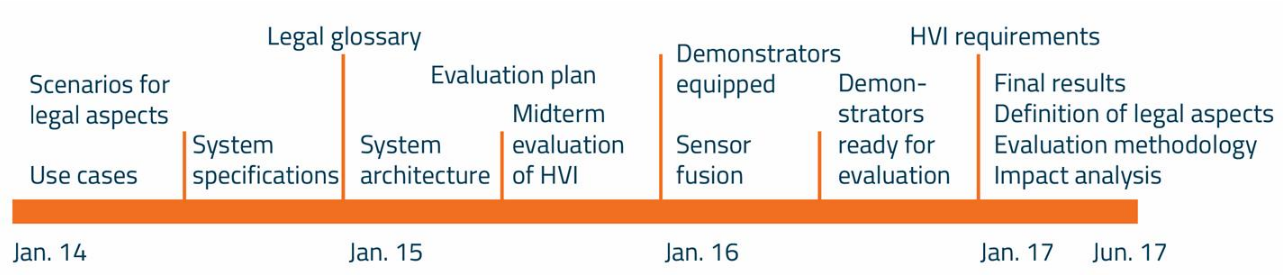


Figure 3.2: Project timeline

Development: The project's second phase addressed application development. This led to the realisation of the demonstrator vehicles (Figure 2.1), equipped with sensors and other specific components, processing units, and HMI. The controlled actuators were generally used from the series production models. The availability of these demonstrators was a major milestone, allowing the start of a first testing phase, aiming to improve the system intelligence, and then a final evaluation according to a pre-defined testing programme. The set of applications eventually chosen for the demonstrators is shown in Table 3.1.

The development work was characterised by close collaborations among all the teams. Several common approaches could be applied to all the demonstrators, based on the high-level architecture and the general perception scheme chosen. In particular, common control concepts were developed regarding Stop-&-Go Driving, Lane Change, and Minimum Risk Manoeuvres. Human Factors recommendations provided by the expert partners were taken into account in several instances.

Fundamental work in the development phase concerning Human Factors was completed in parallel. After defining a number of research questions pointing to open issues, empirical studies were performed, mostly based on driving simulators. The topics under examination included: driver in & out of the loop, driver state, secondary tasks and transitions between automation levels, shared control, and HMI. This work led to the production of a structured catalogue of recommendations for the user-centred design of automated vehicles, which is now available for future studies. These conclusions were also applied to improve the solutions and HMI approaches in the demonstrator vehicles.

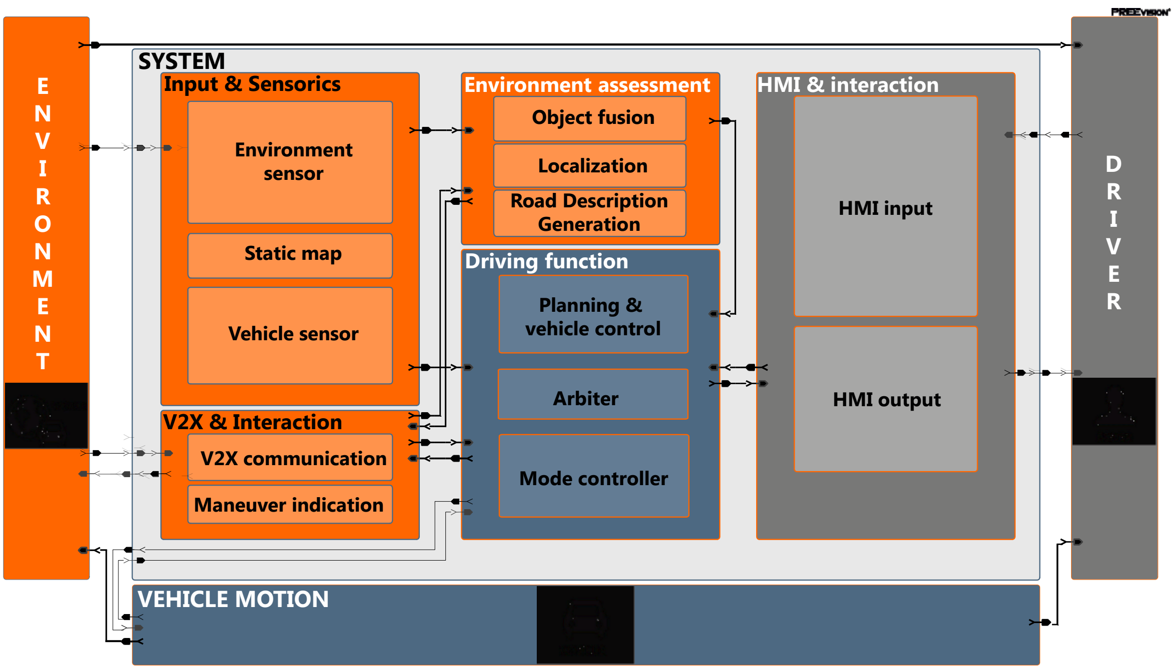


Figure 3.3: Logical diagram of the high level common architecture

Table 3.1: AdaptIVe functions and allocated demonstrator vehicles

Subproj.	Function Name	Demonstrator
SP4	Remote Parking Aid	FORD Daimler IKA (Test Vehicle)
	Automated Parking Garage Pilot	
	Automated Valet Park Assistant	
SP5	City Cruise	CRF VCC BMW
	City Chauffeur	
	Supervised City Control	
	Safe stop	
SP6	Enter and exit highway	VW BMW CONTIT VTEC
	Following lane and lead vehicle, stop-&-go driving lane change, and overtaking	
	Cooperative filter – in manoeuvre based on V2V communication	
	Speed and time-gap adaptation at highway entrance ramp	
	Minimum risk manoeuvre	

Evaluation: The third and final phase of the project addressed the evaluation of the developed applications. Here the work started by surveying the existing evaluation methods for driver assistance systems. The study showed that these methods do not cover the requirements of automated driving, and therefore new approaches and test methods were needed. This is why AdaptIVe conceived a complete framework for dealing with evaluation methodologies. Aiming to create a comprehensive work, the partners considered three areas: technical assessment, user-related assessment, and in-traffic behaviour. Moreover, efforts were dedicated to an impact analysis, with a focus on safety and traffic efficiency. In the final phase of the project, these methods were applied and validated by testing selected demonstration vehicles, with several sessions of data acquisition and data analysis. In contrast, the study regarding the impacts of automated driving was conducted by using specific simulation tools at the macro level.

After the three phases of work, the partners are in a position to improve their leadership in the area of automated driving and to identify future steps for exploitation. This topic is discussed in Chapter 11.

In order to present the achievements of the project to all the stakeholders, including the general public, an AdaptIVe Final Event has been organised on June 28-29, 2017. This event allows participants to experience AdaptIVe's technical innovations in a tangible form, and includes demonstrations of all the vehicles on the roads, a dedicated conference, and an exhibition showcasing key scientific and technical results.

3.4 System Overview and Architecture

Some additional topics, mostly related to the work on legal aspects, are outlined in this section since they clarify aspects of the project work. They are: system classification, evaluation of sensor limits, and safety validation.

System classification: The classification of automation levels was not well developed at the beginning of the project. NHTSA, SAE, and VDA were proposing their own definitions based on previous work done in Germany by BASt. After careful consideration, the SAE definitions – which were finalised meanwhile - were adopted by AdaptIVe and used – with some extensions when needed – in the context of the complete work [Bartels 2015].

The logic behind this approach was the appropriateness of performing an analysis on a whole set of characteristics for an automated function. The level of automation is only one parameter relevant for classification. Other features must also be taken into account such as vehicle speed, duration of the manoeuver (short, long), road type (parking place, urban or rural road, and highway), driver location (in the vehicle, outside of the vehicle), and others. The challenge was to collect and consider all relevant parameters without blowing up the number of classes to a vast size. The results were harmonized within the consortium, recognizing the needs of different manufacturers and suppliers, and led to a unified understanding. A decision tree was developed in the project to categorize automated driving functions using the SAE nomenclature as a basis. A further benefit was a basic glossary in the field of highly and fully automated driving, which was published as a project deliverable [Bartels 2015].

As a reference, the automation levels for the project demonstrators are presented in Table 3.2.

Table 3.2: Automation levels in AdaptIVe

Automation level	Functions
1	City Cruise
2	Remote parking aid
2	Supervised City Control
2	Automated valet parking assistant
2	Enter and exit highway
3	City Chauffeur
3	Following lane and lead vehicle, stop-&-go driving, lane change and overtaking
3	Automated Parking Garage Pilot

Automation level	Functions
3	Cooperative filter-in manoeuvre based on V2V communication
3	Speed and time-gap adaptation at highway entrance ramp
4	Minimum risk manoeuvre
4	Safe stop

Evaluation of sensor limits: Sensing systems play the key enabler role, as creating an accurate perception of the surrounding environment is an important parameter for such systems. Hence, the first step was to review the capabilities of all sensing systems and information sources. Thereafter, an exemplary sensor setup was used to derive complete system capabilities and find the white spots in typical sensor setups.

To overcome the disparities between the technical sensor limitations and real-world driving, the system limits were analysed based on typical driving scenarios. The following road types, defined in the AdaptIVe public deliverable D2.1 in “Definition of different road classes”, are considered:

- Highway;
- Interchange;
- On/Off-ramp;
- Construction site.

The main limiting factor for automated driving is sensing the environment. In contrast to the past, when this conclusion was fully valid, many new information sources and corresponding computing power are available.

At the moment, driver assistance systems are directly implemented in the sensor or actuator hardware. But additional computing power is needed for automated driving – more objects must be detected. Additionally, no sensor type works well for all tasks and in all conditions, so sensor fusion was necessary to provide redundancy for automated functions and, naturally, a full understanding of the vehicle’s surroundings.

As automated vehicles are still in research and development, no resilient state-of-the-art exists. Much work is still to be done, but the science and engineering of sensors and mature algorithms are rapidly developing to be able to predict random behaviour of drivers and vehicles, to react quickly to avoid damage to vehicles, and, most importantly, to increase the safety for human lives.

Safety validation: A basic technical prerequisite for the introduction of automated driving is system reliability and safety. The manufacturer must guarantee that the vehicle will work in a safe state under all circumstances. Thus a fail-safe/fault tolerant architecture is a key requirement. Since procedures for safety validation are not available in this new field, the AdaptIVe partners investigated the state-of-the-art regarding safety validation within different sectors and disciplines. A comprehensive survey was assembled, not only for the automotive sector but also for other transportation industries, such as railways and aviation. This allowed the evaluation of how to transfer existing methodological approaches to emerging automated driving technologies. Experience from other industries suggested that industry-wide databases help to improve simulation and test methodologies. The knowledge of well-known critical and hazardous situations can lead to faster and better safeguarding in an early development stage, generating a safe and time-efficient development process. Furthermore, even large-scale test drives (on-going discussions indicate large mileages up to millions of kilometres) are not efficient, particularly when considering economic aspects, manpower, energy, and time demands. An integrated approach leading to a robust and reliable application could be based on the standard V-model used in engineering: developers should consider safety concepts, system architecture, and design on the one hand, and verification and validation on the other. As there is currently only very little experience for series production in automated driving, we still need to figure out which safety measures and metrics can support the complete validation process. The project partners have put together the basis for the future definition of a Code of Practice as a means for systematically leading to a reliable product.

4 The Legal Perspective

4.1 Introduction to Legal Aspects

The development of automated vehicles is, above all, a technological challenge. Nevertheless, every debate on new computer assistance systems inevitably leads to unsolved or ambiguous legal issues. In order for automated driving to reach the next stage in its evolution, the automotive industry will need a clear legal framework. This is also central to public acceptance of the technology.

Naturally, motor vehicles also cross national borders. This could mean that the legal requirements placed on drivers, as well as the liability regimes in case of accidents, literally change “from one meter to the next”.

It is also unclear how the enormous amount of data collected during automated driving operations should be dealt with. Automated vehicles have already warningly been characterized as “data octopi”. Questions of data protection and data security must therefore be taken seriously. Response 4 addresses these questions and examines whether legal norms now in force will also apply to the new technologies.

The law must move in parallel with increasing vehicle automation and adapt, if necessary, in order not to become an “obstacle” to a technological development that could ultimately benefit countless people.

Specifically, automated driving is the independent, purpose-oriented driving of a vehicle in real traffic using on-board sensors, downstream software, and map data stored in the vehicle for recognition of the vehicle environment. While driver assistance systems only take over aspects of driving tasks, in the case of automated driving systems the assistance provided goes a decisive step further. In certain situations – and initially for limited periods of time – they completely take over the task of driving. During these periods, both the lateral guidance (positional change of the vehicle on the road) and the longitudinal guidance (speed regulation) of the vehicle are taken over by the system. In order to characterize levels of automation as much as possible, several delimitation criteria (delineation criteria) and step models were developed [Bartels 2015]. In general, higher degrees of automation mean less stress on drivers.

The main legal issues are discussed and analysed below. Road traffic laws are considered, followed by an analysis of liability and then data protection law for automated driving.

In the area of regulatory law, it is necessary to examine whether a transfer of driving tasks to computer systems can be reconciled with the requirements of applicable road traffic laws, laws that were written with human drivers in mind. This broaches the most fundamental question of all, namely whether automated systems can and should be used at all. Our starting point is the

Vienna Convention on Road Traffic (1968), which is intended to make road traffic safer through the harmonization of contracting parties' road traffic rules. The most recent amendments to the convention, as well as proposed amendments, show that states all around the world have already recognized the positive potentials of automated driving. In addition, the requirements of technical approval law must be discussed. The United Nations Economic Commission for Europe (UNECE) regulations, which contain a catalogue of mandatory specifications for technological functions, are the authoritative rules here.

In addition, the question of who is liable in the event of accidents is particularly relevant. Response 4 addresses those degrees of automation (Levels 3 and 4) in which the driver no longer influences the immediate driving behaviour of the vehicle, either through their own decisions, spatially or temporally. In order to conduct specific, individual-case assessments of liability, event sequences have been developed which describe the greatest possible number of potential accident scenarios. The analysis focuses on users, vehicle owners, and manufacturers.

During the operation of automated vehicles, a nearly inestimable quantity of data is generated; data on the vehicles, on their surroundings, on all traffic situations, and on their drivers. Legal issues related to this data collection also need to be examined. In this context, it is necessary that the various different reasons for data collection and further processing both be differentiated, and that the specific legal requirements for each respective purpose-related data collection be determined. This is the only way to ensure transparent and legally compliant handling of data. In addition to finding out whether specific “goals” of data collection are permissible in the context of data protection law, the legal requirements for the safe handling of data collected, i.e. data security, also had to be researched.

In addition to challenges in international law, EU law, and domestic law, various legal traditions also need to be compared. Thus, the legal situation in the countries where the various project partners are located were included in the evaluation. In addition, the American approach also needs to be considered. This will make broad and in-depth discussion possible, from which the entire project can benefit. Response 4 examines initial proposed solutions and will make its own contributions to the development of automated vehicles that are legally compliant and low risk.

4.2 Liability Issues

With the increase in the level of automation, the number of available automated manoeuvres will continually grow. For Level 3 systems and above (Level 3+), it is expected that the driver will turn their attention away from the driving task and does not need to monitor each and every manoeuvre the automated systems executes. AdaptIVe's main topics were the development of automated driving functions and identification of possible hindrances to market introduction. Consequently, an overview of product liability issues was made necessary. In the absence of any court decisions for automated vehicles or systems of Level 3 or above, a set of possible scenarios was deployed. The legal assessment was made under the assumption that the relevant law already allows the use of a Level 3 and Level 4 system. Furthermore, current legislation was taken into account as was existing experience with current laws and case law.

All countries assessed in this study have implemented the Product Liability Directive 85/374/EEC into national law. The purpose of the directive was an approximation of the laws of the member states concerning the liability of the producer for damage caused by the defectiveness of its products. In most of the relevant European countries, a manufacturer's total liability for damage resulting from death or personal injury is unlimited. Only in Germany is there a limitation to an amount of EUR 85 million. Besides that, German traffic law provides strict liability for the registered owner of the vehicle, which seems to be unique in the relevant European countries. There is a limitation of liability for damages, resulting from death or personal injury, too. The maximum amount for compensation will be EUR 5 million in case of death or bodily injury and EUR 1 million in case of property damage. All countries considered stipulate a deductible of injured parties for damages to property and a limited period for claims under product liability law. Only the designated amount and the statuary onset of the time of limitation differ slightly.

If an accident occurs while using an automated driving system, the crucial issue may be the question of liability. Either the driver or the system, and thus the manufacturer, could be responsible. Under product liability law, the injured person has to prove the damage, the defect, and the causal relationship between defect and damage. If the driver is allowed to turn their attention to activities other than driving, the responsibility could (and the further statements are theoretical) exclusively lie with "the vehicle". In this case, the driver cannot be held liable. The consequence could be a shift in liability from driver to manufacturer. The manufacturer would then have to exonerate itself and prove that the driving system did not cause the accident. Consequently, manufacturers could be involved (and ultimately be liable) in many more cases than today. It can be noted that the United States of America has no uniform legal framework covering all aspects of automated driving. Some states already allow fully automated driving, at least for testing purposes, while others don't. Therefore, a "state-by-state" legal assessment concerning liability must be made.

Another aspect that might indirectly affect product liability is the impact of automated driving on insurance law. For reasons such as liability, data collection, misuse or manipulation of data, and cyber attacks, insurance coverage seems to be necessary, particularly for the manufacturer, the driver, the registered owner, and the software providers. It is unclear whether autonomous driving will result in higher costs for insurers. Identification of the responsible party in particular could push up the costs for litigation. An alternative could be a change in the right of recourse. Perhaps the insurer could plan to take recourse from the manufacturer in general if an autonomous driving system was in use. Therefore, a shift from third-party insurance towards manufacturer's product liability could be under discussion. Even if an automated driving system was in use, the injured party will continuously be able to claim directly against the insurer.

4.3 Data Privacy

Questions regarding data privacy and data security are directly linked to liability issues. Automated vehicles are likely to collect a substantial amount of data. This data can be related to a physical person and the issue is therefore within the scope of personal data regulations. This report focuses specifically on the privacy issues raised by data recorders installed in automated private vehicles, excluding public transport. The new EU data protection framework was adopted on 14 April 2016: the General Regulation on Personal Data Protection (Regulation 2016/679) will replace the current Directive (95/46/EC) on 25 May 2018. The new regulation is intended to protect "personal data", meaning information relating to an identified or identifiable natural person. For example, data collected by a vehicle while carrying out its actual driving tasks can then be combined with other information, such as the current location of the car. The same applies to all kind of information that enables unambiguous identification. A spatial restriction does not exist in the territorial scope of this regulation, as article 3 GDPR stipulates that the rules are applicable irrespective of the place of processing if the collecting body is located in the EU.

Automated vehicles are likely to process a certain amount of personal data and shall therefore comply with the principles and requirements set by the regulation. In particular, the data collected must be proportionate to the announced purposes and securely processed. The principle of consent is also highlighted. The consent of the driver shall be obtained before processing any personal data and after proper and transparent information has been given (unless the data collection is imposed by law). The consenting person must be able understand the implications of their decision, meaning they must be able to foresee what will ultimately happen with their data. It is also necessary to ensure an adequate level of data protection. This may include, for example, measures for the pseudonymization or the encryption of personal data.

Of particular interest - not only for insurance companies - is data recorded shortly before, during, or immediately after accidents. This data enables the reconstruction and analysis of accidents, making it easier to identify the responsible party. So-called Event Data Recorders (EDR) are systems embedded in a vehicle in order to record the relevant data. AdaptIVe's Deliverable D2.3 focused on a particular type of EDR especially for automated vehicles, which are referred to as Data Storage Systems for ACSF (Automatically Commanded Steering Function), in short, DSSA, and how the new legal framework on data protection will apply to the parameters collected by DSSA. This will primarily be information regarding the driver's actions (such as interaction with the steering wheel or the pedals) and the system's operations (such as special manoeuvres or signals for the driver). This information will be crucial in order to determine who was driving in case of an accident.

DSSA will have to comply with the new regulatory framework taking effect in May 2018. In particular, the regulation does not allow the collection of sensitive data (such as health data) unless the consent of the person concerned is "explicit". Moreover, data relating to criminal offences such as vehicle speed can only be collected under the control of public authorities. The regulation also sets framework conditions and requirements for the collection, storage, and processing of personal data. In particular, DSSA shall have several limits regarding the period of storage, the amount of data stored, and its relevancy, who can access this data and how. In addition, the purposes for which this data is stored must be "legitimate" and clearly determined before collection.

4.4 Regulatory Law and Rules of Approval

Today's legal framework was developed on the assumption that there will always be a human in charge of driving. In order to make the vision of automated driving a reality, various legislators have already taken action. To determine the status quo of current legislation, the legal framework of different EU member states regarding automated systems was reviewed.

There seems to be no conflict of current regulations with assistance systems up to Level 2 of Standard J3016. Yet, with regard to higher levels of automation (Level 3+), there could be difficulties in regulatory law, liability law, and the Vienna Convention on Road Traffic. This is due to the fact that the law presumes that every car has a human driver who is responsible for every movement of the vehicle. At higher levels of automation the driver will gradually be released from all tasks. The Vienna Convention Articles 8.1 and 8.5 stipulate, firstly, that every vehicle shall have a driver, and, secondly, that the driver shall be in control of the vehicle at all times. Yet, there are different interpretations on a national level.

Article 8.5 of the Vienna Convention states that every driver shall at all times be able to control their vehicle. After the latest amendments (para. 5bis), ADAS shall be deemed to be in conformity with paragraph 5 if they either meet the requirements of the UNECE regulations or can be overridden or respectively switched off by the driver at any time. The precise consequences for all contracting parties remain unclear. Although future generations of cars will still have a human driver, it is doubtful whether they will be able to intervene in time whenever the system is overtaxed. Some countries, such as Italy, have not yet modified their regulatory framework in order to implement Article 8.5bis. However, the Italian Senate is working on a draft law to do just that. To date there is no official interpretation from the French Government regarding the compatibility of highly automated systems with the Vienna Convention. This issue is still being debated in UNO-ECE-WP1. The requirements of the Geneva Convention on Road traffic are comparable to those of the Vienna Convention; there also needs to be a human in charge of driving. Level 3 systems are probably admissible, since they anticipate the presence of a driver who must be able to intervene at any time. As for Level 4 systems, it is possible that the individual responsible for activating the automated mode might be considered to be the driver.

It is still unclear whether a driver may focus their attention on any other activity than driving. The current legal framework can be interpreted either way, while only some regulatory works offer provisions. The Highway Code, applicable to England, Scotland, and Wales states: *You must exercise proper control of your vehicle at all times. Do not rely on driver assistance systems such as cruise control or lane departure warnings*. Although there is no clear definition under English law, control requirements means actual engagement by the driver. Consequently, ADAS may be used, but cannot be relied on. The driver must monitor the vehicle's movements at all times and be ready to intervene without notification.

Under current legislation in the relevant European countries for this project, autonomous driving, in particular using a Level 4 and Level 5 system, is not yet allowed (excepting Sweden, where test experiments with self-driving vehicles on the road will be allowed as of May 1, 2017).

4.5 Road Traffic Law and Rules of Approval

The main goal of this research was to collect and summarize the most salient aspects of legislation relevant to this technology as it exists today in the various different EU member states. The second objective from a legal perspective was to foster mutual understanding and identify possible areas where it might be necessary to harmonize the law within those member states. This objective was achieved through a comprehensive review of the current legal frameworks with respect to automated systems. The review covered regulatory law (e.g. national road traffic law), the Vienna Convention on Road Traffic, and road traffic liability (of the driver/ vehicle owner).

When considering the general objective to develop new functionalities, the basic question is raised as to whether legislation is keeping pace with current technological advances.

Therefore, in addition to technological aspects, we addressed important legal issues that might have an impact on the market introduction of automated systems. Today it is both a basic legal assumption, as well as a requirement, that the driver must be able to control their vehicle at all times. When moving to automated driving, disparities between what is technologically possible and what applicable law demands need to be identified.

