Safely towards
self-driving vehicles

SWOV
INSTITUTE FOR
ROAD SAFETY RESEARCH

Safely towards self-driving vehicles

New opportunities, new risks and new challenges during the automation of the traffic system

Report documentation

Summary

There are more and more systems on the market to support the driver in his vehicle. Step by step the automation of our vehicles increases, the traffic system is in a transition towards self-driving vehicles. The automation offers opportunities to make our traffic safer, cleaner and more efficient. However, new risks are emerging, particularly in the transition period.

This report describes which developments can be expected during the automation of the traffic system. The report also discusses the implications of these developments for road safety: the opportunities and the risks.

The report concludes with the presentation of a research agenda in which the topics are clustered into three groups:
1. *Interaction of the driver with the new technology in the vehicle.*
   This concerns, among others (changes in) task load, switching between automated and manual driving ('transition of control'), situational awareness and hazard perception during (the transition to) automated driving, and the interaction of elderly drivers with the new technology.
2. *Interaction of (partly) automated vehicles with other traffic.*
   This concerns, among others, mixed traffic, the interaction with other road users, and specifically also the interaction with vulnerable road users.
3. *Smart infrastructure and safety effects on the traffic system.*
   This concerns, among others, the safety effects on the network level in the situation of traffic with various road users at different levels of automation ('mixed traffic'), intelligent infrastructure and vehicle communication (V2X), and 'roads that cars can read'.

SWOV aims to make a substantial and identifiable contribution to the improvement of road safety during the transition to higher levels of automation through research on these topics.

Other important new risks that are not within SWOV's specific expertise, but also of interest for the safety in the transition to higher levels of automation are: system errors, cyber security, protection of data and privacy, ethical issues, legislation and legal liability.

Contents

1. Introduction

1.1. Securing road safety

For a safe traffic system, it is important to look at the whole system of human, vehicle and road and a good interaction between them. It is also important to look at the whole 'accident chain': from the occurrence of crashes to limiting the injury severity in crashes (see *Figure 1*).

For the development of new measures, it is important to learn from the current unsafe situations and see how these can be prevented in the future. It is also important to look at the future developments and their potential effects on road safety. There are three main social trends that will affect traffic in the coming decades. These are:
1. the increasing **automation** and application of increasingly sophisticated, more intelligent information technologies in vehicles, between vehicles and between vehicles and infrastructure;
2. the further **ageing** of society and at the same time, the changing mobility needs of physically vulnerable elderly; and
3. the ongoing **urbanization** in the Netherlands with the need for cleaner, quieter and healthier modes of transport, which ask for a safe integration in urban accessibility.

Prevent crash .... Limit crash impact

| Macro factors | Traffic system | High risk situations | High risk groups | High risk behaviour | Near-crash | Crash | Limit injury | Injury treatment |

Figure 1. *Chain approach road safety.*

1.2. The automation of the traffic system

The increasing automation concerns the vehicle as well as the road and traffic management. It intervenes with many elements of the crash chain (*Figure 1*). Automation can prevent (near) crashes and limit injury. It can also be used to prevent crashes, to reduce risky behaviour, provide support for high risk groups or high risk situations. Automation is closely connected with the other two trends; automation offers opportunities for keeping the elderly longer mobile and for developing new concepts for urban transport. It is expected that Intelligent Transport Systems (ITS) will play an increasingly prominent role in the future traffic-and-transport system. This also has consequences for the number of casualties in road crashes. The latest forecast is that by 2020 developments in the field of vehicle automation and driver support could result in an annual decrease of 10 road deaths and 300

serious road injuries in the Netherlands alone (Weijermars et al., 2015). The forecast for 2030 is that the decrease will be about ten times higher, for the Netherlands this would mean a possible reduction of 90 road deaths and 3300 serious road injuries per year. This estimate does not yet include the effect of electronic stability control, which is expected to reduce the number of road deaths by approximately 10 per year and the number of serious traffic injuries by 100 per year, for 2020 as well as for 2030.

1.3. Securing road safety during the automation of the traffic system

This report discusses the transition from the current traffic system to a system with self-driving vehicles in relation with new opportunities and new risks for road safety.

Chapter 2 discusses which developments are expected in connection with automation of the traffic system and when these are expected. We will first look at long-term scenarios for what the traffic and transport system of the future may look like. Then we will look at the transition phase, the 'transition towards the self-driving car'. Step by step new systems will be introduced during the transition phase; this will result in a gradual increase in the level of automation of the entire traffic system. Based on 'roadmaps' we will discuss which systems are to be expected at which point in time.