As previously mentioned, automation up to SAE Level 2 seems to be unproblematic with regard to current law. However, in some countries it is expected that conflicts will arise between current regulatory law, liability law, and Vienna Convention on Road Traffic law when higher levels of automation are introduced. These conflicts may arise because the law makes demands on the driver as the party responsible for operation of the vehicle, which the driver is no longer involved in driving at higher levels of automation. Specifically, Vienna Convention Articles 8.1 and 8.5 stipulate, firstly, that every vehicle shall have a driver, and, secondly, that the driver shall be in control of the vehicle at all times. Somewhat different rules may exist at national level. Of course, in cases of full automation, i.e. Level 5, a driver is no longer required at all. This obviously sets up conflicts with the requirements of the Vienna Convention.

Automated driving is a clear example of the complexities introduced by the development of new components for the road traffic system, in this instance the vehicle. The technology cannot be developed in isolation as it will have a major impact on road traffic systems and needs to interact with humans, vehicles, infrastructure, and society in order to have the maximum positive impact. Moreover, the technology is being developed quickly and many different stakeholders are involved in or affected by its development. This complexity means it is impossible to predict or precisely steer development of the technology.

Although we do not want current statute law to impede the development of autonomous driving, we should avoid introducing amending provisions that cannot be applied to other countries' drivers and vehicles, or which will require revision in the near future because technological development is progressing so quickly. The fact that road traffic rules in various different countries have been harmonized has been a success for all types of road transport for a long time. Therefore, the optimal solution would be to tackle the issue of specific traffic regulations, specific road signs, and other arrangements made for automated vehicles internationally within the UNECE framework.

In order to ensure the safety of motor vehicles, technical approval requirements are imposed on the design of motor vehicles. However, it is no longer left to individual states to set the minimum requirements for vehicle technology. The approval of vehicle types has been harmonized internationally. At the level of the European Union, EU directives were proposed by the European Commission in Brussels that set out legal rules for technical approval. The most important of these is framework directive 2007/46/EG for cars (as well as 2002/24/EG and 2003/37/EG for two-wheeled and three-wheeled vehicles as well as vehicles for agricultural or forestry use). These directives are transposed into national legislation within each EU member state. United Nations regulations (UN) created by the United Nations Economic Commission for Europe (UNECE) are referenced in Annexes IV and XI and come into play as EU vehicle-type approval requirements as far as referenced. Additionally, there is a link to UN Global Technical Regulations (GTR) in place in the EU.

Further considerations can be made for the on-board actuation systems. Obviously there are two main parameters of control – longitudinal and lateral – while driving a vehicle. These take place by accelerating/braking and by steering. With regard to the automation of driving tasks and related technological requirements, a closer look must therefore be taken at the rules for braking (UN R13; braking system) and steering (UN-R 79; steering system). In addition, UN-R 48 regulating lighting equipment is relevant to automated driving.

A first consideration is that the classifications of steering systems are *not* consistent with present levels of automation. The current definitions contained in UN-R 79 state:

Autonomous Steering System means a system that incorporates a function within a complex electronic control system that causes the vehicle to follow a defined path or to alter its path in response to signals initiated and transmitted from off-board the vehicle. The driver will not necessarily be in primary control of the vehicle.

Advanced Driver Assistance Steering System means a system, in addition to the main steering system, that provides assistance to the driver in steering the vehicle but in which the driver remains in primary control of the vehicle at all times. It consists of one or both of the following functions:

Automatically commanded steering function means the function within a complex electronic control system where actuation of the steering system can result from automatic evaluation of signals initiated on-board the vehicle, possibly in conjunction with passive infrastructure features, to generate continuous control action in order to assist the driver in following a particular path, in low-speed manoeuvring, or parking operations.

Corrective steering function means the discontinuous control function within a complex electronic control system whereby changes to the steering angle of one or more wheels for a limited duration may result from the automatic evaluation of signals initiated on-board the vehicle in order to maintain the basic desired path of the vehicle or to influence the vehicle’s dynamic behaviour.

Systems that do not themselves positively actuate the steering system but that instead, possibly in conjunction with passive infrastructure features, simply warn the driver of a deviation from the ideal path of the vehicle, or of an unseen hazard, by means of a tactile warning transmitted through the steering control are also considered to be corrective steering.

Advanced driving assistance systems must be designed so that they do not restrict the basic steering function in its performance. In addition, the driver must be able to override the advanced driving assistance system at any time. “Corrective Steering" is allowed. In contrast, “Autonomous Steering” is prohibited. UN-R79 describes “Autonomous Steering” as outside its scope. The situation is different concerning “Automatically Commanded steering”, which is very limited and only allowed at low speeds for steering manoeuvres up to 10 km/h. For enabling automated driving, it is necessary that the limitation on the automatic steering to max. 10 km/h be repealed and possibly replaced by a new limit or by other reasonable restrictions while still addressing safety concerns. In addition, one must consider under which further conditions and with which requirements automated steering systems will be allowed. Probably the biggest need for changes lies with respect to UN-R 79, which must be changed regardless of level of automation. However, there might be further requirements for automated steering depending on the level of automation.

4.6 Outlook and International Initiatives

Even though the current laws were written well before automated traffic became a hot topic, many problems resulting from this new form of transport can be resolved using existing rules. This applies to all the countries examined.

Yet it is difficult to give binding answers to many questions concerning automated road traffic. Some major questions cannot be answered definitively without legislative action. Regulatory laws for higher levels of automation remain unclear. There is no clear response to uncertain matters, for instance whether the driver is allowed to focus their attention on tasks other than driving. Another point is whether civil liability regimes will cover future claims to ensure compensation of accident victims. Legal recourse to manufacturers as it currently exists in product liability law will continue to exist. It cannot be ruled out that a shift in the risk of liability will take place to the manufacturers' disadvantage. This is particularly to be expected as the influence exerted by human "drivers" on the driving of motor vehicles continues to be reduced. The attribution of fault must be reconsidered and a new calibration of the relevant error concepts, namely "product defect" and "informational defect" (failure to warn), must be undertaken in order to establish precise rules of liability and thereby ensure legal certainty for manufacturers and users.

Data protection law remains a challenge. Companies collecting data must adhere to the new General Regulation on Personal Data Protection. Data collection must be kept to a minimum and processing has to be limited to what is necessary. Furthermore, transparency and data security needs to be guaranteed. Due to the large amounts of data collected, attention must be paid to compliance with data protection law.

As a matter of fact, a uniform legal framework covering all aspects of autonomous vehicles (admission to public road traffic, safety standards, liability rules, insurance matters) does not exist in the US either. However, there is an increasing amount of regulatory activity by states, and federal legislators have been expanding activity primarily with respect to safety standards. In the American legal system, the division of regulatory responsibility for motor vehicle operation between federal and state authorities has traditionally been fairly clear. States have responsibility for vehicle licensing and registration, traffic laws and enforcement, and motor vehicle insurance and liability regimes, while the National Highway Traffic Safety Administration (NHTSA) regulates motor vehicle performance, each state owns and the rights of way for roads within its respective territory. The NHTSA usually establishes safety standards for motor vehicles, which are binding as minimum safety standards on all manufacturers and importers of motor vehicles. The NHTSA already made a statement as regards autonomous driving that requests such standards to be taken into consideration by manufacturers and importers of motor vehicles.

Several countries, of which Sweden is exemplary as shown by its recent initiatives in Working Party 1 of the UN, are lobbying for the adoption of a secure legal framework to regulate automated road traffic. In particular, such initiatives are hopeful signs that legislation will soon be enacted by the respective national parliaments and that international treaties will be amended accordingly. The law must be adapted so that it does not hinder the development of new technology. Technology should serve society, and the law should support the development of this technology.

5 Human-Vehicle Integration

With the increase of automation, the role of the driver is gradually going to change from that of an active driver to a passenger, at least for some part of the drive. In this chapter we discuss the empirical investigation of drivers' behaviour, focusing on Human Factors methods, to identify a number of important behavioural implications of vehicle automation.

Simulator experiments were used in this research to provide an understanding of driver behaviour, which enabled the development of recommendations for the system design. This chapter aims to provide a description of the rationale behind the experimental investigations as well as describe the methodology and procedures used. The main results achieved through this research are presented along with a summary of how these results provided general guidance to the project design phase. Gaps in current knowledge are also be identified, along with some recommendations as to where future efforts should be directed.

5.1 Use Cases and Requirements

The basic requirement that automated driving needs to operate within mixed traffic implies that the reference for assessment needs to be human manual driving behaviour. In this section we introduce the rationale behind the use cases we considered in this project as well as the requirements that stemmed from them, and hence guided the development of the AdaptIVe framework.

In AdaptIVe, use cases were established by the vehicle developers in subprojects SP4-5-6, with the coordination of Human-Factors experts from SP3. Alternative flows of events were considered to cope with different possible scenarios. In particular, the project focused on the development of minimum-risk manoeuvres, where the system is expected to have safeguards in place to deal with situations such as: an out-of-the-loop driver, invalid environment model, a vehicle defect, loss of sensor data, etc. A key role of the use cases was to provide a precise description of the required functionalities to be used as a basis for defining functional requirements.

The use cases presented in this section are grouped into three sets, providing a precise description of the required functionalities, which were then used as the basis for specifying functional recommendations for different demonstrator tasks:

- **Automation in close-distance scenarios -** for slow movement but a wide field of direction;
- **Automation in urban scenarios -** for gradual introduction of vehicles performing automated manoeuvres with different levels of automation;
- **Automation in highway scenarios -** for supervised automated and cooperative driving functionalities on highways with velocities of up to 130 km/h.

A total of 23 situations are briefly described here. More detailed descriptions of the use cases are available in D3.1.

5.1.1 Close Distance Scenarios

Use Case 1: Activation

Parking function activated with or without the driver in the car. Alternatively function activation fails.

Use Case 2: Parking in

Parking manoeuvre to park in a free spot. Alternatively, parking space is blocked, resulting in function not being completed.

Use Case 3: Parking out

Move the vehicle away from the parking spot. Alternatively, the trajectory may be blocked by other objects.

Use Case 4: Drive to parking lot

Drive to the parking lot. Depending on the circumstances, one of three different alternatives may be engaged.

Use Case 5: Construction site manoeuvre

Drive vehicle in a construction zone of a predetermined 30 km/h speed limit.

Use Case 6: Deactivation

System deactivates with or without the driver in the car, or the system takes over in the situation where the driver does not respond.

5.1.2 Urban Scenarios

Use Case 1: Activation

Urban automated driving system activated for specific lanes at speeds of up to 60 km/h. Alternatively, the activation conditions are not met and hence the system fails.

Use Case 2: In-lane lateral and longitudinal control

The automated driving system is controlling the vehicle speed and position. This information is fed back to the driver through one or more modalities.

Use Case 3: Lane change

The automated driving system decides whether the vehicles needs to change lanes, and if that is feasible.

Use Case 4: Intersection handling

The automated driving system either handles the intersection or requests that the driver takes control.

Use Case 5: Roundabout handling

The automated driving system either handles the roundabout or requests that the driver takes control.

Use Case 6: Traffic lights handling

The automated driving system either handles the approach to traffic lights or requests that the driver takes control.

Use Case 7: Deactivation

Driver deactivates system in different scenarios.

5.1.3 Highway Scenarios

Use Case 1: Activation

System activation is either successful or fails according to certain preconditions.

Use Case 2: Lane following

Following the lane - conditional automated driving with or without driver supervision.

Use Case 3: Lane change

System or driver initiates a lane change. The completion of this function will depend on the surrounding conditions.

Use Case 4: Cooperative merging speed adaptation

Vehicle interacts with the driver to determine a driving strategy while the vehicle is on the highway, using automated lane keeping and V2X communication.

Use Case 5: Cooperative merging lane change

Vehicles interact to determine driving strategy while they are on a highway in automated lane/vehicle mode and detect V2X communication.

Use Case 6: Cooperative response on emergency vehicle

Vehicle is driving on the highway in automation mode, interacting with V2X communication when another emergency vehicle wants to overtake. Alternatively, function may be not possible due to lane obstruction.

Use Case 7: Enter highway

The vehicle is initiating a lane change for entering the highway either with the supervision of the driver or in the control of the driver. Alternatively, a lane change for merging into traffic may not be possible.

Use Case 8: Exit highway

The vehicle is initiating either automated merging out of traffic, or the driver does. Alternatively, the system detects and informs the driver that this function is not possible and instead the vehicle continues to follow the lane on the highway in partial automation mode.

Use Case 9: Deactivation

Driver initiates function deactivation and shifts to manual steering for various reasons.

Use Case 10: Driver state

The conditional automation function requires the driver to verify their state. If verification is valid, automated driving will continue. If not, then minimum-risk manoeuvres will be initiated to bring vehicle into a safe state.

The use cases outlined above provided a set of requirements that mostly relate to the expectations of the AdaptIVe system in terms of objectives, operating conditions, constraints, driver-interaction, perception, and actuation. These requirements emerged during the use case identification work, and represented initial input for the unique AdaptIVe framework architecture. An overview of which project constraints were mapped to adaptive architecture components is given below:

Design constraints

The project aimed to provide solutions that can be integrated into existing vehicles from ordinary production. Recent models equipped with ADAS, advanced active controls, and communication capabilities were employed. Therefore the on-board equipment and the standard automotive architectures provided the basis for the planned developments.

AdaptIVe made use of simulation techniques as used in control engineering in order to investigate how the system could react in a variety of situations. This approach allowed a comprehensive understanding of functional requirements and safety issues as well as making system development more effective.

V2X communication will be developed according to the most recent trends as regards regulatory and standardisation demands for connected vehicles, thus making use of available and generally accepted previous results.

Test constraints

In recognition of legal rules, some of the functions active at higher speeds have clear legal constraints. These restricted the testing to well-defined environments such as driving with professional test drivers or on test tracks. Some low-speed manoeuvres, particularly at speeds below 10 km/h, are already possible on public roads and are available as the driver-supervised parking aids in series vehicles. Efforts were made to demonstrate the solutions in real conditions, or at least in situations as close as possible to the real world.

In order to properly address potential Human Factors issues, experimental research was used to provide insights into driver behaviours in selected scenarios which were then used to inform automation design guidelines. The use of driving simulators enabled the testing of safety-critical scenarios that would not have been possible in on-road evaluations. The project aimed to investigate several key Human Factors research questions regarding driver-system interactions based on the use cases. Ethical and privacy issues were taken into account during all subject tests.

A list of all requirements identified per demonstrator vehicle is provided in D1.5.

5.2 Experiments

In this section we discuss the experimental analyses that were carried out to investigate how drivers' intentions and actions should be taken into account in the design of partly, highly, and fully automated vehicles. We only describe the most important aspects of our experimental setup. Please note that a detailed description of all of the experiments is available in D3.2.

The shifting role of the human driver from an active controller of the vehicle to a more passive supervisory role may lead to problems of inattention and reduced situational awareness. To address this issue, a series of research questions aimed at enhancing our understanding of how to safely and efficiently re-engage the driver, and how to take a human-centred perspective in designing the automated functions.

Following a number of iterations, research questions, and functional human factors recommendations were categorised using the "4As" structure:

- Agent state

  (Driver state, automation state, environmental state)

- Awareness

  (Situation awareness, mode awareness, role and task awareness)

- Arbitration

  (Interaction & decision, meaning & scheduling, modes & transitions, modality, adaptivity)

- Action

  (Physical constraints, motor constraints, lack of skills, controllability)

Outputs of the studies conducted per partner and the respective conclusions are given below in a high-level format:

LEEDS Experiments

Objective: Assess drivers' attention during automation and in the transition to manual control, and examine the different decisions made by drivers in manual, partially automated (SAE Level 2), and highly automated driving (SAE Level 3).

Results: In an evaluation of the effects of varying the level of information available to a driver during automation, drivers' vertical and horizontal gaze was more dispersed when the road scene and dashboard were completely occluded than when they had full visibility of the scene. The type of activity a driver engaged in during automation also had an impact on their first point of gaze fixation after being asked to attend to the driving task. However, it only took one second for the differences between groups to be resolved. Drivers who were late to identify a hazard during an uncertainty alert were more likely to crash than those who fixated on the hazard quickly. A separate study examining drivers' decision-making and lane changing behaviour in manual, partially automated, and highly automated driving showed that resuming manual control from a partially automated driving system led to poorer vehicle control during overtaking than in manual driving, at least in terms of higher lateral and longitudinal accelerations. In this study, questionnaire ratings suggested that drivers prefer a highly automated system in which the system maintains control of the overtaking task than the partially automated system which required them to re-take control.

Conclusion: An encouraging finding across all of the studies was that drivers' understanding of and ability to control an automated system increased with repeated exposure to the same type of event. Accordingly, automated driving systems need to be able to direct drivers' attention as early as possible towards any hazard that may lead to automation disengagement, and drivers need to possess an accurate and confident understanding of their role and the capabilities of their PAD systems. However, across all of the studies, drivers' vehicle control performance was less stable during the transition from automation than during fully manual driving.

DLR Experiments

Objective: Develop a consistent interaction strategy that supports the driver in multiple scenarios and different levels of automation with a colour-coded ambient light display.

Results: The ambient light display is highly salient and has the potential to support drivers in understanding which automation level is currently activated and which automation level is available for activation. In addition, the ambient light display supported the shift of attention, enabling better driver situation awareness and faster reaction times in situations where the driver needs to take over control. Furthermore, the ambient display can support the driver in the anticipation of automation failures, which leads to a better controllability in critical scenarios.

Furthermore, the overall acceptance of the ambient light display was very high in all three experiments, and even higher than conventional HMI designs (studies 1 and 3).

Conclusion: Three experiments were conducted: two in a driving simulator, and one in a test vehicle. The results of the three studies showed that the ambient light display could be successfully used as an HMI for automated vehicles in different automation levels and different driving scenarios.

FORD Experiments

Objective: Evaluation of future parking automation systems. Focus on usability, controllability, and acceptance of the remote parking smartphone application and key-fob control.

Results: No significant differences emerged between countries when it comes to the usage frequency and perceived usefulness of parking assistance systems. Particularly, high usability was indicated for the parking automation system developed by Ford within the AdaptIVe project, and the system in general received positive evaluations. The smartphone application-controlled valet parking aid system developed by IKA was also well assessed overall.

Conclusion: Parking automation is highly valued. Both key-fob and smartphone-app based control concepts might be employed to control these systems. Care must be taken to evaluate them with regard to their usability to ensure high overall customer acceptance.

WIVW Experiments

Objective: Determine how drivers can be effectively assisted during mandatory transitions from automated to manual driving.

Results: Findings indicated that drivers prefer to be notified considerably in advance of the system limit. It has a positive effect if the system provides information about distance, remaining time, and required manoeuvre prior to a system limit. Just-in-time notification also proved to be sufficient, but was rated as being less comfortable.

Conclusion: All in all, the results support the hypothesis that an advanced HMI concept has the potential to make automated driving a comfortable experience

VTEC Experiments

Objective: Explore different aspects of truck drivers' interaction behaviour with automated systems during e.g. transitions, unexpected events, take over reactions/handlings while engaged in secondary tasks, understanding visual and auditory messages, etc.

Results: A number of interesting findings emerged from the experiments. For example, the interaction design seems to have an effect on the time to resume control after an automation failure. Moreover, messages and symbols should be coherent with the drivers' intentions, actions, and observations of the surrounding environment to enhance mode and task awareness and acceptance of automated systems. Future interior cab design needs to consider non-driving secondary tasks for safe and efficient driver-system interactions.

Conclusion: The truck drivers were generally positive about the automated systems. The HMI design can influence the time to resume control. Being a "passive driver", i.e. monitoring the driving or being engaged in a second task while in the automated driving mode, has negative effects on the driver's ability to resume control. Further studies should investigate areas in which we currently have limited knowledge such as the long-term effects of automated driving (drowsiness, boredom, inattentiveness) along with the effects of issues such as familiarity, learning effects, and coping strategies.

VCC Experiments

Objective: HMI design for controlling transitions between highly automated driving and manual driving.

Results: Deactivating HAD was not easy the first time, despite drivers receiving clear instructions as to how to use the system only minutes before the first attempt. However, learning was fast and failure rates dropped rapidly with exposure. Furthermore, when drivers truly engage in a secondary task while in HAD, they also completely disengage from driving. As a result, participants perceive cueing to resume manual control as "sudden", "loud", and "alarming" despite modality levels being low to moderate. For brake profile, Pulse-plateau mode leads to lower speed loss than Linear mode and should therefore be used (if context allows) to achieve minimum speed differences relative to surrounding traffic during mode transitions.

Conclusion: While these results can be used to inform current best practise, little knowledge exists about the long-term effects of being in HAD mode or of having HAD available on a daily basis. Most research to date comes from simulator studies. Getting data from controlled field trials is the next level required to further our knowledge.

5.3 Functional Human Factor Recommendations

The development of novel automated functions requires the consideration of both technical and Human Factors requirements. Using a traditional requirement engineering approach, an iterative process was developed to establish and refine the most important Human Factors recommendations for the user-centred design of automated vehicles.

The following steps were formulated to prospectively identify and organise Human Factors knowledge in the context of vehicle automation and to present preliminary recommendations to inform and guide system development. The form of this presentation was intended to be a helpful tool for vehicle system developers who design their systems and functions for human users.

Step 1: **Suggest method for selecting HF recommendations.** A systematic approach incorporating the 4A structure was used to achieve an HF-recommendations structure.

Step 2: **Describe existing HF recommendations.** A list of existing HF recommendations relating to the design and implementation of automated vehicle systems was compiled in order to better understand the current state of practice. The list was not intended to be exhaustive, but rather to provide a diverse and representative range of system recommendations, with examples of designs and interface configurations.

Step 3: **Identify new HF recommendations.** The research identified 27 in-vehicle Human Factors challenges across 4 main categories using the 4A structure (Agent state, Awareness, Arbitration, and Action). These challenges addressed specific automation levels and corresponded to the particular subprojects. Previously developed approaches to dealing with each of the new Human Factors recommendations were also documented.

Step 4: **HF implementation activities by VSPs.** For each Human Factors recommendation, a description of partner activities was provided, including the technical information needed, and a pictorial example of implementation.

During an iterative application of these four methodological steps, a catalogue was compiled with 27 functional and 80 non-functional Human Factors recommendations. Furthermore, 364 corresponding examples were also included in the catalogue. More information is provided in a tabular format in AdaptIVe public deliverable D3.3.

6 Automation In Close Distance Scenarios

6.1 Introduction

This chapter presents an overview of SP4 *Automation in close-distance scenarios* and its goals, starting with the description and setup of the SP followed by a subchapter about the developed functions. Results are presented within the *Key Achievements* subchapter.

SP4 was dedicated to the development and testing of supervised automated driving applications in close-distance scenarios in the low-speed range. The speed threshold was 30 km/h. For practical applications, the driven speed was closer to 5 km/h and less. This excluded a road construction site manoeuver on highways, where typical speeds are 40 to 80 km/h. Another close-distance application, trailer backup-aid, was concerned with the various geometries of the combination of lead car, trailer, and hitch point and is already available as a series application – although still requires close human supervision. The approach in SP4 followed low-speed automated driving and it is expected it will be realised for early deployment of some functions since the infrastructure support requirements are minimal.

Low-speed scenarios included primarily driver-support manoeuvres into tight spaces and repetitive trajectories, which were implemented and linked to parking-related comprehensive functionalities. The driver, while requesting the manoeuver, can be located either inside or outside of the vehicle. However the manoeuver itself, i.e. lateral and longitudinal movement, must be continually monitored.

The scenario for close-distance manoeuvres is characterised by low-speed movements but a wide field of direction. Another difference in contrast to urban and highway scenes, is that pedestrians and other manoeuvring vehicles are present and their movement cannot always be well predicted. The manoeuver is often closely following along and/or against an object (wall, other vehicles) with sensors close to their near-field limitations of 10 to 30 cm.

Those functions were tested according to the evaluation guidelines and the test plan provided in SP7. Hence the envisaged SP4 functions, which implement and support automation in close-distance scenarios such as parking and manoeuvring in crowded environments, were the following:

- Automated valet parking assistant (Automation Level 2)
- Remote parking aid (Automation Level 2)
- Automated parking garage pilot (Automation Level 3)

For any parking solution, there is no one-size-fits-all when it comes to automated or partially automated systems. Each solution has its own unique goals, challenges, and constraints, and selecting the best system to meet those needs required careful planning. In the AdaptIVe case, the planning for SP4 entailed several potential challenges. The challenges identified were:

- Close-distance manoeuvring requires sensors and algorithms that were not currently available or needed reprogramming by the manufacturer for low-speed sensitivity or increased number and frequency of detections. Sensor sensitivity must be based on the traffic situation, allowing the vehicle to reliably detect other objects and free space over close distances and to navigate in this area by selectively giving priority to one direction over the other.
- Fully automated parking requires a learning vehicle, where the vehicle can train itself by learning typical environments. The vehicle shall then be able to drive and manoeuvre within a similar environment. Learning in this context is meant as training or recording a trajectory for later replay.
- Another challenge is the incorrect assumption of a less risky environment as suggested by the term “low speed”. The mass and energy of a vehicle must be under control in all conditions. If the distance between vehicle and wall is small, time delays incurred via sensor-perception-controls-decision-actuator add up to become the TTC (time to crash) of free space; thus with a delay of one second at a speed of 1 m/s (equal to 3.6 km/h, a comfortable walking speed) the vehicle has moved one meter (and possibly touched a wall or another vehicle).

The specific subproject objectives were as follows:

- Development and testing of automated driving applications for low-speed, close-distance scenarios focusing on those with measurable comfort and efficiency benefits.
- Development of automated parking systems for private garages and outdoor environments (i.e. street, parking lot, home garage).
- Provision of a robust and safe vehicle architecture suitable for close-distance manoeuvring
- Detailed and reliable sensing of the environment (including pedestrians) and completeness of the environmental model focusing on close-distance sensing for parking and low-speed manoeuvres.
- Demonstration and testing of close-distance automated applications in the low-speed range in two demonstrator vehicles (additional vehicles will be used for development and testing purposes).

Demonstrator vehicles from Ford (Kuga), Daimler (Mercedes-Benz E350) were built during the AdaptIVe project. The demonstrators shared a common high-level architecture and specific implementations according to the needs of the various use cases.

FORD demonstrator vehicle

The Ford passenger vehicle will be the demonstrator vehicle used for highlighting the park assistant and the trajectory-follow functions. The vehicle is equipped with standard actuators as electronic gas, brake, and electric-assisted steering, which required minor modifications, and available environmental sensors such as cameras, radar, and ultra-sonic sensors.

Figure 6.1 Kuga AdaptIVe demo vehicle

DAI demonstrator vehicle

A second vehicle from Daimler will demonstrate the *automated parking garage pilot* function. The vehicle, similar to the Ford, is loaded with similar equipment and is additionally using newly developed sensors that have significant situation-dependent sensitivity, including the detection of partially occluded pedestrians as well as providing 3D environmental perception.

Figure 6.2 Mercedes-Benz E350 AdaptIVe demo vehicle

IKA Simulation

Furthermore, the *automated valet parking assistant* function will be shown in the IKA test vehicle, which was mainly used for testing trajectory planning and vehicle control algorithms.

Figure 6.3 VW Passat AdaptIVe demo vehicle

6.2 Description of Functions

From a technical point of view, current technology for automated driving in close-distance scenarios in controlled environments is quite mature. The demo vehicles used for showcasing deployed functions use state-of-the-art sensors (radar, LiDAR, DGPS, and camera vision systems) combined with high-accuracy maps, allowing on-board systems to identify appropriate navigation paths as well as obstacles and relevant signage. In SP4 we addressed a number of low-speed scenarios with speeds well below 30 km/h.

<u>Automated parking garage pilot</u>

This is a Level 3 conditional automation function. The function can be demonstrated in parking garages or other parking areas with available map data. SP4 implemented the SLAM algorithm as part of the perception layer. This technique is mainly used for supporting the exploration of an unknown parking environment in order to find free parking. This appears to be a viable approach for localization in the context of covered parking applications (with no GPS coverage).

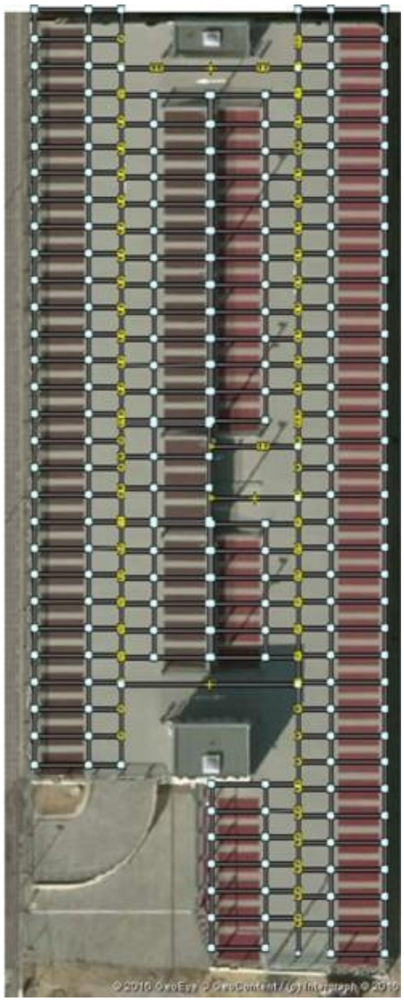
Although prior mapping is crucial for automated vehicle applications, it may suffer from inaccurate blueprints or permanent changes in the environment. Offline mapping processes can be adopted to solve these problems by enhancing the static map with new information from sensors. AdaptIVe SP4 decided to use LiDAR sensors for the mapping process within a SLAM context once again because of their high representational accuracy.

The scenario for the function is quite simple: the driver manually drives the car to a supported parking garage and stops at the entrance. The perception system recognizes the entrance of the parking garage. The driver can select a desired target area and define the acceptable deviation. After the gate opens, the driver can start the function. As soon as the driver has released the brake pedal, the car starts driving to the allocated area. Once the car has reached the park position, it will engage the park gear and inform the driver about successful completion of the manoeuvre.

The garage can be multi-level and can have more complex geometry, such as the asymmetric positioning of the vehicle for parking in a two-car garage. The function allows for more efficient management of parking spaces and reduces the time and energy needed to find vacant parking spots. The map for the parking application is either preloaded or can be provided by the garage via cooperative services.

Another function, called trajectory learning, allows drivers to teach their “own” trajectories to the car. The procedure is relatively simple: the driver teaches a parking process, including the drive to the parking lot, e.g. to a reserved parking lot in a parking garage or to a private parking garage. During the teaching trip, the car “learns” the map of the area. On the next trip, the car recognizes the learned starting position and provides the possibility to take over.

Table 6.1: Function comparison

	
Trajectory Learning • Teach a trajectory to the car • At least one teaching trip • Car builds its own map using on-board sensors • After learning, the car should be able to follow the trajectory on its own • SLAM is useful • Car needs to solve kidnapped robot • Level 3 automation	Automated Parking Garage Pilot (APGP) • Map is provided by the parking garage operating company • Map is in OSM format • Mapping sensors are different from sensors in car • Car needs to validate map • No need for SLAM, but could be useful • Car needs to solve kidnapped robot • Level 3 automation

Remote Parking Aid

This Level 2 (partial automation) function is made possible by the use of an integrated two-way remote radio key fob that provides the fencing-in of a controlled area around the vehicle. Specifically, the Remote Parking Aid works on the basis of twelve advanced ultrasonic sensors and four 79 GHz radars for sensing the environment. In the current version, the following use cases were implemented:

- Activation with driver outside car
- Parking in
- Parking out
- De-activation with driver outside car

The partial automated parking scenario presents parking in and out from a selected rectangular parking spot in public areas. As the parking is initiated via remote key, the start of parking can be triggered in front of a tight parking space that would not allow for comfortably exiting or entering the car.

In private homes, the parking can also extend to include a recorded trajectory for a longer manoeuver from a drop-off zone to a home garage. Drivers must continually monitor the system and stop the parking manoeuvre if it is required. For improving the integration of (and removing redundant) sensors, emphasis was placed on the sole use of radar. Besides the parking aid (a key application of ultrasonics), radar can be utilized for several other applications. If more use cases can be developed with radar only, the hurdle (cost) of radar applications in smaller cars will be lowered.

Automated Valet Park assistant

The automated valet park assistant is a prototype Level 2 automation function. The function is designed to work in a parking garage or area where a-priori map information is available. The a-priori map information is based on available blueprint information and is integrated into the perception layer. The function is able to take over the tasks of navigating to and parking into the desired spot. Thus the vehicle uses the map of the parking garage, including all available parking spots and the information as to whether or not the parking spots are vacant. The driver can exit the vehicle in a drop-off zone and choose a vacant parking spot. The vehicle then finds a feasible path from the drop-off zone to the desired parking spot and parks itself into the spot.
Twelve ultrasonic sensors, four short range radar sensors, and a laser scanner are used to sense the environment while driving. Without a driver in the vehicle who must exit the vehicle after parking, tight parking spots will not be a problem and vehicles can be placed closer together in a space-saving way. Those attributes apply to the deployed use cases listed below:

- Activation without driver in car
- Drive to parking lot
- Parking into a tight spot
- Parking out
- De-activation without driver in car

The function is initiated by using a smartphone. The desired parking spot can be chosen upon beginning the parking procedure and the vehicle can stopped anytime during the process using the smartphone. After the parking manoeuver has been successfully completed, the vehicle can be called back to the drop-off zone.

6.3 Key Achievements

When AdaptIVe began, applications were available as research demonstrators that showed how to park a vehicle into a specified parking space. Even the automated drive to a parking space from a distance of 20 to 40 m was possible. These vehicles had prototype sensors (radar, ultrasonic, LiDAR) and local maps that were tailored to the application.

The vehicles in SP4 are much different from this. The sensors are series products (e.g. the SRR2 Radar from Delphi), the maps can be derived with a process described in the literature, and the localisation and mapping process, a common topic in robotics, has found applications in automotive research.

Special tools such as differential GPS, optical position measurement, and LiDAR have been used to measure parameters including position, orientation, and loop closure, but were not needed to operate the function. The cost of having these excellent tools in a series vehicle is still prohibitive.

The following lists a collection of key points of the AdaptIVe work on parking. This work has made considerable contributions to the level of knowledge in research, especially as it is accompanied by a working demonstrator vehicle. The range of the knowledge runs from the step-by-step learning of a trajectory, to improved orientation via maps, to recording, to valet parking (where the driver starts the application from outside the vehicle). However, the “driver outside” the vehicle was a research topic in SP4 and not intended to be deployed soon - although series applications already exist where the operation requests the driver’s full attention.

Representation

A real-time SLAM approach was developed and published. The accuracy of the approach was estimated via an optical ground truth system, which allows highly accurate measurements inside parking garages (in contrast to differential GPS systems).

Classification

The objects are classified with trained parameters (e.g. vehicles, poles, curbs, overhanging structures) and are used to improve localisation in a SLAM step (Simultaneous Localisation And Mapping).

Driveability

For manoeuvring, it is essential to have a means to describe whether an object is an obstructing obstacle (such as a wall or a curb) that can be part of the correct manoeuver. Radar-based height estimation within the classification process delivers further semantic information used to identify the drivability of the sector they are located in.

Localization

A SLAM approach with objects was applied to increase localisation accuracy. An optical measurement was developed with accuracy below 10 cm in manoeuvring.

Height measurement

Curb height can be determined with the help of additional radar (perpendicular mount). This helps to better torque control for curb mounting manoeuvres.

Longitudinal control

Manoeuvres in a multi storey parking garage require smooth uphill and downhill driving. The small manoeuvring space, especially in spiralling ramps, can now be driven without harsh corrective torque switching.

Contour application

An occupancy grid was built from the radar detections with independent probabilities for free space and occupied. This allowed the development of a contour for open/occupied space that indicates possible parking locations.

Doppler localisation

The radar-based Ego Motion calculation algorithm from literature was implemented and enhanced in the contour application, resulting in improved ego vehicle trajectory, enabling a consistent mapping of the environment during pass-and-return manoeuvres, and U-turns.

Blueprint Scan Matching

A novel approach enables calculation of a global position based on radar data and OSM digital blueprint data only.

Target classification

A new method for generating a separate, two-dimensional free-space grid map for ADAS based on data from radar sensors has led to a patent application.

Visualization

For an optimal development process, a specific 3D representation of radar data was realized especially for algorithm evaluation purposes that improved scene understanding with a viewing perspective centred at the ego-vehicle.

Gateway

A gateway was programmed to allow the optional use of different CAN protocols for two sensor types and two vehicles, providing more flexibility for software applications.

Mounting detection

The mounting orientation and position of the radar sensors must be exactly known for the radar-based localization algorithms to work properly – but these are difficult to determine in the real vehicle. An improved algorithm was developed to precisely calculate this value.

Firmware changes

The sensitivity and number of the detections delivered by the radars used in the Ford demonstrator and IKA test vehicle were increased. Results are not yet conclusive at the low-speed operations and amount of clutter found in our scenarios.

Open Street Map (OSM)

Digital maps for parking in a garage require the definition of new OSM objects that represent the structure of a parking area. AdaptIVe SP4 extended the existing OpenStreetMap (OSM) XML format to be able to accurately represent the specific environment in two SP4 parking scenarios. The extension focused on parking areas and its primary goal was to improve the whole automated parking process. An automated vehicle supplied the extended OSM map will be able to plan its trajectory a priori and more efficiently, while more accurately detecting a free parking spot at the same time.

Using the extended OSM format defined by AdaptIVe SP4, we created digital OSM maps from blueprints to be used as additional data for orientation and path planning.

Digital parking maps generation

Prior knowledge about an environment is beneficial for autonomous navigation. This knowledge is usually acquired through a digital map.

Parking blueprints' digitalization

The full OSM representation of two parking garages, a Daimler indoor garage and an outdoor garage at RWTH Aachen University, was created (with manual inspection and with the help of the JOSM editor) using the corresponding blueprints (made available by the IKA and DAI teams), which included accurate dimensions and positions of all objects and structures inside the parking area.

Groundtruth maps with LiDAR data

Although prior mapping is crucial for automated vehicle applications, it may suffer from inaccurate blueprints or permanent changes to the environment. Online mapping processes are usually adopted to solve these problems by enhancing the static map with new information. AdaptIVe SP4 decided to use LiDAR sensors for the offline creation of a complementary-to-blueprint digital map because of their high precision for environment representation in adverse lighting conditions.

Mapping comparison and evaluation

Two SLAM methods for obtaining groundtruth data from LiDAR were applied for two different garages. The first method for the first parking garage used a line feature-based Extended Kalman Filter algorithm since the garage's geometry is mostly linear. For the second parking garage, which has a more complex structure and had many parked vehicles at the time of data recording, an incremental maximum likelihood approach using raw sensor data was implemented. New comparison metrics were introduced and showed that both LiDAR-based approaches yielded consistent maps based on the blueprints' grountruth data for the two garages.

Map-based trajectory planning algorithm

An algorithm was developed to calculate a precise path, including vehicle dynamics, from a drop-off point to a selected parking spot. The trajectory is planned using map information in an OSM format. The algorithm can also deliver a path for retrieving the vehicle from the parking spot and driving it back to the drop-off zone.

Handling with smartphone

The automated valet park assistant is controlled with a smartphone; the parking spot can be selected on a map display.

Human-vehicle interface

SP3 recommendations on the best interaction between human driver and machine application machine interface were considered for how information is provided and how the user operates the application.

Legal aspects

The early builds of our vehicles were instrumental for SP2 for better understanding of the issues in close-distance scenarios (with and without driver in the vehicle).

Test and Evaluation

The demonstrators were instrumented to the requirements of SP7 and underwent the necessary tests for data collection, further analysis, and the impact assessment.

Implementation

The applications, functions, and algorithms were developed and implemented in two demonstrators and one test vehicle, which consumed a major part of our time and efforts. Although internet hype these days suggests that any vehicle can be easily pirated remotely – the actuators still need extra software, connections, and jury-rigged solutions to open up to external controls.

In summary, close-distance scenarios provided many opportunities for development towards better mobility and more efficient use of parking space. Valet parking, unattended by the driver and fully automated with a smartphone, is now possible in the research lab with all due safety measures considered and applied. Aside from the achievements (where many false paths were taken and have not been shown here), further, non-trivial obstacles remain before the first series applications for vehicles are offered to the public. The robustness of perception and control, in short the level of trust, reached in our demonstrators still has potential for improvement. This improvement was not part of the AdaptIVe objectives. It must be developed for the target hardware and in tandem with a redundancy concept to ensure safe operation/safe stop under all circumstances, including mixed environments of vehicles and other road and driveway users outside of the danger zone of roads. The almost final product then needs enough miles driven – or hours parked – to come to a full close.

The common theme in all SP4 applications was the focus on the use of radars for perception and localisation. The realised functions demonstrate the wide expertise from supplier, OEM, and research that was successfully applied to achieve a view towards comfortable, close-distance experience for the user, i.e. the driver who wants to park the vehicle.

7 Automation In Urban Scenarios

7.1 Introduction

The massive, ongoing process towards urbanization means that 70% of the world's population is expected to live in cities within the next decade. Along with this rapid development, the need for the implementation of automated manoeuvres to address specific urban scenarios has become evident. SP5 envisioned the deployment of solutions in new vehicle models that are characterised by a high level of complexity and by a speed range from 10 to 60 km/h in specific urban operational design domains in less than five years.

A pre-condition that characterises all urban scenarios is the assumption of a gradual introduction of vehicles performing automated manoeuvres at different levels of automation (as defined by SAE); therefore the coexistence of equipped and unequipped vehicles is an important aspect to be taken into account in all urban scenarios.

The urban scenarios targeted by SP5 included the automation of the lateral and longitudinal control in a city environment. Furthermore, the functions were to handle special scenarios prevalent in urban areas including roundabouts, traffic lights, and intersections. Lane changes were also implemented. Cooperative systems based on V2I communication were considered to support specific use cases. There will be differences in driver versus system initiation.

An important AdaptIVe target was to provide free time to drivers in the feeder and ring-road network that is part of larger cities, where drivers spend a significant amount of time each morning and afternoon.

SP5 focused on developing embedded solutions to address the most demanding driving scenarios in a city in order to adequately address this complexity:

- City Cruise (Automation Level 1);
- Supervised City Control (Automation Level 2), and;
- City Chauffeur (Automation Level 3).

The goal for the urban scenarios addressed by this subproject was to develop automation functions that can handle different driving situations, that operate at an automation level adjusted to the driver's request, and that adapt to the vehicle and road environment and the driver situation. This means that the automation level activated by the system is what was requested, possible, or necessary in the specific situation.

Consequently, the developed automation functions in the subproject were organised in a hierarchical structure, from normal driving to highly automated. The different automation levels (apart from the full automation level) are highlighted in Figure 7.1. Each level is possible only when the necessary information is available; otherwise, the control switches down to the level below or, if the driver is not responding when requested, performs an automated safety manoeuvre.

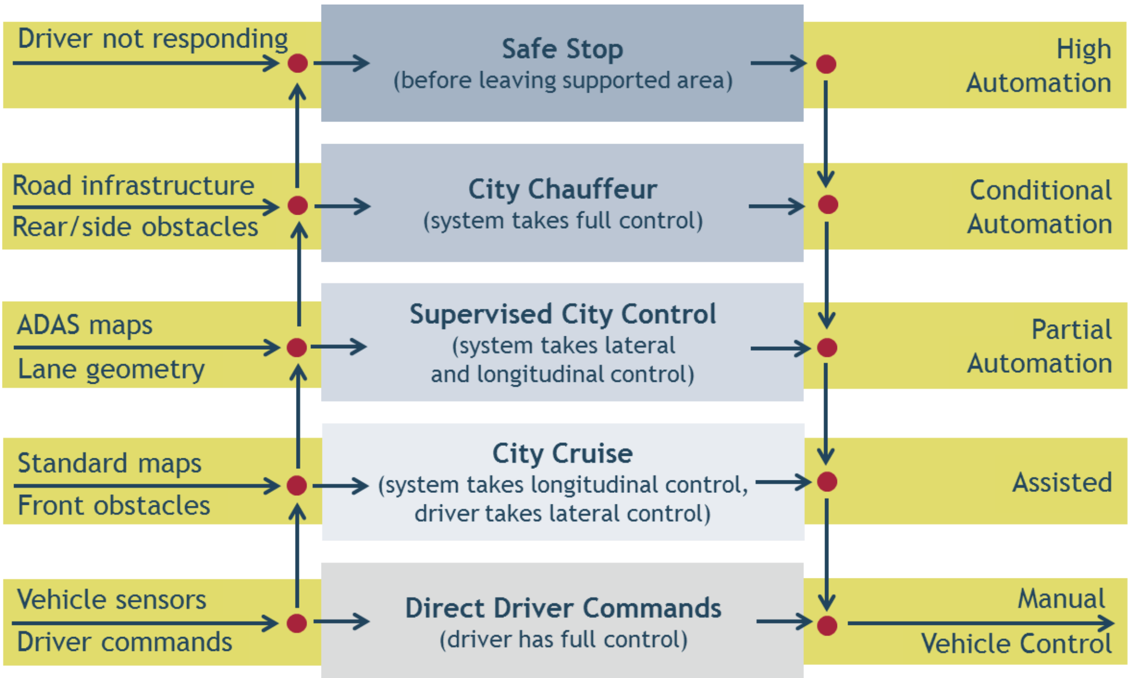


Figure 7.1 Automation levels for urban driving

Urban scenarios present special challenges due to the environment's higher degree of complexity and dynamic behaviour. Traffic is dense, several types of road users or static obstacles are present, and the driving tasks include negotiating traffic at roundabouts, intersections, and merging manoeuvres. Hence urban traffic requires interactions on the same thoroughfare between not only vehicles and other actors but also public transportation systems such as busses and trams.

A key point for developing systems that can support the driver in urban environments is the integration of existing and new functions into one single system: examples include automated braking, feedback on the steering wheel, automated cruise control, and supervised automated control. The level of support given to the driver ranges from longitudinal control only (in assisted mode) to automatic guidance (in automated modes). Communication with the infrastructure and other vehicles provides enhanced information for early recognition of constraints and possible intensions of road users, thus reducing the potential for conflicts.

Moreover, this incremental approach to autonomous driving facilitates the introduction of new driver support functions and their extensions as intermediate steps before being able to manage the urban environment’s high complexity.

The subproject objectives were defined as follows:

- Different automated and driving support functions integrated into a unique system;
- The level of support given to the driver in such complex scenarios, from longitudinal control (Assisted Level) to automatic guidance (Conditional Automation Level), was adapted with respect to road infrastructure, current scenario, and driver requests;
- Implementation of an artificial Co-driver, which reproduces human-like driving from low-level motor primitives to high-level behaviours, thus mirroring human sensory-motor activity and enabling interactions based on the “understanding” of human intentions;
- Detection and reaction to vulnerable road users (VRU);
- Communication with the other vehicles in order to anticipate their intentions and avoid conflicts, mainly at crossings.

Demonstrator vehicles from CRF (Jeep Renegade), BMW (335i), and VCC (XC90) were built and used during the project. The demonstrators shared a common high-level system architecture, where all necessary components and connecting networks were implemented according to the needs of the various use cases. All demonstrator vehicles were realized using components currently available for production as much as possible and the building of extra layers with respect to current vehicle architectures.

CRF demonstrator vehicle

The CRF vehicle, the dedicated SP5 demonstrator, will be used for a range of functions, from *City Cruise* to *City Chauffer*, including obstacle following, stop and go, speed limit adaptation, lane following, and overtaking. The specific vehicle was selected for its ability to offer some components and functions that are useful for the automatic system developed in the project.

Figure 7.2 Jeep Renegade AdaptIVe demo vehicle

BMW demonstrator vehicle

A second vehicle for SP5 from BMW was modified with research hardware and has demonstrated *Supervised City Control*, a Level 2 city lane keeping and vehicle following function, and also a Level 3 function to relieve the driver so that they carry out secondary tasks on the highway. The challenge for the BMW demonstrator was the common integration of several functions from SP5 and SP6 into a single demonstrator using a common platform. For SP6, a Level 3 Conditional Automation function was demonstrated on the highway.

Figure 7.3 BMW 335i AdaptIVe demo vehicle

VCC demonstrator vehicle

The *Supervised City Control* function implemented in the Volvo demonstrator presents the feasibility of partially relieving the driver from the driving task. (Partial in the sense that the driver needs to monitor the road, but may remove their hands from the steering wheel for a limited time.) The city automatic function with *Safe Stop* is implemented during highway driving on an approved road.