Chapter 3 discusses what these developments mean for road safety. The developments offer new opportunities to make traffic safer, more efficient and cleaner, but also bring new risks. To secure road safety during and after the transition, it is important to make use of the opportunities for greater safety and to identify potential new risks and limit these.

On the basis of the identified hazards, in *Chapter 4* we present a research agenda for securing road safety during the transition towards the self-driving car. We will specifically discuss the research SWOV aims to perform as a contribution.

2. Which developments are to be expected?

2.1. Scenarios for the future

To gain insight into the long-term developments in transport we looked at scenarios for the future. Future scenarios indicate what traffic may be like in the future based on relevant developments that are expected in, among others, technology and society.

A very recent study by the Netherlands Institute for Transport Policy Analysis (KiM) describes four scenarios for the future traffic and transport systems (Tillema et al., 2015). These scenarios are determined by two uncertainties that are decisive for the development of the traffic system:

- the level of automation, and
- the extent to which car ownership and car journeys are shared.

These two uncertainties lead to four scenarios that are shown in *Figure 2*, with the level of automation on a horizontal axis and the degree of sharing on the vertical axis.
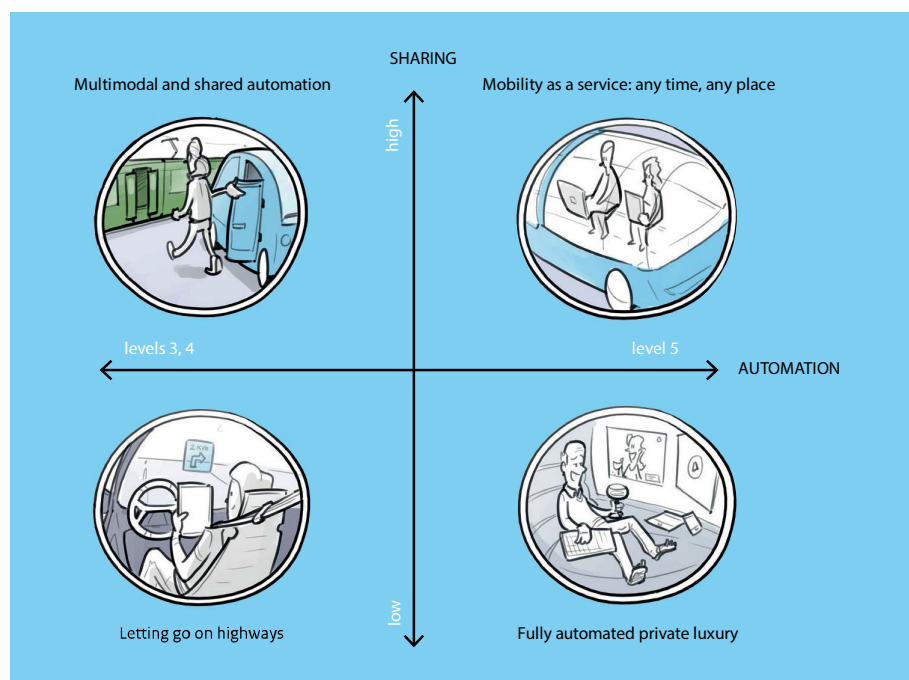
Figure 2. *The future traffic and transport scenarios of the Netherlands Institute for Transport Policy Analysis (Tillema et al., 2015) by the extent of sharing (vertical axis) and the level of automation (horizontal axis).*

The first uncertainty is the level of automation – the horizontal axis in *Figure 2*. The left end of the axis indicates 'conditional' automation: there is a certain degree of automation where the driver acts as a 'backup' during the entire journey or parts of the journey. The right end of the axis indicates full automation, in which the car is fully automatic at all times and places. The

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horizontal axis is based on the automation levels as defined by SAE and which are described in *Section 2.3* of this report.

The extent to which car ownership and car journeys are shared is the second uncertainty – the vertical axis of *Figure 2*. One end of the axis represents a high degree of car sharing and the other end a low degree. Sharing can be done in two ways: sharing a car or sharing a ride. When a ride is shared, more than one occupant share a car for a specific (part of a) ride.