Figure 7.4 Volvo XC90 AdaptIVe demo vehicle

7.2 Description of Functions

This chapter describes the AdaptIVe SP5 functions tests, evaluations, and demonstration scenarios designed in the project. The demo vehicles used for showcasing the deployed functions are equipped with long-range radars (LRR), short-range radars (SRR), cameras, ultrasound sensors, Electronic Horizon, GNSS receivers, and V2X communication. These sensors provide the demonstrator vehicle with sufficient information about the vehicle's surrounding environment. The information is processed and fused to build a local map to show where the demonstrator vehicle can navigate autonomously in a safe manner. The interaction between vehicle and driver is addressed in "HMI and Interaction", which keeps the driver informed about the vehicle state and also handles take-over situations. In SP5 we addressed a number of urban scenarios with speeds up to 60 km/h where different automation levels are supported.

<u>City Cruise</u>

At the first Automation Level (assisted), the driver releases their feet from the pedals but keeps their hand on the steering wheel while the system controls vehicle speed based on front obstacles and map information.

In this functionality, the system performs speed control based on the available knowledge of the traffic scenario. The driver can easily override the system in order to take longitudinal control by pushing the pedals, and in the same way can easily release control by leaving the pedals.

This kind of interaction follows the idea to use primary commands as much as possible to negotiate control between the driver and the system so that the system is easy to understand, even in critical situations, and also give the driver a clear idea of splitting tasks between the system and driver.

City Cruise can support drivers in situations where the road infrastructure is insufficient to engage higher automation levels.

Supervised City Control

Supervised City Control is available and can be engaged by the driver when the necessary conditions are fulfilled, particularly when the lane is visible and the road description is sufficiently accurate (this information is derived from maps with ADAS attributes).

At this stage the driver can release their hands from the steering wheel and the system takes over both longitudinal and lateral control. However the driver must monitor the traffic situation (Partial Automation Level).

In Supervised City Control, the vehicle follows the lane and adapts the speed to front obstacles, road geometry, and posted speed limits. At this level, the driver can overtake by taking the steering wheel and complete the lane change before giving lateral control back to the system by releasing the steering wheel (driver-initiated lane change).

Crossings without traffic lights and roundabouts are not supported at this level. The driver is asked to take over vehicle control when the vehicle approaches these situations.

With respect to traffic lights, if the vehicle has the detection capability, it can automatically manage the traffic light. If the vehicle is not equipped with appropriate devices, it will ask the driver to take over vehicle control.

If the driver does not take control when requested, the vehicle slows down before getting into a situation that the system is unable to manage.

City Chauffeur

When the vehicles enters an area where a higher automation level is allowed (information that can be derived from a specific map or V2X, and is basically derived from the existence of a road or infrastructure operator who supervises the road and traffic conditions), the system can switch up to City Chauffeur functionality (Conditional Automation) if requested by the driver.

At this level, the system performs automatic lane change and overtaking manoeuvres. If the necessary V2X infrastructure is present on the road and/or in other vehicles, intersections and roundabouts can also be supported.

The system asks the driver to take over vehicle control before leaving the supported area. If the driver does not respond as requested, the system performs a safe stop manoeuvre before leaving the supported area.

7.3 Key Achievements

Vehicles equipped with the urban automated driving systems are capable of driving at different automation levels on urban roads at speeds of up to 60 km/h. The functions can be activated when all necessary information for safe operation is available at the required quality.

Those attributes apply to a large variety of usage scenarios and specifications, but our focus was set on the following:

- Lane following and speed adaptation;
- Vehicle following in lane (Stop & Go handling);
- Obstacle or VRU on the road;
- Lane change (automatic or driver initiated), and;
- Traffic lights.

The different automation levels are allowed only where necessary conditions are met. The system asks the driver to take back the control (handover) with sufficient anticipation time when the vehicle is leaving the area where a specific automation level is allowed. If the driver does not take back control, the systems safely stops the vehicle before leaving the area where that automation level is not supported.

Moreover, the following points are listed the as main achievements for SP5 in order to bring the benefits of autonomous driving in our cities:

- Structuring of automated driving functions on automation levels from assisted to high automation, depending on road and traffic scenario and driver requests;
- Clear splitting of tasks between system and driver at each automation level;
- Definition of HMI to synthetically describe the current situation, current automation level, and driving goal followed by the system;
- Definition of control negotiation rules between driver and system for lateral and longitudinal control at different automation levels;
- Equipment on demonstrator vehicles as an extra layer with respect to production vehicle architecture;
- Implementation and tests on real demonstrator vehicles and in simulation environment;
- Development of Co-driver module to plan optimal manoeuvres at different automation levels (L1 to L3).

As an example of the specific development of the co-driver approach: the CRF demonstrator vehicle has been equipped with an artificial driver, which uses an architecture that "mirrors" the human motor system. In particular, the artificial driver recognises all possible short-term actions latent in the current environment and simultaneously produces motor strategies for all of them.

The most appropriate action is selected only afterwards, which gives the agent an intrinsically adaptive behaviour with the ability to dynamically react to situations changing moment-by-moment.

Moreover, since driving means merely controlling two degrees of freedom (longitudinal and lateral control), the possible actions can be represented in a two-dimensional space (that has direct analogies with the human motor cortex), whereby dangerous actions are completely inhibited. This leaves the agent to choose only between safe manoeuvres (hence the system is in principle safe). The adaptive behaviour, i.e. the continuous selection of the movement by moment-optimal option, increases safety and provides robustness against misinterpretation of the trajectory of other road users (adapting the agent manoeuvre as soon as deviations in other agents' trajectories are detected).

Finally, because the system is similar to human motor control, it can be used at partial automation levels by adapting the action selection mechanism, for example taking the optimal longitudinal control predicted by the system in the subset of all possible actions that match the lateral control implemented by the human (City Cruise).

8 Automation In Highway Scenarios

8.1 Introduction

Highway driving automation allows travelling on the highway while the vehicle controls the lane-keeping and speed-adaptation tasks. The latest technology allows for sensing the road ahead with good reliability. The SP6 subproject developed and demonstrated supervised automated and cooperative driving functions intended for highways (or highway-like roads) with speeds up to 130 km/h. There are strong interactions between SP6 and other SPs concerning scenario definition (SP2, SP3, SP7), safety validation (SP2), HMI design (SP3), driving strategies for minimum-risk manoeuvre and driving in a traffic jam (SP4, SP5), and the evaluation and impact analysis (SP7).

Highway scenarios demand careful consideration of the different automation levels and the added value provided by cooperative approaches. Using the most up-to-date technologies, the project pushed the performance of automated systems towards higher degrees of automation while incorporating cooperative functionalities in several cases where multiple actors are involved. Besides the basic functionality of following the lane and the vehicle ahead, the subproject considered applications regarding lane changes and merging into a traffic flow. Additionally, predictive automated driving to reduce fuel consumption was implemented. All of these functions are described in more detail in the section 8.2.

The characteristics of highway driving were taken into account in order to define basic scenarios. The key aspects included the focus on long-distance drives, the exclusive use for rapid transit for people and goods, and naturally the specific infrastructure with lanes, markings, guard-rails, and traffic signs. The traffic flow can extensively vary from freely flow to a traffic jam.

- Based on the above mentioned characteristics, the following relevant driving scenarios were considered, keeping the continuous operation of the automated system in mind: Conditional automated driving following a lane, and operating in a traffic jam situation.
- Conditional automated lane change and overtaking manoeuvres.
- Fully automated minimum-risk manoeuvre, bringing the vehicle to a safe stop in a safe location such as the emergency lane (if available).
- Cooperative automated driving using on-board sensors and digital map data, especially as regards manoeuvres at an entrance ramp, with ACC, speed and time-gap adaptation.

The research faced many challenges. A first aspect was the transition between automation levels, including driver take over from partly or highly automated driving. A second key point was developing a fault-tolerant and resilient system architecture. Finally, the project had to implement and test new extensions to existing V2V communication protocols based on ITS G5 to enable dialog and negotiations among involved vehicles before and during a lane change or a filter-in manoeuvre. Altogether, the work was characterised by four overall objectives:

- Definition of requirements at functional, system, module and component levels;
- Design and realisation of the environment perception subsystem, including sensors and software modules for data fusion;
- Development and implementation of supervised automated and cooperative driving functions intended for highways - with speeds up to 130 km/h, and;
- Testing and evaluation of the applications by means of the demonstrator vehicles.

The automated driving functionalities were developed using three passenger cars from VW (Audi S6), BMW (335i), CONTIT (VW Passat), and one heavy truck from VTEC (FH Rigid).

VW demonstrator vehicle

The VW vehicle is equipped with front and side radars, a LiDAR, ultrasonic sensors, and a communication unit. The focus was to develop long-distance automation. Therefore a specific HMI solution is installed in the car. The available applications include lane change and overtaking, predictive automated driving, and cooperative manoeuvres when filtering-in or entering the highway. This vehicle was presented to the public during the EUCAR Conference in 2015.

Figure 8.1 Audi S6 Avant AdaptIVe demo vehicle

BMW demonstrator vehicle

The BMW demonstrator vehicle combines highway and urban functions in order to evaluate issues related to the integration of several applications. The driver can delegate the driving task to the system in appropriate situations. Highway driving incorporates the observation of traffic rules and a situation-based safe mode. Two specific use cases are *lane following* and *entering/exiting a highway*.

Figure 8.2 BMW 335i AdaptIVe demo vehicle

CONTIT demonstrator vehicle

The demonstrator developed by CONTIT also provides the basic functionalities for the highway environment. An important work for this vehicle was the development of a fault-tolerant architecture, enhancing the reliability of the sensor system consisting of two cameras and several radars. A particular feature is the multimodal lane detection.

Figure 8.3 VW Passat AdaptIVe demo vehicle by CONTI

VTEC demonstrator vehicle

The VTEC demonstrator was developed with the requirements of professional drivers for trucks travelling very long distances in mind. Cooperative merging based on V2V communication facilitates lane changes and filtering-in by means of coasting and braking with speed adaptation. A minimum-risk manoeuvre comes into effect in case the driver does not take over when prompted. A particular focus for this vehicle is the HMI, which includes a graphical display, LED lights to enhance awareness of the automation mode, and dedicated driver input devices such as a gap sensor in the steering wheel and adjustments for the lateral position.

Figure 8.4 VTEC FH Rigid AdaptIVe demo vehicle

8.2 Description of Functions

The essential driving scenario on highways is influenced by the different traffic densities. Just like a human driver, automated vehicles must follow the traffic, whether it is freely flow or stop and go. Therefore the speed must adapt to the current traffic situation. Besides following the lead vehicle, overtaking scenarios must be taken into account.

Other relevant driving scenarios are the filter-in and filter-out manoeuvres at highway entrance and exit ramps. There must be a differentiation as to whether a human driver or the automated vehicle conducts the manoeuvre; both cases must be considered. A basic condition for all highway scenarios is the gradual introduction of vehicles performing automated manoeuvres with different levels of automation. Hence it is important to investigate the mixed traffic of equipped and unequipped vehicles. Particularly the filter-in and enter and exit highway scenarios show the significance of interactions between automated and non-automated vehicles.

<u>Highly automated driving</u>

This Level 3 function implements the “lane-following” use case. The host vehicle is on the highway in conditional automation mode with the goal of following the current lane. The system detects the lane markings and works out the vehicle’s position. Then the system uses a distance sensor to measure the distance and speed relative to vehicles driving ahead. The speed of the host vehicle is adjusted considering various factors such as keeping a safe following distance to the vehicle in front or obeying the speed limit or other traffic regulations.

The driver may change the desired speed of the automated driving system at any time. In this use case, the host vehicle is following the lane in conditional automation mode and the driver makes a request to change the driving speed, similar to setting the speed with an active cruise control system. The system must register this new set speed from the driver as the new desired speed with which to keep the lane and should display the new desired speed to the driver as a confirmation of the action.

<u>Lane change and overtaking manoeuvres</u>

The next use case considered for automation Level 3 is “lane change”. The demo vehicle is on the highway in automated lane/vehicle following mode. The system monitors the areas to the left and right of the vehicle and decides that a lane change is necessary. If the planned function is system approved, then the HMI informs the driver about the manoeuvre in progress (e.g. via a display) in order to ensure mode awareness. Otherwise the system waits until either the manoeuvre can be safely conducted or the need for a lane change no longer exists. Once the lane change has been completed, the host vehicle continues travelling in automated lane/vehicle following mode in its new lane.

<u>Minimum risk manoeuvre</u>

The Level 3 & 4 driving function brings together several use cases related to cooperative driving by joining several traffic actors. Two applications were developed at this level, “Stop & Go” and “Coming to a safe stop”, and were common for the subprojects dealing with urban and highway traffic. This is not the case for close-distance manoeuvres, where the low speed and the environmental characteristics call for different requirements. Actually, the minimum-risk manoeuvres are relevant for different types of environment (urban, rural, highway) and all speed ranges (low, medium, high). They are activated in the event of an emergency or if a malfunction occurs and are therefore an integral part of all automated driving applications. The case of an emergency vehicle is also considered, particularly on the highway. This vehicle uses V2X communication to inform other road users that it wants to overtake. Based on the communicated information, the host vehicle will perform a lane change in order to let the emergency vehicle pass. The driver will be informed during the manoeuvre via the HMI. Five use cases were defined under this functionality plan: predictive automated driving, enter and exit highway, stop-and-go driving, cooperative response to an emergency vehicle, danger spot intervention.

<u>Cooperative automated driving using on-board sensors and digital map data</u>

This function deals with two usage scenarios: “Cooperative merging with speed adaptation” and “Speed and time gap adaptation at highway entrance ramp”.

The main objective was to increase safety in situations where vehicles interact. Energy efficiency is also enhanced through collaboration. The flow of events is explained below:

In cooperative merging, the host vehicle is on the highway in automated lane keeping mode and is approaching an entrance ramp when it detects by V2X communication that a vehicle wants to enter the highway. Based on the communicated data, a driving strategy will be decided, e.g. which vehicle should speed up or slow down to do the merging in an optimal way with respect to fuel consumption and traffic flow on the highway. The vehicle interacts with the driver via the human-machine interface to make the manoeuvre transparent to the driver.

The second use case dealing with speed adaptation provides a safer, automatic way for a vehicle to join flowing traffic, as at a highway entry. The host vehicle is initially on an entrance ramp and the system has already been activated in partial automation mode, requiring the driver to supervise the full operation. The system initiates a lane change for merging into traffic, informing the driver in order to support their supervision. Once a lane change is possible, the host vehicle conducts the manoeuvre. After merging into traffic from the entrance ramp, the automation mode is changed to conditional automation and the host vehicle seamlessly finds itself in the lane-following use case on the highway.

8.3 Key Achievements

The focus of SP6 was to implement driving functions and cover basic highway driving features such as lane following with speed limit adaption, vehicle following, and driver-initiated lane changes. Additionally, more complex functions were implemented, including system-initiated lane changes and cooperative behaviour that allows other vehicles to more easily merge from entry lanes. Clear evidence was provided that merge manoeuvres are improved with a vehicle-to-vehicle connection, exchanging collaborative perception messages. Possible system failures were also considered, and a minimum-risk manoeuvre was realised in case the driver does not take over when prompted.

In the case of the truck, a baseline controller for hands-off lateral highway driving was established. It was designed to accommodate different vehicle configurations and gross weights. Moreover, a driver-triggered lane change functionality was developed, a reusable functionality to automatically trigger a lane change.

The evaluation results have verified the driving functions, including a general conformity to human-like driving behaviour. It was concluded that conditional automation combining longitudinal and lateral control works well with proper highway road conditions.

Another significant achievement in this subproject was the concept for redundant and fail-operational hardware architecture in connection with a reliable and redundant sensor platform. Exemplary implementation of this architecture is a fail-operational lane recognition algorithm as well as a failure-triggered minimum-risk manoeuver tested on the prototype vehicles. The question of cost efficient functional safety for higher level of automation is still open, but there are examples to be evaluated and good indications from this work in AdaptIVe.

In addition to architecture and driving function considerations, the novel HMI solutions play a significant role in ensuring the proper operation of automated driving on highways. The developed concepts provide a comprehensive Human-Machine Interface for Level 3 and 4 automated systems, with a focus on the suitable engagement of the driver when requested to supervise, to recognize a system state transition, or to take over the driving task. The specific implementations – according to the human-factor recommendations from subproject SP3 – were preliminarily tested, showing satisfactory acceptance.

The question of cost-efficient functional safety for higher automation levels on highways is still open, but there are examples we will evaluate and learn from AdaptIVe and other projects.

9 Evaluation Framework and Methodology

Besides developing automated driving functions within AdaptIVe, a comprehensive evaluation framework for automated driving functions ranging from SAE Levels 2 to 4 was also developed [Rodarius 2015]. The framework split the evaluation into technical, user-related, in-traffic, and impact assessment, addressing safety and environmental effects of automated driving, as shown in Figure 9.1.

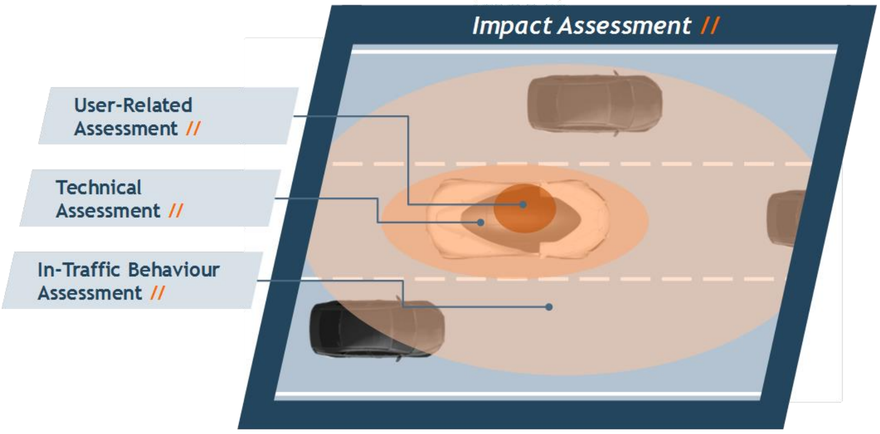


Figure 9.1: Evaluation areas in AdaptIVe

This chapter describes the key aspects of the evaluation methodology as described in [Rodarius 2015]. In the following chapter, "Key Results from the Evaluation", the developed framework will be exemplarily applied to the developed AdaptIVe functions of SP4, SP5 and SP6.

9.1 Objectives

As described previously, different aspects were analysed in the several evaluation areas. The performance of the functions was investigated in the technical assessment. The user-related assessment analysed interactions between the functions and the user as well as the acceptance of the developed functions. The in-traffic assessment focused on the effects of automated driving on the surrounding traffic as well as non-users. The impact assessment determined the potential effects of the function with respect to safety and environmental aspects (e.g. fuel consumption, traffic efficiency). The overall approach for the evaluation in AdaptIVe is shown in Figure 9.2.

The initial starting point for the evaluation was a detailed description of the function[1] or system[2] under investigation itself. Based on the description of the function or system, a classification

[1] A function in the context of the AdaptIVe project is a functionality that performs a certain driving manoeuvre. Examples include the lane following or the lane change functions.

[2] A system in the context of the AdaptIVe project is a bundle of functions that is combined in an automated driving system that can handle different driving manoeuvres (e.g. City Chauffeur).

was made in order to determine which evaluation methodology for a certain assessment was most appropriate.

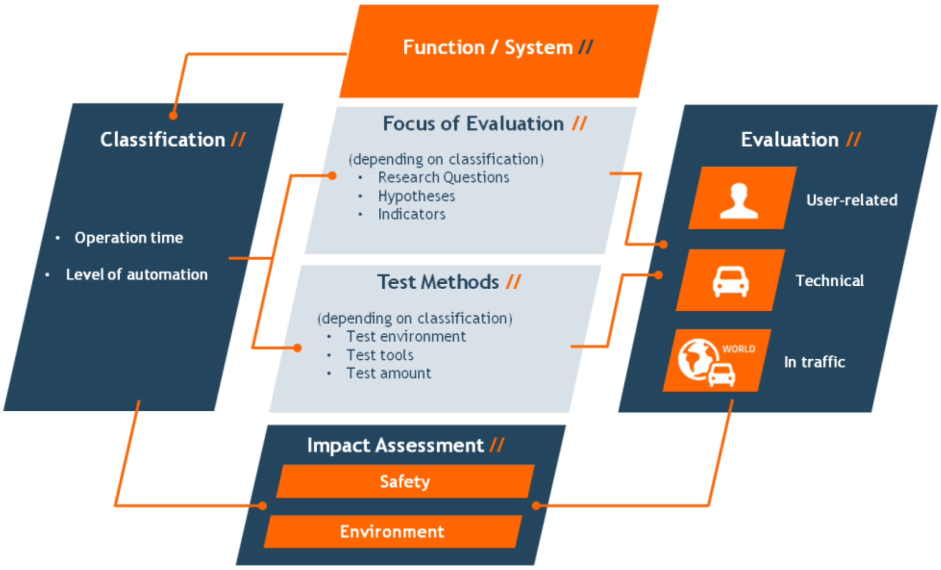


Figure 9.2: Overall AdaptIVe evaluation approach

In the first step, the AdaptIVe functions and systems were classified according to the SAE classification [SAE 2014] and the automation level they address [Bartels 2015]. The automation level was just one aspect that had to be taken into account when deciding on the appropriate test method. Another important aspect was the operation time of the function or system that describes how long a function operates while driving, since the operation time is linked to the type of test and the duration of a test. Here, the AdaptIVe functions and systems were divided into two categories:

- Functions that operate only for a short period of time (seconds up to few minutes). Typical examples include automated parking functions and the minimum-risk manoeuvre function that defines the vehicle reaction in case of a system failure or if the driver is not responding to a system takeover request. These functions are called **event based** operating functions in the following;
- Functions that can be operated over a longer period of time (minutes up to hours) once they are active. A typical example for this type of function is a highway pilot or a highway automation function. These functions are called **continuous operating** functions in the following.

The evaluation focus and applied testing methods were decided for based on the classification. With respect to the applied testing methodology, the test environment (e.g. test track, public road, driving simulator) and the required testing tools (e.g. balloon cars) were selected depending on what function of system was being tested. Presently existing test environments and test tools were used, which enabled a more efficient assessment of the developed automated driving functions.

9.2 Technical Assessment

The technical assessment's objective was to evaluate the performance of the automated driving functions. A major challenge within this assessment was to limit the testing efforts to a manageable amount while ensuring that all the important aspects were covered. Since automated driving systems address the whole driving process, nearly all driving situations were relevant for this assessment. It may have been desirable to test the function behaviour in a high number of driving situations and different variations of these situations, however considering the limited resources for the assessment, this was not feasible. Therefore, a prioritisation of the test approach within the technical assessment was required. As mentioned previously, there had to be differentiation between event-based and continuously operating automated driving functions.

9.2.1 Event-based Operating Functions

An approach similar to ADAS functions was selected for the event-based operating functions, which was based on use cases as utilized in PReVAL [Scholliers 2008] or InteractIVe [Larsson 2012] as examples. In a first step, the use cases for the tested functions were determined based on relevant situations including accidents or the function description. Afterwards, the test cases were described based on these use cases. Varying the test conditions allowed a detailed analysis of the function's performance, which meant that the amount of testing effort highly depended on the amount of use cases covered. If a function covered nearly all driving situations, this results in an unfeasibly high number of test cases. Therefore this approach was selected for those functions for which the use case can clearly be described.

The first step of the approach for the event-based function was the formulation of the scope of evaluation by means of research questions. The function's description had to be analysed in order to decide which aspect the focus should be on during technical assessment. Based on the research question, hypotheses were defined that were analysed during the technical assessment, and adequate performance indicators and evaluation criteria were chosen.

Once the definition of the evaluation requirements was completed, the relevant test cases were defined. The basis for the definition of the test cases was normally the use cases of the functions and/or situations that were considered relevant (e.g. certain accident scenarios). The actual testing was the second to last step of this approach. The tests were typically conducted in a controlled field – mainly a test track or closed test garage for parking scenarios, and the test case parameters (e.g. velocities or relative distances) were varied during the testing. The evaluation of the test data was the last step of the methodology, which included the calculation of derived measures as well as indicators. Derived measures are signals that cannot be directly obtained during the test but instead need to be calculated during the evaluation. A typical example is the time to collision (TTC), which describes the remaining time to collision when the vehicles' current movement is kept constant. In contrast, indicators are single values that describe the test run in a certain way. Examples include the maximum, minimum, or mean values of signals and/or of derived measures. The analysis of the hypotheses based on the indicators was performed in the last step.

9.2.2 Continuously Operating Functions

It was difficult to identify certain use cases for continuously operating systems, since the whole automated driving is the use case for the system. Therefore the use-case based approach did not seem to be applicable for those functions. Instead of investigating certain test cases in detail, a broader approach was taken, meaning that the objective was to investigate many different driving situations.

A so-called "scenario-based assessment" was used to assess the automated driving functions. Instead of defining single test cases, a (small) field test was conducted to assess the automated driving functions. During the field test, the function had to be able to handle driving situations that were covered according to the function's specification and that occurred during the test drive. Afterwards the driving data was clustered into relevant driving scenarios in which the functions were assessed by analysing two aspects:

- **Change of frequency** of relevant driving scenarios compared to reference behaviour, and;
- **Change of performance** of automated driving functions in driving scenarios compared to reference performance.

Adequate indicators were needed in order to investigate the performance in the defined driving scenarios. Besides the indicators, the baseline to which the function behaviour was compared also had to be described. For this purpose, the basic requirements of automated driving functions and systems needed to be considered. These requirements were:

- Safe driving;
- Operating in mixed traffic conditions, and;
- Not affecting other traffic in a negative way.

These basic requirements implied that automated driving systems must operate within the range of normal driving behaviour and should at least be as safe as non-automated driving. The baseline for the assessment should be the human driver or their behaviour. Since the driving behaviour of each human driver is different, it can only be described with distributions. These driver behaviour distributions had to be obtained before the actual assessment was performed, so euroFOT data was used to obtain these distributions.

Approaches based on detection rules [Benmimoun 2012] or machine learning [Reichel 2010], [Roesener 2016] could be used for identification and classification of the defined driving situations. These approaches were used to identify the scenarios defined in Table 9.1

Table 9.1: Definition of driving scenarios within Technical Assessment

Scenario	Scenario classes	Semantic description
Free driving/ Vehicle following	Free driving	No predecessor, ego vehicle is following lane
	Vehicle following	Ego vehicle's intention is to keep the lane and is influenced by a predecessor vehicle
Lane change	Lane change right	Ego vehicle's intention is to change to a near lane
	Lane change left	
	No lane change	
Cut-in of other vehicle	Cut-In	Passive, another traffic participant intention is to merge into the lane of the ego vehicle
	No Cut-In	

After classification of the relevant driving scenarios, the predefined hypotheses could be evaluated. An appropriate method had to be identified for determining whether the behaviour of the automated driving function was within the range of normal driving behaviour and to further quantify the deviation from normal driving behaviour. Thus the use of the quantitative measure "effect size" was proposed for this approach, which according to [Coe 2002] is a simple way of quantifying the difference between two groups that has many advantages over the use of statistically significant tests alone. As shown in [Coe 2002], the effect size is a standardized mean difference between two groups and emphasizes the size of the difference rather than confounding this with sample size. The effect size d was calculated in order to estimate the deviation of the behaviour of the automated driving function as compared to human driving behaviour by using the following equation:

$$d = \frac{\mu_{experimental} - \mu_{Reference}}{\sqrt{\frac{\sigma_{experimental}{}^2 + \sigma_{Reference}{}^2}{2}}}$$

The assessment approach for continuously operating functions is summarized in Figure 9.3. Based on the data sources, which were euroFOT (reference) and data from the AdaptIVe demonstrators (test object), a scenario classification was completed by using time-series classification algorithms of this data. Afterwards, the automated driving function was assessed by analysing the changes in frequency of these scenarios and the changes in effect within them by analysing the effect size statistical indicator.

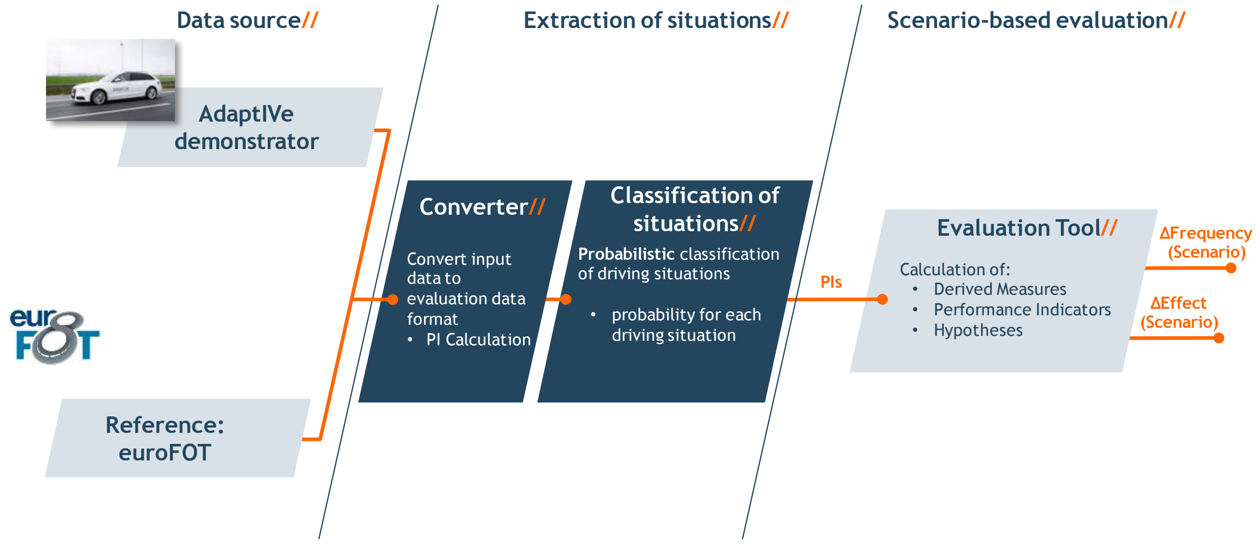


Figure 9.3: Method for technical assessment of automated driving functions

9.3 User-Related Assessment

The user-related assessment of automated driving applications involved a great variety of issues such as the understanding of automation, trust and reliance, locus of control, resuming control, skill degradation, mental workload, stress, boredom, fatigue, situational awareness, out-of-the-loop performance problems, behavioural adaptation, automation-related complacency, automation bias, usability, and acceptance. These issues are discussed in the AdaptIVe Deliverable D7.1 [Willemsen, 2015].

A comprehensive "ideal" evaluation set-up for user-related assessment included tests in a naturalistic driving environment (real traffic) as well as tests in a driving simulator with naïve (normal) test drivers. Observation of driver behaviour in real traffic gave the highest validity of results, while a driver simulator experiment allows for staging situations where situational awareness and possible complacency could also be studied. It is understood that carrying out all of these tests was demanding on both resources and time, hence the set-up of the final evaluation plan was limited to the most rewarding ones.

Considering the available resources and time, the objective of the user-related assessment in AdaptIVe was to evaluate effects on driver related issues such as behaviour when driving with automation, experiences, reactions, expected effects, and acceptance of automated driving functions.

The first step of the approach for the user-related assessment was the formulation of research questions addressing all levels of automation based on scientific literature and earlier experience from studies of driver support systems. Questions about adequate performance indicators and evaluation criteria were selected based on this research.

The performance indicators when driving with automation were to be compared to those when driving without automation, hence the test drivers, recruited from the public (representing both genders and various age groups), drove along the same public highway route once without automation and once with the system activated. The order of driving was balanced in such a way that every other test driver first drove with the system switched off and then with the system switched on. For the following test driver, the order of driving was reversed. By doing this, the effects of biasing variables such as getting used to the test route, or to the observers, and the test situation cannot be eliminated, but such effects can be spread evenly across the situations.

During the test rides, driving data was logged and driving behaviour was observed by two observers in the car. After the first drive, the drivers answered a short workload questionnaire and after the second drive, a more comprehensive questionnaire. The questionnaire covered issues such as subjective workload, understanding the system, trust, usability, usefulness, satisfaction, HMI issues, experienced effects, expected benefits, expected usage, and willingness to pay. Established "standard" methods and tools presented in AdaptIVe Deliverable D7.1 [Willemsen, 2015] were employed to study these issues.

9.4 In-Traffic Assessment

The objective of the in-traffic assessment methodology developed in AdaptIVe was to provide a framework for the in-traffic assessment of automated driving functions across a complete range of traffic situations. The set of test cases was to resemble the variation found in actual real-life traffic for this assessment.

In this work, we presented a new way of assessing the in-traffic performance of automated functions in which parameterized scenarios were extracted from recorded driving data. These parameterized scenarios were used for generating test cases for Monte Carlo simulations. Because real driving data was used, the assessment allowed for conclusions to be drawn regarding how the ADF would perform in real traffic. Since the simulations allowed for probabilistic results, there was also no need to actually drive all (one billion) kilometres before being able to draw conclusions. Furthermore, we demonstrated that importance sampling allowed us to emphasize critical test cases without the need for a-priori knowledge of what might be critical.

The first step in this methodology was to gather the data and extract the scenarios from the data with the results as a set of scenarios with their own variations. To generate test cases from this, a fitted probability density function (PDF) of the parameters was used that defines the scenario. We did not need to make assumptions of the underlying distribution; the only requirement was to have enough data in order to describe the PDF. The generated test cases were drawn from the PDF and therefore the test cases must not be observed. The generated test cases were used for Monte Carlo simulations.

New test cases could be generated to emphasize performance-critical situations by processing the results of the Monte Carlo test case simulations. Hence there was no need to simulate many hours to encounter a certain number of critical situations. The generation of the critical test cases was data-driven, i.e. no information of what might be critical was required beforehand.

The proposed method was demonstrated by assessing the performance of an extended Traffic Jam Assist (TJA) system. Moreover, the influence of the vehicle equipped with TJA on its surrounding traffic was evaluated. Using importance sampling, we showed that we could estimate the probability of a critical test case more accurately.

9.5 Impact Analysis

The impact assessment investigated the potential effects of automated driving on the road traffic compared to today's situation.

The impact assessment had to take into account that the determined effects of automated driving functions were calculated based on the information available during the project duration and the current state of knowledge in this area. Since the real impact of automated driving functions depends on many different factors that cannot all be controlled and predicted, or that might be developed in a different manner, the real impact of the considered functions may have differed from the calculated effects.

The impact assessment considered traffic safety aspects as well as environmental aspects in terms of fuel consumption, traffic flow, and travel time. The environmental impact assessment was conducted for all target areas covered in AdaptIVe, whereas the safety impact assessment focused on the motorway scenario (see Table 9.2). The reason for the limitation in the safety impact assessment was the expectation that automated driving functions would first be introduced in this environment. Thus relevant effects with respect to traffic safety could also be expected for the motorway environment[3].

Table 9.2: Overview of the conducted impact assessment and target areas

AdaptIVe target areas	Safety impact Assessment	Environmental impact Assessment
Motorway	X	X
Urban		X
Close Distance Manoeuvring (Parking)		X

[3] Automated parking function properly introduced at the same time. However no relevant effects were expected with respect to traffic safety.

The approach for determining the impact of automated driving on road traffic was based on the methodology defined in AdaptIVe deliverable D7.1 “Test and Evaluation” [Rodarius, 2015]. A brief explanation of the approaches taken in both assessment types is given in the following sub-chapters.

9.5.1 Safety Impact Assessment

AdaptIVe applied a virtual assessment approach for the safety impact assessment that combined scenario-based stochastic simulations with continuous operation simulations. The chosen approach is illustrated in Figure 9.4.

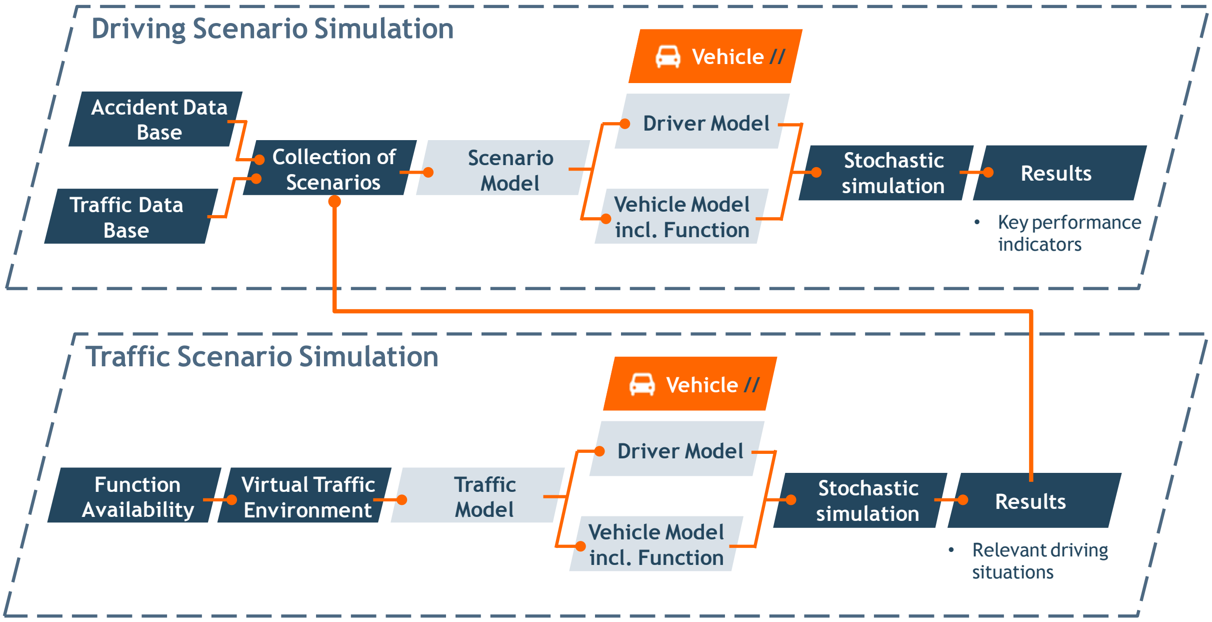


Figure 9.4: Simulation approach for traffic and driving scenario simulation.

The results of the traffic simulation, the analysis of accident data, and the challenging scenarios based on the function descriptions were additionally used to identify the most relevant scenarios, the so-called “Top Scenarios”. The chosen approach is illustrated in Figure 9.5. The Top Scenarios were investigated in detail using simulations.

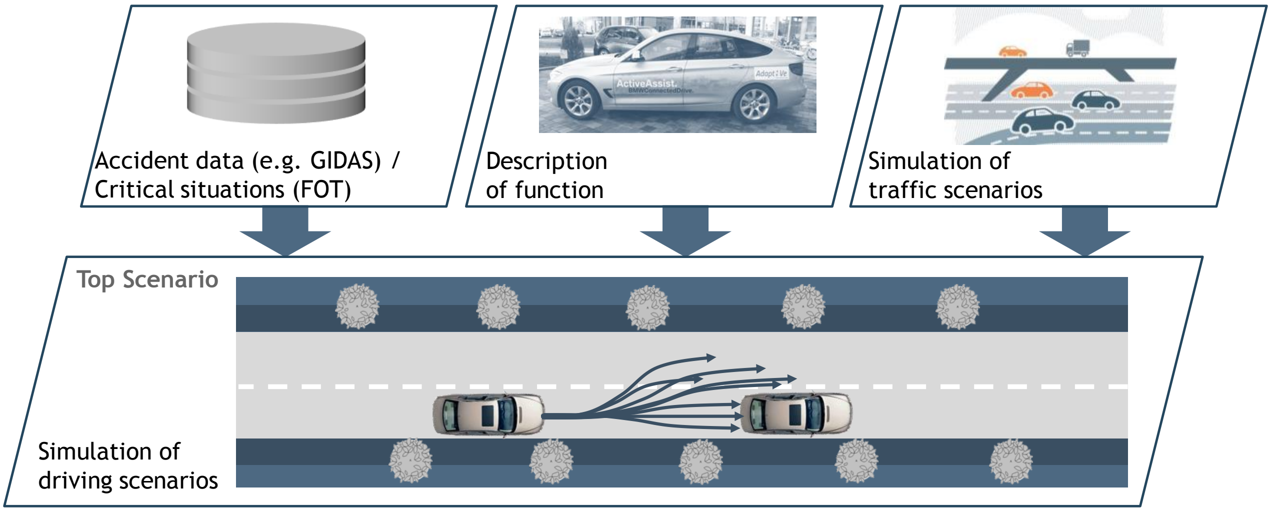


Figure 9.5: General procedure for the safety impact assessment of automated driving functions.

The traffic scenario or **continuous operation simulation** worked with a virtual traffic environment that was temporally and spatially extended. The virtual traffic environment's objective was to analyse the behaviour of the automated driving function in the traffic context while considering changes in the frequency of certain driving scenarios. Therefore the traffic scenario needed to provide a representative variation of traffic context to trigger realistic variations in the system response.

Critical situations, accidents, or general abnormalities observed during the continuous operation simulation were registered and analysed. As long as they were caused directly or indirectly by the automated driving functions, the driving situations were specified as new driving scenarios and added to the scenario collection for the scenario-based simulation.

The **driving scenario simulation** focused on safety-relevant driving scenarios that were limited in time and space and represented different conflict types. Safety performance of human drivers and the automated driving functions was determined and compared by simulating the driving scenarios in a replicable way. In principle, an automated driving function can affect nearly all accidents scenarios. Due to limited resources, an investigation of all the situations was not feasible. Therefore the decision was made to focus on relevant scenarios for the detailed analysis by means of simulation. Here the focus was on those scenarios in which the effect of automated driving functions was questionable and/or was of high relevance for traffic safety, again the Top Scenarios. Overall seven different top scenarios were defined as seen in Table 9.3.

Table 9.3: Top Scenarios for the safety impact assessment

Driving Scenario		Proportion of accidents in GIDAS
Top 1	Cut-In	16,1%
Top 2	End in Lane	1,1%
Top 3	Obstacle in the lane	3,3%
Top 4	Approaching Traffic jam	14,4%
Top 5	Highway entrance	1,8%
Top 6	Rear-end accident	15,8%
Top 7	Single driving accident	20,6%

In the simulation, each traffic participant was controlled by a behavioural model (and, if necessary, combined with a vehicle model) that acted similarly to a human driver in similar conditions. The driving scenario model, the driver model, and the vehicle model could all be parameterized stochastically.

9.5.2 Environmental impact assessment

The general approach for the environmental impact assessment that was applied to analyse the considered effects (fuel consumption, traffic flow, and travel time) is shown in Figure 9.6. It was expected that different user groups would benefit in different ways. Thus the environmental impact assessment also analysed the benefits for different user groups.

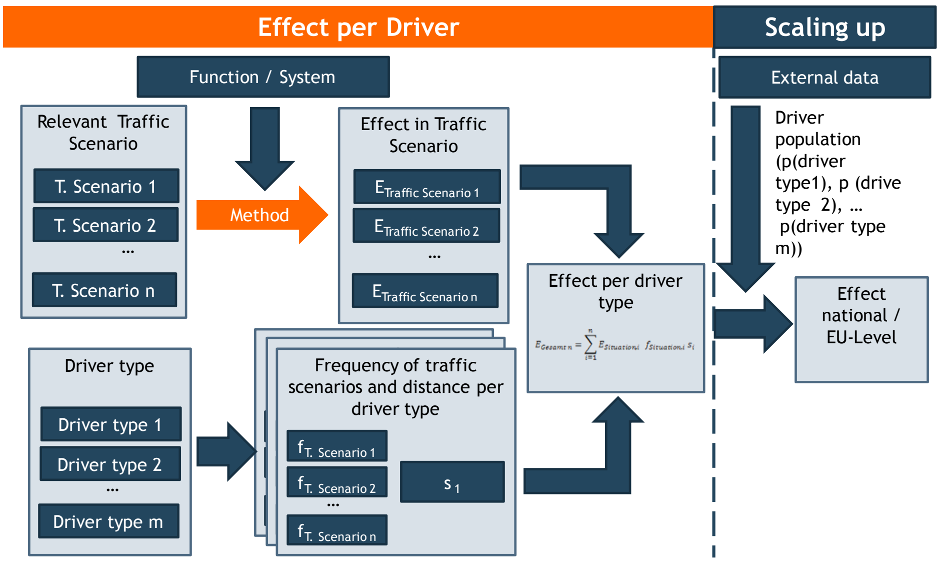


Figure 9.6: Methodology for environmental impact assessment

The evaluation was conducted with simulations and considered different traffic scenarios. In each traffic scenario the effects were analysed for high numbers of vehicles and a certain section of road.

First, the relevant environmental parameters as depends on the analysed function were identified and aggregated in relevant scenarios. These scenarios formed the reference and thus the baseline for assessment. Afterwards the automated driving function to be assessed was added to the previously defined scenarios to estimate its effects in the scenario. The indicators used for the analysis are given in the Table 9.4.

Table 9.4: Overview on indicators for the environmental impact assessment

Evaluation aspect	Indicator	Description	Equation
Travel time	Mean velocity	Mean velocity of all vehicles in the analysed traffic scenario	$\bar{v} = \frac{\sum v_i}{n}$ With v_i velocity of i-vehicle and n number of all vehicles
Energy demand	Positive Kinetic Energy (PKE)	Ability to keep the kinetic energy of the vehicle as low as possible	$PKE = \frac{\sum(v_f^2 - v_i^2)}{x}\ when\ \frac{dv}{dt} > 0$ Where v_f and v_i are respectively the final and the inital speed and x ist the total distance
Travel time	Mean velocity (urban roads)	Mean velocity of all vehicles in the analysed traffic scenario	$\bar{v} = \frac{\sum v_i}{n}$ With v_i velocity of i-vehicle and n number of all vehicles
	Mean loss time (urban intersections)	Time difference between uninfluenced driving and driving with traffic lights/ other vehicles influences	$\overline{t_{Loss}} = \frac{x}{v_{act}} - \frac{x}{v_u}$ With v_{act} as actual velocity and v_u as uninfluenced velocity
Parking space	Relative Change in the number of parking spots	Number of calculated parking spots compared to the number of available parking spots	$p = \frac{n_{\text{calculated parking spot}}}{n_{\text{standard parking spot}}} - 1$

Along with quantification of the effect per traffic scenario, the effects for different driver types were also investigated. The different drivers were described based on travel behaviour (km driven per year and proportion usage of different road types), and the (spatial) frequency of the different traffic scenarios was obtained for each driver type. Different data sources (FOT data, traffic observations, questionnaires, and statistical data) were used for this.

The effects in certain driving scenarios, the frequency of the scenario, and the driven distance per year were obtained. The effect for different driver types could be calculated: see Eq. 9-1.

$$E_{\text{Driver Type}} = \left(\sum_{i=1}^{n} E_{\text{scenario,i}} \times f_{\text{scenario,i}}\right) \times s_{\text{Driver Type}} \qquad \text{Eq. 9-1}$$

In the last step, the single results for each defined driver type were scaled up to a national or European level by considering driver populations.

10 Key Results from the Evaluation

10.1 Technical Assessment

In this section, the previously presented method for technical assessment was exemplarily applied to the AdaptIVe highway demonstrators. For this assessment, euroFOT data [Benmimoun et al. 2013] from 98 vehicles and a total of 8,000 hours of driving was clustered in the considered scenarios and was used as a reference for human driving. First, the performance of the automated driving functions was compared to human driving performance from euroFOT in the considered scenarios. Afterwards there was an analysis of the changes of frequency between human driving and automated driving for the considered scenarios.

Changes of performance in relevant scenarios

This chapter presents the effects of automated driving functions within the considered driving scenarios. The “lane change” and “vehicle following” scenarios were considered in the following. The effects of automated driving on the scenarios were estimated by calculating the “effect size” statistical indicators. Regarding the lane change behaviour of automated driving functions, it turns out that there were only slight differences to human driving behaviour. While the maximum lateral accelerations during a lane change manoeuvre were similar to human driving in terms of mean value (effect size = 0.10), uncomfortable lane changes with high lateral accelerations did not occurring with automated driving.