The four scenarios distinguished by KiM (Tillema et al., 2015) are:
1. **Mobility as a service: anywhere, anytime.** There is a high degree of automation and of car sharing. Persons are transported with automatic 'taxibots', that park outside the city boundaries. There is no traditional public transport more, but there is a flourishing share economy. Walking and cycling are also popular.
2. **Fully automated, private and luxurious**. There is a high degree of automation: 'platoons' on the motorway in which trucks are connected by the wireless network, drive in convoy drive, and have no driver and possibly not even a cabin. There is a low degree of car sharing. Private cars are also 'fully connected' and, for example, no longer have a steering wheel. For people who do not have a car, there is a special transport system instead of the traditional public transport system.
3. **Hands-free on the motorway**. In this scenario, there is a limited degree of automation and a low degree of car sharing. Automatic driving occurs mainly on the motorway, because the technology is not sufficiently developed to enable automated driving in the urban environment. On the motorway trucks drive in platoons and in the urban environment drivers are supported by systems, but they still need to drive the vehicle themselves.
4. **Multimodal and shared automation**. A high degree of car sharing and ride sharing and a limited degree of automation: automated driving on motorways, but fully automated driving is absolutely impossible. This is due to too little support on the one hand, and, on the other hand, because the technology is not developed sufficiently.

In a traffic and transport system with a low(er) level of automation (scenarios 3 and 4; Tillema et al., 2015) automated driving is possible on the motorway, but in an urban environment drivers still need to drive the car themselves. They are supported in this. For example, drivers are alerted if cyclists or other cars come too close and the a system intervenes in near-crash situations (e.g. an emergency stop) and the car could park itself.

In a traffic and transport system in which there is a high degree of car and ride sharing (scenarios 1 and 4), travellers will make use of an ICT application that helps them choose the most efficient journey (Tillema et al., 2015; Van Voorst tot Voorst & Hoogerwerf, 2013). This digital travel assistant supports the traveller from the beginning to the end of the journey, especially in the scenario with much multimodal travel, from public transport (e.g. metro, train) and bicycle to the shared car. It will therefore be easy to combine between individual and collective transport.

In addition to KiM, Van Voorst tot Voorst & Hoogerwerf (2013) have also detailed a number of future scenarios for the traffic and transport system:

− **Transport on demand**: There are autonomous vehicles without drivers, there is more possession of one's own vehicle, but market parties offer transport services. When planning the journey a 'smart agent' is used which not only provides the planning, but also, for instance, the settlement of the costs.

− **Non-transport**: in this concept physical presence is no longer (always) necessary, but virtual meetings are often used instead. This scenario also has 'smart agent' which advises the user about the choice between a virtual or a physical encounter.

− **Limited transport**: mobility is reduced when it is harmful to public health or the environment. External costs are calculated by use.

Future mobility can be more efficient, cleaner and safer than it is today, and an important role is reserved for ITS (AutomotiveNL, Connekt & DITCM, 2012). There are all kinds of developments that are intended to make future mobility cleaner or safer or more efficient. Smart mobility solutions are needed for the increasing mobility and the accompanying challenges in the future. There are high expectations for the potential to improve the climate and road safety. Traffic management, information services and intelligent in-vehicle systems are combined to achieve a smart, safe and sustainable mobility (AutomotiveNL, Connekt & DITCM, 2012).

Faster and cheaper communication between the various systems will eventually result in self-driving vehicles. It would be better, argues for instance Van Arem (2010), if a car drives itself rather than being controlled by people. Both in routine acts and in critical situations the human being is not as infallible as the technique, for example in response time. Self-driving vehicles can also reduce congestion (Wallace & Silberg, 2012). Travel times can be more accurately determined in advance. And if travel times are shorter because there are fewer traffic jams, the available work and holiday time will be used more efficiently (Wallace & Silberg, 2012). Automation also offers opportunities for energy efficiency. The energy consumption can drop because vehicles get lighter and more energy-efficient, driving can be more efficient, and the route choice and use of the road network may be more efficient. The greater safety and reduced congestion can result in considerable economic savings.

2.2.   **The transition towards self-driving vehicles**

The transition towards self-driving vehicles is already in full swing and will gradually develop further. Step by step new intelligent systems and services are introduced and an increasing number of systems is are already available on the market.