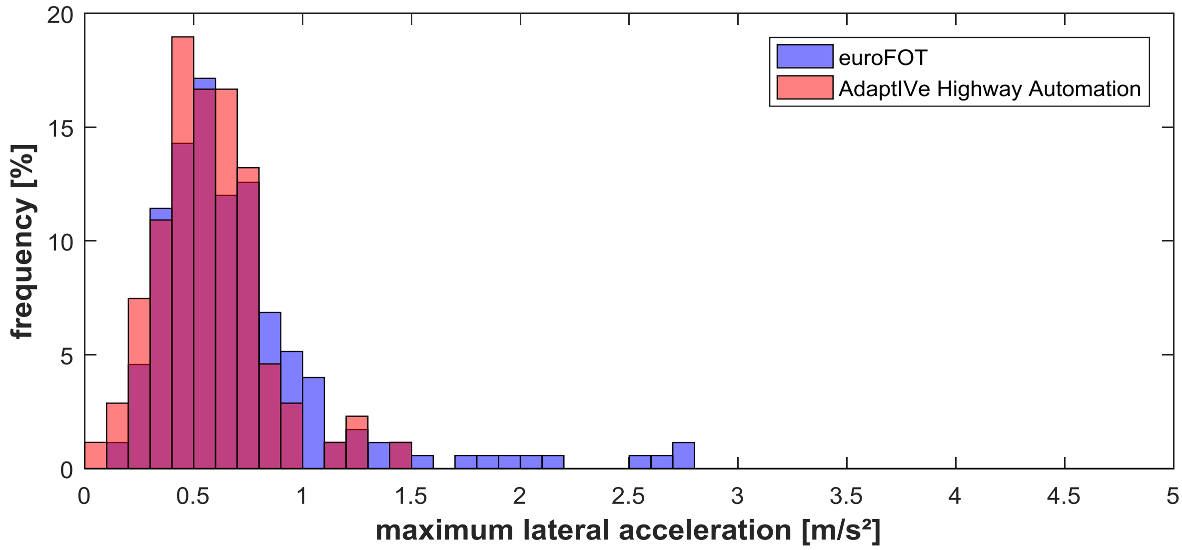


Figure 10.1: Indicator “maximum lateral acceleration” in the lane change scenario

Considering the duration of lane change manoeuvres, automated driving functions realized behaviour similar to human drivers (effect size = 0.18). Even more, the share of lane changes with small durations (manoeuvre time < 3 s) could be reduced, which led to more determined and predictive lane change manoeuvres. This in turn leads to automated vehicle driving behaviour that could be more anticipated by other (human) traffic participants.

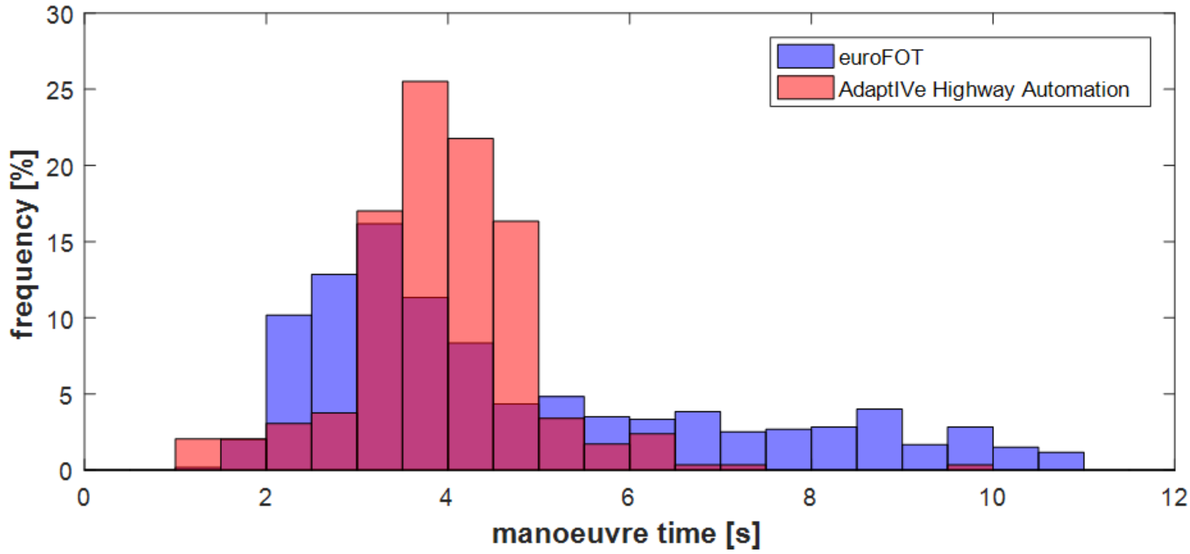


Figure 10.2: Indicator “manoeuvre time” in the lane change scenario

For the “vehicle following” scenario, the indicator time headway was assessed and compared with human driving behaviour; time headway is the front-to-front distance between two following vehicles related to the ego-vehicle velocity. While the human driver population showed a time headway distribution with a large standard deviation, the automated driving function showed a smaller standard deviation (see Figure 10.3).

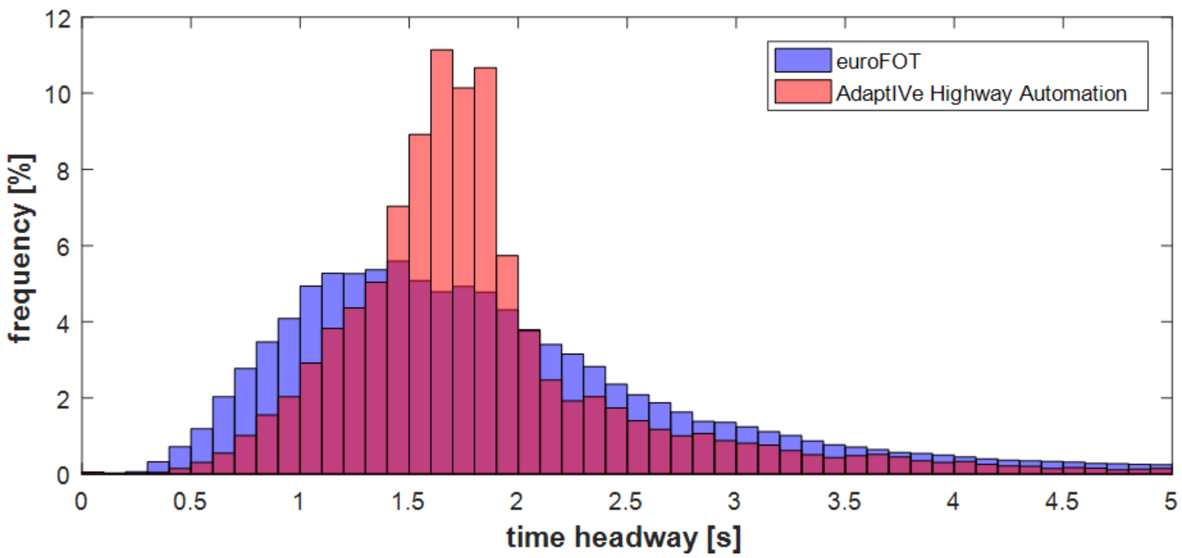


Figure 10.3: Indicator “time headway” in the vehicle following scenario

The automated driving function's small standard deviations led to fewer situations with small headways, meaning there were fewer occurrences of situations with small distances.

Changes of frequency of relevant scenarios

Besides analysing the performance of automated driving functions as compared to human driving in several driving scenarios, the changes of occurrence for these driving scenarios as compared to human driving were also analysed (see Figure 10.4). The results show that the frequencies for both lane change and cut-in scenarios increased.

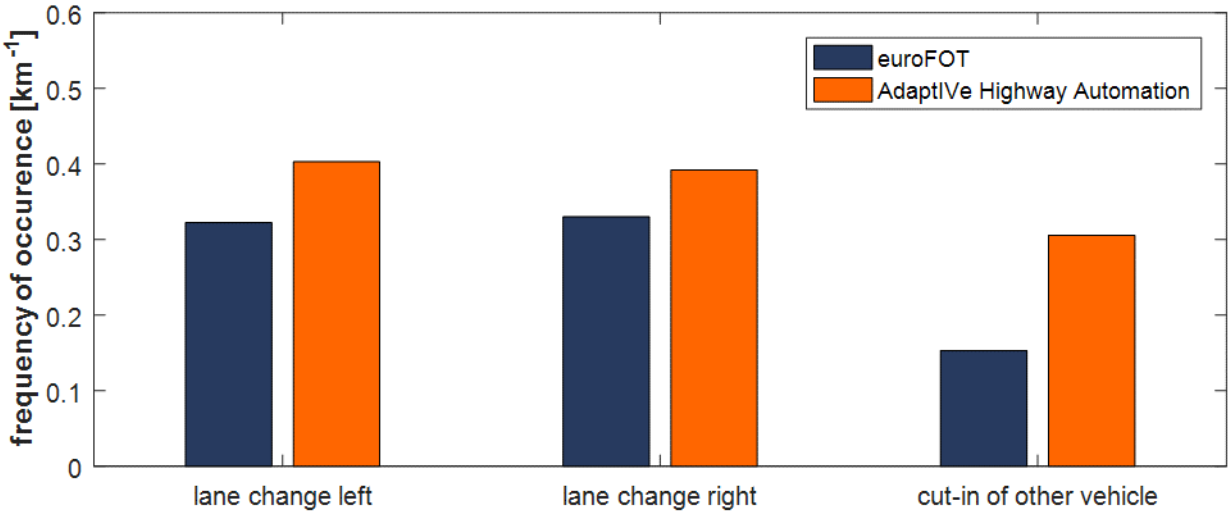


Figure 10.4: Changes in frequency of occurrence of driving scenarios

10.2 User-Related Assessment

10.2.1 AdaptIVe Urban Automation

Most participants thought that "the system performed competently" and that they also had "confidence in the advice given by the system". The majority expressed that they "can rely on the system to do its best every time". Considering whether the driver could depend on the system, the majority of the answers were on the "disagree" side and partly neutral. Only one respondent agreed strongly that they can depend on the system. Considering the statement "I can rely on the system to behave in consistent ways", most of the responses were in the middle, i.e. close to neutral, however two participants agreed strongly. Considering "trust in the system", most of the responses were in the middle, i.e. close to neutral, neither agreeing or disagreeing, with two participants agreeing strongly.

Most participants found the system easy to learn and use, and not unnecessarily complex. They were confident using the system and that they would use the system frequently. However there was not strong support for the statement that the "various functions of the system were well integrated" and there was not much disagreement with the statement that "there was too much inconsistency in this system".

The total System Usability Scale (SUS) score was 80, which is considered high usability. On the usefulness/satisfactoriness scale, the system was perceived as useful ("useful", "good", "effective", "assisting", but not "raising alertness") and partly satisfactory ("pleasant", "nice", but not "desirable" or "likable").

Considering the HMI solution, the participants found that it was easy to activate the function with the steering wheel paddles. They found the way to turn the system on and off was intuitive and they felt safe when enabling the system. The participants felt acceleration and braking while the car drove itself comfortable. Concerning "the comfort of the steering while the car drove itself" and "how good the system was able to drive the car on the whole", there was a wide variance of answers and the "mean" answer cannot be differentiated from "neither comfortable nor uncomfortable". The participants found that the information given in the displays was both understandable and not distracting.

The participants' answers indicated that they are not fully aware of the system's limitations. There were clear expectations among the respondents for decreased fuel consumption and increased driving comfort. The participants estimated the highest usage rate of the system on highways in their everyday driving. The majority of the participants indicated that they would be willing to pay between EUR 1,000 and 4,000 to purchase the system.

Answering the question about what they would do while regularly "driving" the autonomous car, a wide range of answers was given, i.e. from full monitoring of driving to a completely relaxed presence and doing things other than driving-related activities.

Some worries were expressed about relying on the system in real traffic – "does the car constantly handle new and different situations consistently in real traffic with a lot of drivers around who cannot drive a car and do a lot of stupid things". Also, one respondent felt that the driving pleasure disappeared with automated driving.

10.2.2 AdaptIVe Highway Automation

The results showed that the drivers used the system as intended. The system was used in almost all situations when it offered to drive automatically. Nevertheless, some situations were observed in which the driver took over from the system because they got impatient with the system (e.g. long overtaking process, early preparation for exiting the highway), or they or the safety driver had to react in a critical situation. Basically, the drivers did not interfere with the system settings. Only in situations in which the system did not recognise the change of the speed limit (variable overhead signs) did they have to manually adjust to the speed limit.

The system affected driving positively in several ways. In general, the automated driving function led to a reduction of velocities compared to human driving. The system always accelerated more smoothly and chose a speed according to the limit and traffic conditions. During driving with the system active, fewer indicating errors, fewer dangerous lane changes, fewer errors in correct distance keeping to the vehicle in front, and less neglecting the prescribed use of the right lane were made.

No differences could be observed with regard to lane keeping behaviour and subjective workload.

Negative effects were observed concerning communication, such as letting other drivers make a lane change by braking and/or accelerating or with communication through hand gestures, which were better when driving without the system. The system did not react to other road users who wanted to make a lane change, especially in situations when they wanted to merge onto the highway. In these situations, the test persons reacted better when driving without the system by reducing speed or by changing lanes. Due to the system's limitation to 130 km/h, some overtaking processes needed quite a long time, leading to aborting the manoeuvre. Cars coming from behind, feeling hindered, honked and then the test person took over from the system in order to accelerate and end the overtaking process more quickly. Conflicts were far more often observed on the rides with the system active when it could not recognise other vehicles indicating their intention to change lanes, or it lost sight of road markings due sunlight reflection. Some of these conflicts were solved by the interference of the system itself or the safety driver, but in most of the situations the test person avoided an accident by either braking, accelerating, or steering. Other non-critical but problematic situations were observed as regards system functions, for example when the system did not correctly recognise the surroundings (other vehicles, road markings, etc.) and it made sudden braking manoeuvres, was driving straight in a curve or kept too small a lateral distance. Such situations, together with the above described conflict situations, made it difficult for the test persons to fully trust the system.

Due to the fact that the test persons used the system for the first time and that some problems with the system were encountered on almost all rides, it was observed that the subjects were continuously checking the system functions, checking if lane changes were really possible to make, and if speed limits were correctly kept.

See the effects of the system on the observed variables in Table 10.1.

Table 10.1: The effects of the system on the observed variables

Variable	Effect
Speed adaptation to speed limit and conditions, speed variation	+
Distance keeping to the vehicle ahead	+
Prescribed use of the right lane	+
Indicator usage	+
Lane change behaviour	+
Driving comfort	+
Trust	+
Usability	+
Usefulness	+
Satisfactoriness	+
Lane keeping behaviour	0
Subjective workload	0
Letting other drivers make a lane change	-
Time needed for overtaking (due to 130 km/h system limit), hindering cars from behind	-
Conflicts with other vehicles	-
Sudden braking manoeuvres (due to not correctly recognising the surroundings	-
Drivers' self-assessed driving performance	-

+ = Improvement;   0 = No major change;   - = Deterioration

The questionnaire results revealed that the system was perceived as useful and satisfactory. The total System Usability Scale (SUS) score for the system was 80, which is considered high usability. The test drivers noted an increase in their driving comfort, but said that their driving performance decreased when driving with the system active. Some of the test persons stated that it was more comfortable and less stressful to drive with the system, others commented that they felt more stressed, feeling that they had to observe even more things (both traffic and system functions) and to be ready to take over at any time. Over half of the participants agreed or strongly agreed that the system was a competent performer, that they would trust it, that they would have confidence in the advice given by it, and that the system behaved in a consistent manner. Nevertheless the answers to the open questions also showed that trust first has to be built up and that it is more stressful to use the system without fully trusting it.

The system received both positive and negative comments. On the positive side, correct driving with regard to distance and speed, enhanced comfort, and possible time "savings" were mentioned. On the negative side, participants pointed out system failures (unrecognized or wrongly recognised vehicles, traffic signs, or road markings), the system's reckless behaviour (not letting others to merge onto the highway), and problems while overtaking due to the system limitation to 130 km/h. Due to these issues, some test persons felt more stressed while driving with the system. For some, this was okay, for others, the system could have driven faster (especially in some situations where a higher acceleration would have been advantageous). Additionally, the setting that the system drive 10 km/h over the actual speed limit was seen both in a positive and negative light; this was totally fine for some participants, while others did not agree with this setting and wondered why it was set in that way.

Nine participants stated that they would pay between EUR 750 and 1,000, and six persons would pay more than EUR 1,000. Four participants stated that they would pay less than EUR 250 (also mentioning that such a system should be standard in all cars).

10.3 In-Traffic Assessment

This section presents the results of the in-traffic assessment. Two different scenarios were used to answer the questions.

In the first scenario, a vehicle in front of the vehicle equipped with the automated driving function brakes. Two followers of the braking vehicle in two different configurations were considered for analysing the in-traffic performance of the tested automated driving function. In the first configuration, both followers were modelled with the Intelligent Driver Model (IDM). In the second configuration, the first follower was controlled using the ADF and the second follower was modelled with IDM. We gained insights on the influence of the ADF on other traffic by looking at the behaviour of the second follower. Ten thousand simulation runs were performed for both configurations. The results showed that the maximum deceleration of the second follower is higher on average when the first follower is controlled by the ADF. The reason for this is that the IDM does not have a delayed response so that its maximum deceleration can be lower. Thus the second following vehicle will also adopt a lower deceleration. A similar behaviour can be seen for the root mean square (RMS) of the jerk (i.e. the time derivative of the acceleration). The ADF has hardly any effect on its following vehicle as regards the minimum distance and minimum time headway. Looking the ADF's safety effects in this scenario, 25 simulations of the 10,000 run ended in a collision. This results in an estimated probability of 0.25% (±0.05%). The accuracy of the probability was enhanced via importance sampling. Using the importance density, it was estimated that the probability of ending a test case with a collision equals 0.16% (±0.01%).

In the second scenario, a vehicle cuts into the lane in front of the vehicle equipped with the automated driving function. The same approach from the previous scenario was used with respect to interaction with other traffic participants: two followers were considered in two different configurations. Again, ten thousand simulations were performed for both configurations. The main difference between the IDM and the tested automated driving function was that the IDM responded to the preceding vehicle when it performs the cut-in, even if the velocity of the preceding vehicle is higher. Furthermore, the IDM's deceleration is not limited, while the automated driving function limits its deceleration to $3\,\mathrm{m/s^2}$. Because the first follower braked much more when it was modelled with the IDM, the maximum deceleration of the second vehicle in this configuration was also larger. This further caused the minimal distance between the second follower and first follower to be lower when the first follower was modelled with the IDM. The differences in the minimum THW, however, were small. The velocity of the follower was analysed to examine the safety performance in this scenario. Specifically, we looked at the difference between the follower's end velocity and the minimum velocity. A common annoyance for an ACC is that it brakes because a vehicle driving faster cuts into the vehicle's lane at a close distance. In this case the velocity difference should be minimized, which also hold true from an economical point of view. This might conflict with some safety requirements, but this was not considered in this scenario. Sixty of the ten thousand simulations resulted in a velocity difference larger than $12\,\mathrm{km/h}$. The estimated probability equalled 0.60% (±0.08%). As with the previous scenario, the accuracy of the probability was enhanced with importance sampling. Using the importance density, it was estimated that the probability of having a velocity difference larger than $12\,\mathrm{km/h}$ equals 0.61% (±0.05%).

The two scenarios showed that the methodology could be used to assess the in-traffic behaviour of an automated driving function with the use of real-life scenarios with Monte Carlo simulations. Furthermore, the influence of the automated driving function on other traffic participants could be investigated using the presented methodology.

10.4 Impact Analysis

10.4.1 Safety Impact Assessment

Seven Top Scenarios were analysed for the safety impact assessment of exemplary automated driving motorway functions [Fahrenkrog, 2017]. The detailed results as well as the limitations and restrictions of the analysis that must always be considered were presented in deliverable D7.3 [Fahrenkrog, 2017]. The following presents the evaluation of the simulation for the "Cut-in" Top Scenario. The overall results can be found in the second part of this subchapter.

The "Cut-in" scenarios analysed situations in which another vehicle is performing a lane change in front of the relevant vehicle, which is either driven by the human driver model or the automated driving function. According to the analysis of the accident data, accidents occur more often in this scenario when a vehicle cuts-in from the right side – thus performing a lane change to the left. Therefore the analysis focused on the cut-in to the left side.

In this scenario, collisions occurred when the relevant vehicle is incapable of slowing down in time. Alongside this, a collision with the relevant vehicle could occur during a manoeuvre in which the relevant vehicle tries to prevent a collision. This manoeuvre could either be a braking manoeuvre (collision with the rear traffic) or an evasive manoeuvre (collision during or shortly after the lane change).

The simulation results for the different analysed “Cut-in” scenarios are given in Figure 10.5 and Table 10.2. The results were presented by means of the survivorship curves (Kaplan-Meier curves), comparing the human driver (vehicles driving by the SCM driver model) with the automated driving function. The Kaplan Meier curves were determined by analysing whether a collision of the relevant vehicles is detected for each simulation run, and – in case of a collision – at which point of time the collision occurs. The second step calculated how many of the eight thousand simulation runs remained collision free for each point. This approach allowed the determination of what the overall benefit of a system under assessment was and at which point of time the benefit was gained.

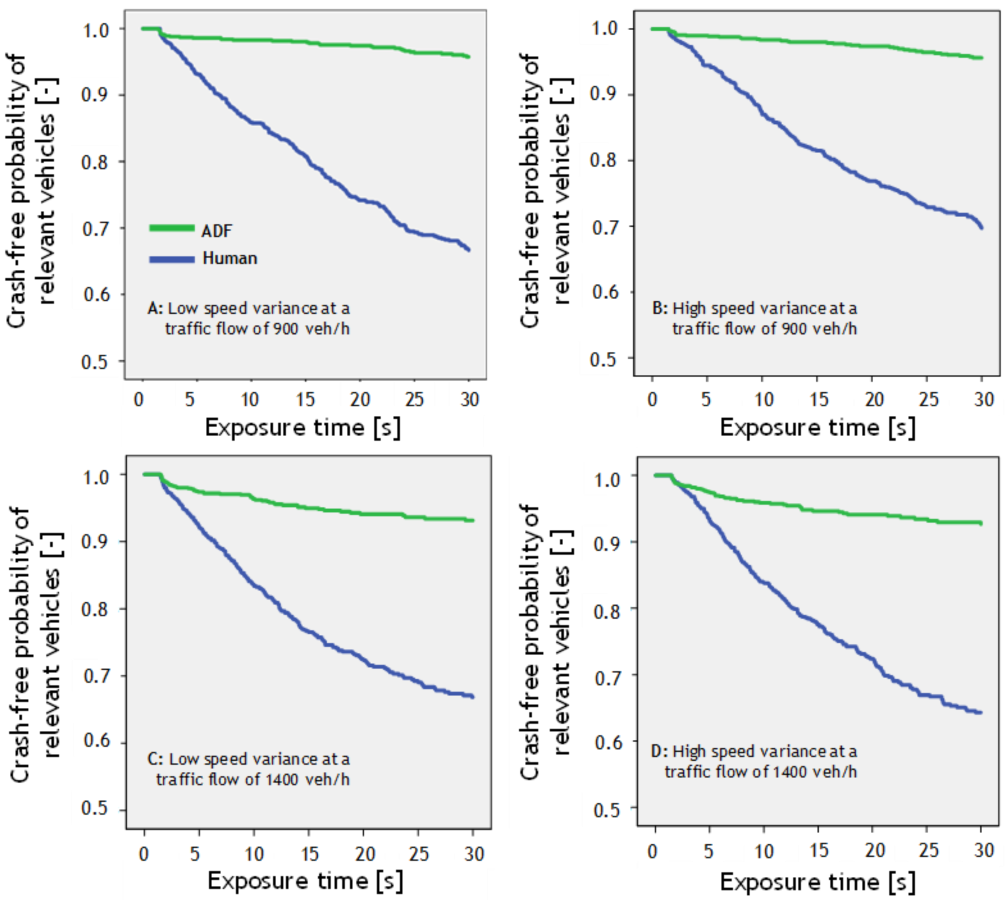


Figure 10.5: Probability of remaining crash free simulations for human driver (SCM) vs. automated driving function by traffic velocity variance (high vs. low) and at different traffic flow levels (900 veh./h and 1,400 veh./h) in the cut-in scenario.

Table 10.2: Results of the “Cut-in” scenario.

Accident reduction for target vehicle due to ADF relative to the human driver per Scenario	Traffic flow 900 veh./h	Traffic flow 1400 veh./h
Traffic speed variance low	-87.7%	-79.0%
Traffic speed variance high	-86.1%	-79.2%
Overall	-83.1%	

The results in Table 10.2 show that at a higher traffic flow (1400 veh./h), the benefit is lower than for a low traffic flow. On the other hand, the traffic variance showed only a weak influence on the reduction of accidents for this scenario. The overall safety benefit in terms of avoided accidents for the “Cut-in” scenario with the assumptions of the conducted simulation is 83.1%. Thus there was a high safety potential for a driving function in this scenario according to the simulation. The other Top Scenarios were analysed analogue to the “Cut-in” manoeuvre example.

Along with the effects in a certain situation, what also had to be considered was how often a function would be able to operate. Here, based on the GIDAS accidents, we analysed how many of the accidents occur within and without the operation conditions. This data was combined with the determined accident reduction between the human driven and automated driven simulations. The results are in Table 10.3: Determine reduction of accident per top accident scenario.

Table 10.3: Determine reduction of accident per top accident scenario[4].

	Top 1	Top 2	Top 3	Top 4	Top 5	Top 6	Top 7
Expected mean accident reduction rate [Confidence interval]	-83% [-76%; -90%]	-14% [-8%; -20%]	-40% [-34%; -47%]	-40% [-25 %; -55%]	-49 % [-45%; -53%]	-73% [-56%; -91%]	-100% [-;-]
Accidents within the operation conditions (including accident at speeds outside the operation conditions)	72% (92%)	67% (83%)	78% (97%)	80% (89%)	95% (95%)	69% (96%)	67% (93%)
Expected safety benefit due to accident reduction per scenario	-60% (76%)	-9% (-12%)	-31% (-39%)	-32% (-36%)	-47% (-47%)	-51% (-70%)	-67% (-93%)

[4] Results base on the available information and are only valid under the mentioned assumptions (see also AdaptIVe deliverable D7.3 [Fahrenkrog, 2017]).

Another aspect that had to be considered addressed the number of accidents that occur outside the function's speed range. Regarding the function's limitation with respect to the driven velocity, it is unclear how this would affect traffic safety. On the one hand, it can be argued that the accidents are not addressed, since they are outside the defined velocity range, which implies that the driver wishes to drive faster and switches the system off. On the other hand, these accidents are addressed – meaning that the function is switched on and the vehicle would be driving slower as compared to the case without the system. The results were calculated for both conditions in order to consider both arguments, see Table 10.3 (the results considering the speed-related accidents are in parentheses and the results without the speed-related accidents are not).

The safety impact assessment projected up the benefit of the different scenarios to a national level. An example German motorway was chosen for this (reasons are provided in deliverable D7.3 [Fahrenkrog 2017]). The overall accident risk reduction in terms of the national accident scene on motorways was calculated by multiplying the proportion with the previously calculated accident reduction per scenario (see Table 10.4).

Table 10.4: Expected reduction of accidents for the example of Germany.

	Top 1	Top 2	Top 3	Top 4	Top 5	Top 6	Top 7	Not Considered
Accident proportion (motorway - Germany)	14.5%	1.2%	3.4%	19.7%	1.4%	22.7%	21.8%	15.2%
Determine effect per scenario	-60% (76%)	-9% (-12%)	-31% (-39%)	-32% (-36%)	-47% (-47%)	-51% (-70%)	-67% (-93%)	0%
Accident reduction in Germany per scenario related to overall accident number	-8.7% (-11.1%)	-0.1% (-0.1%)	-1.3% (-1.6%)	-6.3% (-7.0%)	-0.7% (-0.7%)	-11.5% (-16.0%)	-14.6% (-20.3%)	0%
Overall change of the accident risk (motorway - Germany)	-43%[5] (-57%)							

Overall results showed a potential accident reduction by 43% to 57% as compared to today's accident data for Germany. The analysis compared the accident risk of a vehicle driving by a fic-

[5] Results base on the available information and are only valid under the mentioned assumptions (see also AdaptIVe deliverable D7.3 [Fahrenkrog, 2017]).

tional automated driving function representing the functions developed in AdaptIVe with the accident risk of a human-driven vehicle. The results showed that the highest safety benefit in terms of avoiding accidents could be gained in the road departure and rear-end scenario, which addressed most of the accident scenarios.

The analysis utilized a rather ideal scenario. In reality, the safety effect will strongly depend on the penetration rate and on the use of these functions. The conducted analysis presumed that the automated driving function was always switched on when the vehicle is driving on a highway and that the operation conditions were fulfilled. Furthermore, the analysis implied that the relevant vehicle was always driven by an automated driving function. Thus the actual gained benefit would be lower – particularly when market penetration is low.

However, due to the lack of required information (implementation, driver reaction), it was impossible to analyse the scenarios that add additional risks as compared to today's traffic. Here for instance we are referring to the transition of control situations in which the automated driving function hands over control to the human driver. All these factors further limit the gain of the automated driving function's safety benefits.

10.4.2 Environmental Impact Assessment

Driver types could be determined from the analysis of the different data sources and the clustering of people's driving behaviour. These were defined by their driving profile, which consists of single traffic scenarios, e.g. intersections, new speed limits, or free driving. Figure 10.6 (left) shows the effect of the automated driving function on the mean velocity of all driver types depending on the daily mileage.

The chart shows that the mean velocity is slightly reduced for nearly all driver types at a penetration rate of 10%. For a penetration rate of 50%, the mean velocity increases for most driver types. The effect is relatively high, particularly for higher daily mileages, because longer trips have more sections of free driving, which cause a continuous increase of in mean velocity for vehicles with an automated driving function as compared to human drivers. In contrast, scenarios such as crossings with priority rules or roundabouts do not raise the mean velocity because they are not addressed by the function. Figure 10.6 (right) shows the equivalent effects for each driver type as regards the Positive Kinetic Energy (PKE).

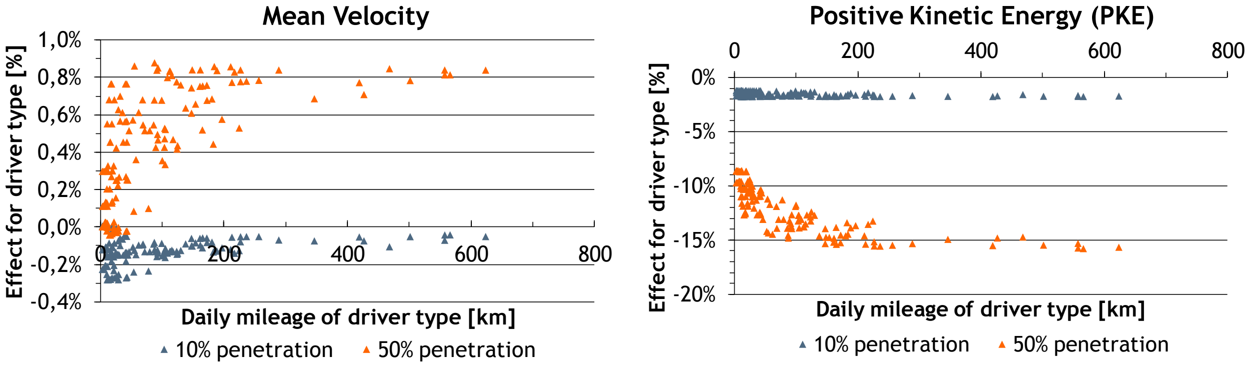


Figure 10.6: Effects on the Mean Velocity and Positive Kinetic Energy for all driver types

The effects of automated driving functions on the PKE were obviously stronger than the effects on the mean velocity. For a penetration rate of 10%, the reduction of the PKE is between 1% and 2%, independent of daily mileage. It increased to up to 16% for driver types who drive high daily mileages when half of the vehicles are equipped with automated driving functions. To get an overall effect of the automated driving functions on mean velocity and PKE, the effects of the different driver types had to be weighted. The aforementioned data sources were used to determine the occurrence of each driver type in the driver population. Table 10.5 presents the effects for the entire driver population.

Table 10.5: Overall effects of the automated driving function for the whole driver population

	Mean Velocity	Positive Kinetic Energy (PKE)
10% penetration	-0.12%	-1.54%
50% penetration	0.53%	-12.77%

The presented results were based on data sets from Germany because the amount of data there was quite comprehensive. The method could be adapted and used for other countries with a similar data basis.

11 Deployment Perspective for Automated Driving

11.1 Introduction

The exploitation of the project's results is a key objective within AdaptIVe. It will help to secure the leading role and competitive power of the European automotive industry. With a leadership in automated driving technologies, the sector will be able to remain innovative and gain key comparative advantage in international competition, and ultimately remain attractive to the end customer. In order to study the deployment potential of the project's outcomes, a holistic and integrated methodological approach was developed, starting with exploitation activities at the very beginning of the project.

The following chapter presents and discusses the main results of the project's exploitation activities. These are not a complete representation of all project results by the partners, but an illustration of major exploitable outcomes in the most important application areas of automated driving technologies.

The first part of the chapter explains the methodological approach applied within AdaptIVe, followed by a presentation of major results that constitutes the main part of the deployment section and refers to deployment challenges and mitigation strategies of how to tackle the challenge of widespread application of AD in Europe. This part will conclude with a presentation of roadmaps for market introduction of the technical functions developed within the project. Finally, a brief outlook will be provided as regards L3Pilot, the largest initiative of the European automotive community on piloting highly automated functions.

11.2 Methods

AdaptIVe applied a multi-stage approach in accordance with the project schedule to study the deployment potential of project results. The research is made up of an in-depth analysis of main challenges, key drivers, and implications for a market introduction of AD functions. Based on these findings, exploitation plans specific to stakeholder groups and deployment trends for automated driving – explicitly focussing on market demands – were elaborated and discussed to finally come up with a roadmap for market introduction for the AD functions developed in AdaptIVe.

The AdaptIVe exploitation approach is essentially comprised of five main building blocks:

1. Survey on legal aspects

   The survey was conducted during a one-day workshop on legal aspects for automated driving in Paris in April 2015. The event, with a total of 77 participants, provided the perfect platform to directly address the specialist legal community and to get first-hand information on legal challenges and key decisions needed for the realization of highly automated driving in Europe. With a response rate of more than 30 per cent, the survey provided statistically sufficient data which were statistically and analytically evaluated.

2. Partner survey on technical aspects

   In the second project year, the exploitation activities set the focus on technical issues. An internal project survey addressing technical feasibility and time to market for AD functions was conducted during the project's General Assembly in April 2016. A total of 37 partners responded to the survey, which included structured and open questions. The results of the questionnaire were again statistically analysed.

3. Expert survey on main challenges for market introduction of AD functions

   An expert survey with internal and external experts was conducted in addition to the partner inquiry as part of a technical workshop in April 2016. Its goal was to broaden the perspective on key deployment challenges for AD functions and gain insights from various fields of expertise, not only technical but also more market-related aspects. The short questionnaire, consisting of only one open and one structured question, was completed by a total of 23 experts. The gathered data was analysed using a qualitative content analysis approach.

4. Partner survey on deployment strategies

   The fourth building block of the AdaptIVe exploitation approach was a comprehensive partner survey, conducted in the final project year (Q1 2017) asking for main project results and deployment strategies. The questionnaire, with more than 16 structured and open questions, was sent to the project partners by e-mail. All types of partners involved in the project – automotive manufacturers, automotive suppliers, and research providers – contributed equally to the survey, with a response rate of 65 per cent. The individual data was aggregated with regard to the stakeholder groups. The main exploitation pattern were analysed and discussed for each group.

5. Expert panel on deployment trends and perspectives for AD functions

   In the final project phase, an expert panel was convened in Berlin in April 2017 to put emphasis on market- and customer-related issues. A group of dedicated experts from the automotive industry, mobility sector, business innovation, and market research discussed both the market potential of AD functions, the need for new mobility service concepts and business models, and marketing strategies for how to approach the customers and increase broad user acceptance of the systems. The discussion was recorded and the minutes were analysed applying a content analysis approach.

It should also be noted that in addition to the project's exploitation activities, the partners significantly contributed to various research initiatives, working groups, and discussions rounds at the European and national levels on deployment challenges for automated driving. An initiative of particular importance is the ERTRAC Roadmap on Automated Driving (2015), which provides a comprehensive overview of the current status for AD technologies and key challenges for implementation in Europe.

The present analysis of deployment challenges and potential for AD functions took into account the findings discussed in the ERTRAC Roadmap and other recent publications. Based on the surveys' results and desk research, all data was analysed using a cross-comparative content analysis approach. The following four major questions served as guidelines for the analysis:

- What are the *biggest challenges* for a successful deployment of automated driving functions in Europe?
- What are most *important drivers* needed for realizing highly AD in Europe?
- What are short- and medium-term *deployment strategies* for AD functions?
- When will AD functions be *on the market*?

11.3 Results

11.3.1 Key Challenges and Main Drivers for Market Implementation

The first major issue of the analysis is the question concerning main challenges for a successful implementation of automated driving in Europe. Different challenge areas were identified based on the cross-survey analysis and regrouped into seven challenge clusters. These clusters reflect a variety of different challenges that in many aspects have been addressed and researched within the AdaptIVe project.

Important drivers and key decisions (orange boxes in Figure 11.1) needed for the realization of highly automated driving were identified for each cluster (blue boxes):

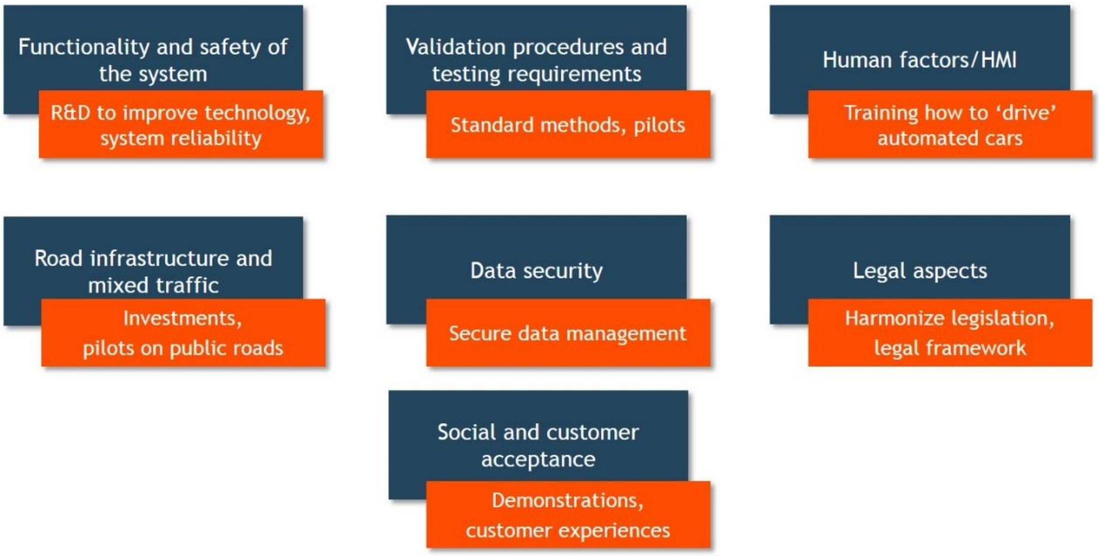


Figure 11.1: Challenge clusters and drivers for market implementation

Since the challenge clusters listed largely correspond with discussions provided in recent publications (e.g. ERTRAC roadmap), Table 11.1 highlights drivers and key decisions needed from all stakeholders involved – industry, academia, legislative and executive power on the national and international levels – to successfully pave the way to automated driving in Europe.

Table 11.1: Key drivers for market implementation

Challenge clusters	Key drivers
System functionality and safety	High effort in R&D to improve technology and system reliability, particularly for city traffic and high speed. Push technology standardization for highly automated functions.
Validation procedures and testing requirements	Common set of methods and procedures to obtain comparable results. Pilots on public roads to test systems in real traffic situations. Harmonized set of rules and legislation to test autonomous driving at the European level.
Human factors and HMI	Recommendations for HMI design concepts to increase drivers' understanding of driving situations, achieve high acceptance, and increase safety and comfort. Standardized solutions for key interactions between system and driver, e.g. take-over request. Training and information on how to *drive* automated cars.
Road infrastructure and mixed traffic	Clear commitment to invest in infrastructure (signs, signals, road markings, C2X communication) to increase environment perception. Pilots on public roads to research interaction between AVs and human-driven vehicles.
Data security	Secure (private) data management.

Challenge clusters	Key drivers
Legal aspects	Harmonize legislation in the EU and create a legal framework for AD. Naming and classification scheme for higher AD functions. Decision and clear definition regarding the allowed remaining risk. Shift of liability from customer/driver to x and new insurance models.
Social and customer acceptance	Increase the general trust in AD technologies and overcome scepticism of potential customers through demonstrations and customer experiences.

11.3.2 Deployment Trends and Strategies for AD Functions – The Technological Perspective

As indicated above, the development of deployment perspectives and strategies for the project's results is a key objective within AdaptIVe. The stakeholder groups involved in the project – automotive manufacturers, automotive suppliers, research providers and academic partners – established unique deployment patterns that may be outlined as follows:

Automotive manufacturers will particularly exploit and further use research results from AdaptIVe for in-house development for new-generation vehicles. Given the typical timeframes for automotive development cycles, it can be expected that AdaptIVe functions will be available in about 3 to 6 years after the end of the project.

Automotive suppliers will mainly exploit the project's results with the sales of sensors and subsystems to the OEMs. Since this usually happens in the beginning of the OEM's series development, the time horizon for deployment is approximately 2 to 4 years after project completion.

Research institutions and academic partners finally exploit the results through licences and development support as well as scientific publications and training for students and staff. The main exploitation effort will largely happen in parallel with the project work.

In addition to the more general exploitation pattern for the different types of project partners, the survey on deployment strategies provided more detailed knowledge about exploitation plans and priorities specific to stakeholder groups. The summary given in Table 11.2 is not a complete representation of all project results by the partners, but an illustration of major exploitable outcomes in the most important application areas.

Table 11.2: Major exploitable results by stakeholder groups

Stakeholder group	Major exploitable results	Sector of application	Time horizon[6]
Automotive manufacturers	Automated parking application with optional cooperative technique that can be used in multiple places (garage, parking lot etc.). Parking spot detection and trajectory planning for parking manoeuvre. Demonstrator that looks like a series car to experience the functionality.	Parking	<2020
	Development of in-house simulation tool for investigating technologies' traffic-safety impact. Results also contribute to OpenPASS simulation framework.	R&D	2018-2019 (OpenPASS)
	System classification for AD technologies. Overview of legal situations, challenges, barriers to ADAS and AD technologies.	Legal aspects	2017
	Overview of safeguarding challenges and requirements outline for future Code of Practice on AD technologies.	R&D	2017
	HMI concept for vehicle automation for commercial vehicles (trucks). PAC – Pre-Activation Concept to facilitate activation when automation becomes feasible.	HMI	2017
	Classification scheme and methodological enhancement for series development of AD functions.	Series development	
Automotive suppliers	Radar tracking development for stationary targets to extend functionality of close distance parking. Signal processing development for next generation sensors.	Parking	
	Advancement of knowledge on system limits of current sensor and fusion techniques and actuators with focus on highway scenarios, an essential prerequisite for maintaining safety. Definition of requirements for the design of AD functions to preserve safety. List of requirements serve as a framework for a future Code of Practice.	Design phase, Validation	
	Systematic method and process for functional safety analysis and assessment for system development. Functional safety architecture design pattern to be used as library pattern, architecture design of functional safety critical systems.	Vehicle system architecture design	
Research providers, academic partners	Catalogue of recommendations and strategies for HMI design concepts for supervised AD use cases, functions. Generic concept and recommendations for HMI design providing knowledge about type, amount, specificity, modality, and timing of presented information to the driver	HMI	2017-2018 (Input to standardization bodies)

[6] The time horizon for expected market introduction of the project's results is only indicated if the survey provided reliable data.

Stakeholder group	Major exploitable results	Sector of application	Time horizon[6]
	to reach high acceptance of AD functions and increase safety and comfort.		
	Advancement of knowledge about effects of AD on driver's behaviour and mental models, (e.g. interactions with non-driving-related tasks), in take-over situations and in case of system failure.	HMI	2017
	Artificial driving agent for different levels of automation.	Validation	
	Framework for in-traffic assessment of AD functions to investigate how surrounding traffic interacts with the vehicle/function without the need of physical tests.	Validation, testing	2017
	Enhanced methodology for impact assessment considering safety and environmental effects. Participation in standardization bodies for impact assessment of AD functions.		2021 and beyond
	Mapping evaluation methodology for simultaneous localization and mapping vehicle algorithms in GPS-restricted environments.	Environment representation, parking	
	Custom OpenStreetMap (OSM) elements for parking areas. Enhancement of current OSM map data with parking area information leads to more detailed map representation to help AD functions to reliably navigate in various urban environments.	AV localization	
	Glossary of legal terms for higher AD functions to provide legal security and clarify legal issues.	Legal aspects	2017
	Analysis of product liability issues for AD functions, relevant changes and discussion of possible solutions.	Legal aspects	2017
	Clear understanding of how automated cars will be influenced by needs of data privacy and security.	Legal aspects	2017
	Analysis of contradictions of various EU member states' traffic laws as a starting point for cross-border harmonization. Comparative analysis of markets and measures taken by legislators to make AD possible.	Legal aspects	2017

11.3.3 Deployment Trends and Strategies for AD Functions - The Market View

In addition to the more technology-oriented discussion of major exploitable results and deployment patterns for the different stakeholder groups, the exploitation activities within the project also considered market-related issues and customer demands. This took the specific form of a dedicated expert panel that was held at the final stage of the project when most of the results were available, where the market potential of the AD functions developed and tested in AdaptIVe was discussed. The discussion touched upon the issues of new business models and mobility concepts for AD systems and explicitly raised questions about customer needs and user acceptance: *Who are our target customer groups? How can we approach them and convincingly communicate the benefit of AD functions? What is the roadmap for implementing L3 and L4* *functions on the market? What are the challenges and barriers to overcome for successful market integration?*

The current view of automated driving is strongly influenced by media and highly visible market entries of start-ups producing the image of fully autonomous vehicles that will become broadly available within the next decade. Since this picture is far from reality, the challenge for the automotive industry is to start with promising use cases that provide significant benefit for a broad or highly visible customer group, leading to successful market entries.

Besides this vision of autonomous driving, the general public perceive the new technology with a mixture of fascination and scepticism. Concerns about the loss of control, data security, and a lack of trust in technology are some of the most common responses in previous customer surveys. It is therefore recommended that an evolutionary approach be applied to increase user acceptance and trust in the technology, particularly by providing various opportunities for users to experience AD functions and their benefits in the real world.

In addition, a successful market launch needs a shift in communication and marketing from using level classification for AD functions (L3, L4) to clear and comprehensible descriptions of AD functions, including rules for allowed non-driving related activities, distinct requirements for take-over requests, and naturally its benefit to customers.

Another challenging issue is the expected jump in price between L3 and L4 functions. Given that recent international studies on user acceptance show customers are not willing to pay extra charge for L3 functions (as they do not see a great benefit in them), the willingness to pay an even higher price for highly automated driving – notably in the transition phase facing the challenge of mixed traffic on the roads – would likely be even less. Many studies on ADAS and AD systems also reveal that customers are quite willing to pay for greater convenience but not for more safety and efficiency.

On the other hand, unlike private drivers, companies might be willing to pay higher prices for AD functions if their employees – professional drivers and company car drivers – would have time to work while driving. Aside from the highway chauffeur, valet parking (e.g. for business travellers at the airport (would be another promising use case, saving time and money for the target group. These cars are usually available on the used-car market after a period of three years, which will have a positive impact on the penetration rate for AD functions for private users as well.

The fast growing sharing economy, notably car-sharing in urban but also rural areas, is also considered a significant use case for AD functions. A great benefit for customers in this case are standardized systems and solutions for HMI, particularly the take-over request, which makes it easy for customers to drive different car models without the need to constantly adapt to new

HMI solutions. On the other hand, it must also be considered that the take-over request solution might be the only standardized solution, as OEMs will provide customized systems to differentiate from those of their competitors.

Looking at a medium-term time horizon of 5 to 10 years, the market experts also considered technological challenges and legal aspects as further key factors for widespread deployment of AD technologies. Besides the functionality and safety of the system, validating processes for instance still need long timeframes, which creates competitive disadvantages for the European automotive industry as compared to international competitors from the US and Asia. Fast decision-making processes in Singapore, for instance, and fewer standardization processes in the US provide crucial competitive advantages, at least in the short term. To remain internationally competitive, new and fast solutions must be found and more research efforts are still needed in order to reduce the time to market for AD systems and rapidly deploy AdaptIVe research results.

11.3.4 Roadmaps

Despite these challenges, the European automotive community expects a broader market introduction for automated driving over the medium-term future. AdaptIVe supports and accelerates the market launch on a large European scale since the functionalities developed in the project are planned for industrial deployment starting at the end of the project.

The roadmaps presented below are based on assessments of project partners and external experts and refer to the three main traffic scenarios used in AdaptIVe: highways, urban environment, and close distance. The figures indicate the expected time horizon for market deployment for the technical functions developed and tested in the project.

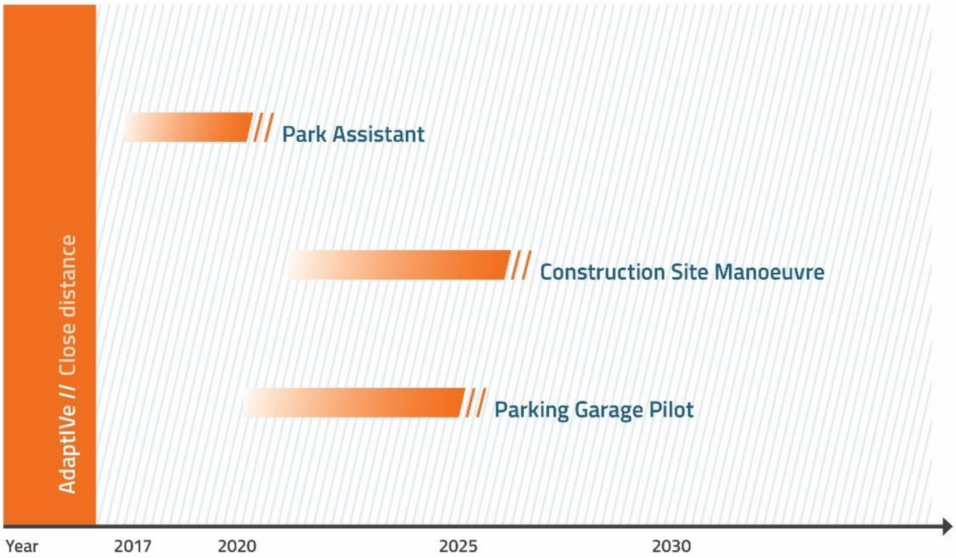


Figure 11.2: Roadmap-Technical functions in close distance scenarios

Parking applications, e.g. parking assistant and parking garage pilot, will be the first highly automated functions available on the market. However, new stakeholder networks and partnerships, e.g. with parking garage operators are needed to facilitate the applications for rapid deployment of the functions.

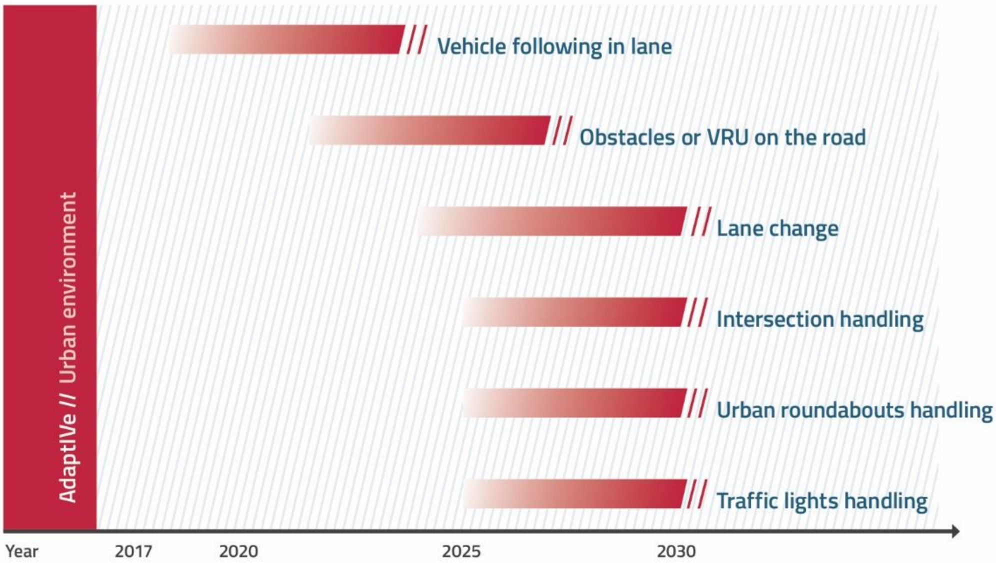


Figure 11.3: Roadmap-Technical functions in urban environments

As compared to close distance use cases, applications for urban traffic are more complex and challenging. Handling traffic lights for instance needs the support from infrastructure operators and traffic management centres to enable the functions' efficient performance in urban areas. Moreover, the detection of VRU and the variety of unexpected situations in dynamic city traffic require maximum reliability and accuracy from sensor systems. Since there is still considerable need for research, the implementation of highly automated functions in urban environments is not expected before 2025.

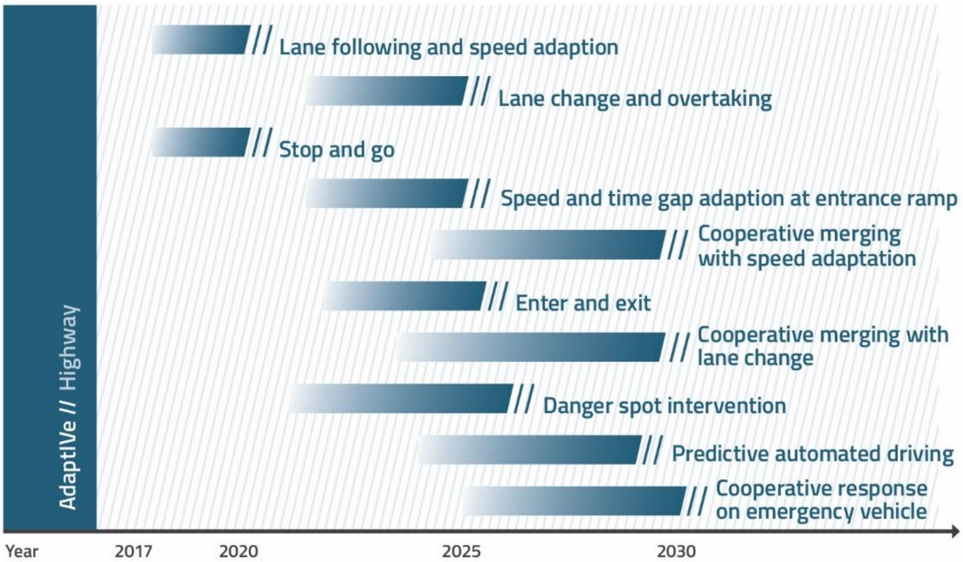


Figure 11.4: Roadmap-Technical functions in highway scenarios

The roadmap for implementing AD functions for highway scenarios shows a more differentiated picture. Whereas the highway chauffeur with lane following and speed adaptation as well as stop-&-go functions will be available by 2020, the more complex functions, such as cooperative merging with lane change, are expected to be launched during the next decade. The broad use of cooperative functions in particular also needs a high penetration rate of C2X communication technology and appropriate infrastructure investments, which is not viewed as a given over the short- and medium-term future.

The analysis of the deployment challenges for automated driving systems and the elaboration of implications for a broad application of the technology in Europe have shown there is still a need for great efforts in research, but also with regard to societal, political, and legal aspects, in order to find suitable solutions. To pave the way to automated driving, the European automotive community will address these issues and join forces in L3Pilot. The project will start in September 2017 and will be the largest initiative on testing and piloting L3 and L4 functions in Europe. More than one hundred automated vehicles will drive on public roads across Europe, additionally providing the opportunity for about one thousand users to experience automated driving in real traffic situations.

12 Conclusions

12.1 Lessons Learnt

This section presents some major lessons learnt in the project, which are shown according to the different areas of work.

Legal issues

- The results on legal aspects significantly contributed to fruitful discussions in other projects and working groups (e.g. OICA, SAE, ERTRAC). Thus the focus on dissemination should be extended when implementing future initiatives. Liaisons with a worldwide perspective are important due to the need to harmonise the approaches globally.
- Lively discussions about regulations and laws for automated driving reflect public interest and institutions' motivation to develop these topics. It is important to consider the needs of all stakeholders: drivers, traffic users, authorities, lawyers, car industries, insurances, infrastructure operators, and service providers.
- Due to the complexity in the legal domain and the required precision, it was important to develop a good starting point and a glossary for the general discussion with experts from different fields. This was quite a challenge, and it was very appropriate to consider this task from the beginning of the project while defining timelines and plans.

Human-vehicle integration

- When investigating transitions from automated to manual driving, response time alone is not enough to provide information on how well drivers can handle a vehicle after re-taking control. Other metrics, e.g. steering and braking patterns, should be considered. In addition physiological measurements are needed to understand drivers' behaviour during automation, and the potential impact of this on their ability to re-take control.
- Standardization is needed, for instance including brand-neutral symbols, messages, and colours, placement of interaction devices, etc.
- Currently there is little empirical evidence from driving in real-traffic environments with automated vehicles. Most knowledge is based on simulator studies, which have some limitations, meaning for instance it is difficult to ensure that drivers behave as they would in the real world. The next steps in knowledge acquisition in this area should be to gather data from controlled field trials.
- There is little knowledge about the long-term effects of driving with automated systems on drivers' inattention levels, boredom, user acceptance, trust, behavioural adaptation, and skill degradation over time.

Automation in close-distance scenarios

- Close–distance has low-speed scenarios and the difference (mental load) to faster scenarios in automation means they might be perceived colloquially as “mighty slow”. The time for finishing an automated manoeuver might be perceived as waiting (“boring”), whereas in highway driving the automation experience is rather of releasing time for secondary tasks (“relaxing”).
- In close-distance scenarios, the vehicle drives along or against an obstacle. Compare to free driving where the normal operation is without obstacles.
- The short duration of a parking manoeuver (as part of a longer trip) lends less splendour to automation than the longer sessions in highway automation.
- Perceived benefits will be stronger for older people when head movements for environment scanning, e.g. for backing up, gets more difficult.
- Close-distance scenarios are difficult since the time for brake controls versus the time for actuation (getting a result) is of same order. Say almost one second for the time span between the presence of an obstacle and the whole chain of action (detect, process, check, decide, activate control command) and the same time until controls take effect (spin-up brake engine, boost brake pressure, move brake disc, reduce speed).
- The full circle to automated valet parking in a multi-storey garage is a chicken-or-egg problem: Providing full safety in a garage (no humans inside garage & inside vehicle) and cooperative information (missing standards) from the garage need high investment for garage infrastructure and the closure of that garage to non-automated vehicles. Deployment of valet-equipped vehicles requires many garages to be considered value-for-money for the buyer.

Automation in urban scenarios

- The activity regarding urban scenarios gave the partners the unique possibility (especially OEMs) of comparing different vehicle architectures with mutual advantage for technical implementations.
- Realizing an effective sensing subsystem required additional efforts in order to face the extremely high complexity of implementing automated manoeuvres in different urban scenarios.
- The specialized activity for application development could really benefit from the complementarity expertise of the OEMs, suppliers, and universities involved – a key factor when considering technical complexity.

Automation in highway scenarios

- Challenges for further development from the functional perspective lie especially in coping with complex scenarios such as automated guidance through highway intersections and cooperative manoeuver planning in dense traffic.
- Integrating highly precise maps and a robust localization into the environment representation using standard sensors remains an ongoing activity. This also accounts for the challenge to automatically keep these maps up-to-date via information aggregated from on-board perception.
- As the role of the vehicle and vehicle ownership changes, so do the requirements towards the vehicle system architecture. A holistic system approach will be required to support function upgrades in the vehicle on demand and to ensure a reliable, available, safe, and secure vehicle system architecture.
- The importance of dependability und roadworthiness of the overall system is increasing rapidly. In conditional and fully autonomous vehicles (SAE Level 4 & 5), the driver disappears as fallback for taking over the driving task in case of system failure. This therefore also means that the responsibility in case of accidents will change. In such cases, a fail-safe system is no longer suitable. Driverless vehicles must be designed and implemented as fail-operational systems and need to ensure safe operations, even in case of a failure. This needs to be covered by complex hardware and software architectures and will become an important task for the automotive industry in the coming years.
- Making automated driving safe, legal, and socially accepted is an ongoing effort for the social community as a whole.

Evaluation

- The availability of a suitable amount of test data based on real-world driving is of particular importance, especially for the future assessment of safety performance. According to a study [Winner 2011], more than 100 million kilometres will be necessary for this task. Thus the use of virtual experiments will be necessary for assessing safety related aspects.
- In order to test automated driving functions in a conclusive manner, the data should sufficiently cover a wide range of driving situations and the combined scenarios should form the total of situations encountered by the functionality in real-life [Stellet et al. 2015]. How much data needs to be collected remains an open question.
- The system to be assessed in user-related tests should be completely flawless.
- Concerning user-related assessment, the final test should be in a real-life setting, where naïve drivers drive on public roads, but also in advanced driving simulators, allowing staged situations where situational awareness and possible complacency can also be studied.

- Test driver selection should include the population of elderly drivers (65+) since this group of drivers are greatly increasing in number and will play an important role in defining the usability of newly developed driving systems.

12.2 Project Results

AdaptIVe designed, developed, and evaluated automated driving applications for passenger cars and trucks in ordinary traffic. The functions implemented and the real-life demonstrations provide a solid basis for future automated driving applications.

The six main pillars developed in the project were presented in the previous chapters, and a brief summary of the corresponding results is given below:

On legal aspects partners contributed to discussions at the international level among all the interested organisations and strengthened the awareness for a harmonized system classification and automation level definition. The following points can be highlighted:

- The project created a set of scenarios to discuss possible cases of liability making abstract considerations more "tangible", and covering a wide range of situations, from technical malfunction to misuse.
- Partners conducted an analysis of road traffic laws of five EU member states.[7] The focus was placed on international treaties, such as the Vienna Convention on road traffic, and the compatibility of the current versions with automated traffic.
- Different liability laws were examined. Not all questions of liability in case of a crash with automated vehicles could be conclusively clarified, at least not until further legislative actions are taken. Due to EU Directives, liability law in the assessed countries is largely comparable. The injured person has to prove the damage, the defect, and the causal relationship between defect and damage. Whether an automated driving system could be solely responsible, and whether the burden of proof will lie with the manufacturer remains to be seen.
- The analysis of the general data privacy framework was carried out with emphasis on embedded Event Data Recording systems. These systems may help to prove, for example, who was driving at a decisive moment, but still they present issues in terms of data protection law.

  Demonstrators were built to deliver the much-needed input for legal discussion. New topics need hands-on representation.

[7] Italy, Great Britain, France, Germany, and Sweden.

Driver-vehicle interactions

Driver behaviour during automation

- When driving in SAE Level 3 automation, drivers made use of their free time by engaging in non-driving related activities, and generally they became highly involved in such tasks.
- Drivers deeply engaged in a secondary task while in SAE Level 4 mode were much more sensitive to multimodal alerts and timing as compared to drivers in manual driving.
- Drivers who did not take up a secondary task presented to them during automation became bored with Level 4 automation very quickly.

HMI Implications

- Drivers responses to “uncertainty messages” from the automation showed that they were able to understand the operation of an automated system and its limitations quite well, only resuming control when it was required.
- Various kinds of “cues” that are able to effectively direct drivers’ attention back to the driving task (e.g. timely announcement of system limits, information about remaining time in automated mode) could enable drivers to get out of the loop during Level 3 automation yet bring them back in a timely manner if their intervention is required.
- An ambient light display was able to support drivers in understanding which automation level is currently activated, and which automation level is available for activation.
- For truck drivers, a concept for automatic activation of the automation was beneficial in terms of maximizing automation usage. The drivers perceived the automatic activation concept to be useful, easy, and comfortable. However some drivers preferred to activate the automation manually in order to be in control of the driving.
- A remote parking aid system received high ratings for usability, acceptance, and controllability, and this was not influenced by the presence of a secondary task.

Quality of Transitions

- Drivers who were late to identify a hazard during an uncertainty alert were more likely to crash, suggesting that where drivers look in the seconds after re-taking control is important.
- Resuming manual control from automation led to poorer vehicle control during overtaking in terms of higher lateral accelerations. This effect did not fully disappear before the end of the overtaking manoeuvre. However it did improve with experience of the system.
- Engaging in non-driving related secondary tasks while in automation mode affected the drivers’ abilities to take lateral and longitudinal control of a truck in a critical situation.

Automation in close distance scenarios

- Localisation results from robotics were implemented and adapted to automotive research.
- The use of maps has been shown to provide tangible improvements in parking.
- Longitudinal control has been improved to include ramp driving in multi-storey garages.
- The concept of “driver outside” has been implemented in two demonstrators.
- OpenStreet Maps have been adapted for localisation inside public parking with Full OSM representation by blueprint conversion (paper map to digital OSM).
- An algorithm has been developed to deliver a precise path for retrieving the vehicle between drop-off zone and parking spot.

Automation in urban scenarios

- A major result is the design and development of automated vehicle manoeuvres per different driving conditions in urban and peri-urban areas addressing driving conditions (like queuing) that are stressful for the drivers.
- A growing level of complexity can only be faced with a step-by-step approach, or alternatively by designing specific applications for urban areas that are closed to the non-automated traffic.
- Complex roads and traffic environments, such as urban scenarios, can be addressed by structuring the autonomous system in behavioural layers according to automation levels. Depending on the available infrastructure, the maximum level of support is provided.

Automation in highway scenarios

- In a speed range of up to 130 km/h, the vehicle allows for lane keeping and system-initiated lane changes. An observation of all traffic rules is included. The highway driving strategy incorporates a situation-based safe mode. Additionally, the functionality shows cooperative characteristics on highway entrances with lane change and speed adaption. Furthermore, changes between motorways are automated. As a conclusion, the driver now can delegate the driving task to the vehicle in appropriate situations.
- Specific solutions for the highway travelling of trucks were developed based on a specific sensor platform, and allowing a combination of lateral and longitudinal controls.
- The vehicle system architecture was defined, specified, and harmonized, covering all kinds of automated driving functions addressed in AdaptIVe. Furthermore, the functional safety impact on the system architecture was investigated following ISO26262. A concept based on Duo

Duplex architecture with fault detection was finalized, focusing on sensor perception and data fusion.

Evaluation

- A comprehensive methodology for evaluation of automated driving functions in the range of SAE Levels 2 to 4 has been developed. A suitable approach was to consider a classification of the automated functions in continuous and event-based operating modes.
- Results for the technical assessment indicate that the AdaptIVe functions show a control capability and variability very similar to human driving behaviour. There are two results that stand out: first, the time required for a lane change is much more uniform, and, second, automated driving shows less variability in headway keeping.
- The user-related assessment was applied to “Supervised City Control” and “Highway Automation”: these functions received high usability scores. Worries were expressed by the test persons about relying on the system in real traffic – whether the car will constantly be able to handle new and different situations. The tests revealed that the system affected driving positively in several ways, however it was reported that the system did not react to other driver’s intention when making a lane change, especially when merging onto a highway. In these situations, the subjects reacted better when driving without the system, either by reducing speed or by changing lanes.
- Regarding the in-traffic assessment, a methodology was developed with focus on the interaction with other traffic participants as well as non-automated traffic participants. The method considered real-life scenarios with Monte Carlo simulations. The approach was mostly data-driven, such that the assessed performances resembled the performance in real-life traffic.
- Regarding the environmental impact of automated driving functions in highway and urban scenarios, the analysis showed that the travel time can almost be maintained while a reduction of energy demand due to acceleration behaviour of about 12% is feasible at penetration rates of 50%.
- For automated driving applications in parking scenarios, the impact assessment showed that an increase in parking space of 10% for vehicles with an average width is possible by using automated parking functions. However constrains with respect to the automation and environment need to be recognized, which might limit the possible effects.

12.3 Potential Follow-Up Activities

There is a general consensus that additional progress is needed for the deployment of automated driving, and a complete coherent picture on how this field will be shaped will be clarified only in the coming years. A suitable route towards automation will require close cooperation between all the stakeholders as well as public understanding of the potentialities and limitations of automated vehicles.

The results obtained in AdaptIVe provide an industrially oriented point of view and provide relevant clues in all the key areas. The project partners believe that legal issues will remain on the international scene over the coming years, especially as regards liability, type approval, and data security/privacy.

At the technical level, specific research needs remain for the next steps. Firstly, a more complete validation of the solutions is required, especially based on pilots and Field Operational Tests with potential users. This task will be specifically addressed by the upcoming H2020 project L3Pilot, which aims to acquire and analyse a large amount of driving data for Level 3 automated applications in order to direct the design of future systems.

Another point in the research agenda is the enhancement of the roadmap for reaching higher levels of automation and figuring out what the optimal functions are. It will be important to consider the interaction of vehicles on the roads at different levels of automation as well as the role of infrastructures and cooperative systems.

From the technology point of view, a key topic remains the improvement of perception, possibly strengthened by new sensors able to cope with diverse situations. A specific area of investigation can be how to combine all-weather and affordable sensors for obtaining environment perception in all the situations that remain cost effective, perception that is traditionally performed by other more sophisticated sensors. Another remaining requirement for perception research is the need of so-called sensor and map open ground-truth data to allow for meaningful evaluation and comparison of new algorithms. In parallel, the on-board intelligence should be enhanced by new, high-performing systems that can more effectively plan driving strategies and that can learn from exposure to various traffic situations. Along with contributing to safety, these intelligent systems also offer great potential for enhancing security and mobility for people and goods. Advancements in communication, networking, and tracking technologies will support this goal.

In the domain of Human Factors, further practical implementations and investigations are needed to develop effective approaches for human-vehicle interaction. With the availability of new systems at a larger scale, the study of long-term effects of automated driving will also become a key point for understanding how both positive and negative factors influence automated driving.

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14 List of abbreviations and acronyms

Abbreviation	Meaning
ACC	Adaptive Cruise Control
ACSF	Automatically Commanded Steering Function
AD	Automated Driving
ADF	Automated Driving Function
ADAS	Advanced Driver Assistance System
BASt	Bundesanstalt für Straßenwesen (German Federal Highway Research Institute)
C2X	Car to X communication (where x equals either vehicle or infrastructure)
CONTIT	Short name for partner Continental Teves AG & Co. OHG
CRF	Short name for partner Centro Ricerche Fiat SCpA
DAI	Short name for partner DAIMLER
DSSA	Data Storage System for ACSF
EC	European Commission
EEC	European Economic Community
EDR	Event Data Recorders
EU	European Union
EUCAR	European Council for Automotive R&D
EN	European Standard, telecommunications series (ETSI deliverable type)
ERTRAC	European Road Transport Research Advisory Council
ETSI	European Telecommunications Standards Institute
FOT	Field Operational Test
GDPR	General Data Protection Regulation
GIDAS	German In-Depth Accident Study
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GTR	Global Technical Regulations
HF	Human Factors
HMI	Human Machine Interface
HAD	Highly Automated Driving
IDM	Intelligent Driver Model
IKA	Short name for partner Rheinisch-Westfaelische Technische Hochschule Aachen
ITS	Intelligent Transportation Systems
JOSM	Java OpenStreetMap editor
LRR	Long Range Radars

MRM	Minimum risk manoeuvre
NHTSA	National Highway Traffic Safety Administration
OEM	Original Equipment Manufacturer
OICA	Organisation Internationale des Constructeurs d' Automobiles (French organisation)
OSM	OpenStreetMap
PDF	Probability Density Function
PKE	Positive Kinetic Energy
SAE	Society of Automotive Engineers
SCM	Supply Chain Management
SLAM	Simultaneous Localization And Mapping
SP	Subproject
SRR	Short Range Radars
SUS	System Usability Scale
TJA	Traffic Jam Assist
TTC	Time to Crash
UNECE	United Nations Economic Commission for Europe
VCC	Short name for partner Volvo Personvagnar AB
VDA	Verband der Automobilindustrie (German Association of the Automotive Industry)
V2V	Vehicle to Vehicle
V2X	Vehicle to everything
V2I	Vehicle to Infrastructure
VRU	Vulnerable Road User
VTEC	Short name for partner Volvo Technology AB
XML	Extensive Markup Language