Advanced Driver Assistance Systems (ADAS), support drivers in their driving task, e.g. by keeping a safe distance to the vehicle ahead or the prevention of crashes with vulnerable road users (AutomotiveNL, Connekt & DITCM, 2012). Also for traffic management various systems have already been or are being developed, such as dynamic speed limits, travel time information, incident management and strategic traffic management. *Figure 3* indicates several systems in various phases in the crash chain that can improve road safety: from preventing crashes to reducing injury.
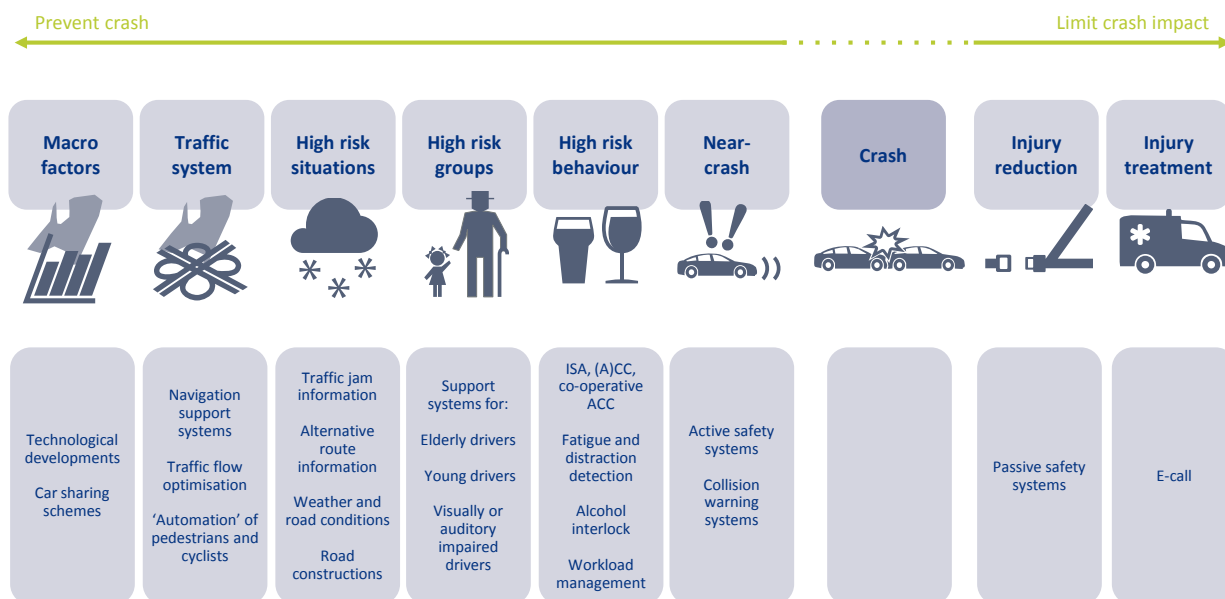
Macro factors	Traffic system	High risk situations	High risk groups	High risk behaviour	Near-crash	Crash	Injury reduction	Injury treatment
Technological developments Car sharing schemes	Navigation support systems Traffic flow optimisation 'Automation' of pedestrians and cyclists	Traffic jam information Alternative route information Weather and road conditions Road constructions	Support systems for: Elderly drivers Young drivers Visually or auditory impaired drivers	ISA, (A)CC, co-operative ACC Fatigue and distraction detection Alcohol interlock Workload management	Active safety systems Collision warning systems		Passive safety systems	E-call

Figure 3. *Systems that improve road safety by reducing the risk in various phases of the crash chain.*

An increasing level of automation of the vehicle changes the role of man as the 'driver' of the vehicle. The role of the driver gradually changes to that of 'supervisor', and finally to that of 'operator' or even passenger. During the transition phase, it is important that new systems are in line with the physical and mental possibilities and limitations of man as driver.

Another important point is the role of pedestrians and cyclists in the future traffic system. The pictures of the future have so far paid little attention to this, even though the number of traffic fatalities and injuries among cyclists increases (Duivenvoorden et al., 2015).

Is there a need for (partially) self-driving cars?
The drivers' needs also seem to change. The rise of the smartphone, tablets, and social media has stimulated paying more and more attention for these activities. This is hard to combine with a (long-lasting) driving task in which one must constantly pay attention. This creates a need for not having to control a vehicle continuously and for long stretches of time. A questionnaire study by Kyriakidis, Happee & De Winter (2014) concluded that people find fully automated driving easier than manual or partially automated driving, but they seem to feel uncomfortable (yet) with the idea that a fully automatic vehicle will no longer have a steering wheel. Subjects seemed to be positive about being able to carry out side tasks (Kyriakidis, Happee & De Winter, 2014; Kauer et al., 2015). In addition to a 'need' to carry out secondary activities, further automation of the driving task or (partially) self-driving vehicles could also meet the need for support. It would increase the mobility of people with disabilities including elderly. Good mobility makes a substantial contribution to the quality of life.

2.3. **Levels of automation**

Most future scenarios assume that the transition towards self-driving vehicles will be gradual: an evolution. There are also scenarios that assume a revolution in which large jumps are made in the developments, e.g. the fully self-driving car driving on public roads within a few years. Whatever the case

may be, during the transition phase there will be different levels of automation. In order to create clarity about the different levels of automation SAE International (SAE, 2014) has drawn up definitions as shown in *Figure 4*; this is a common and much-used division into six levels:

- *Level 0*: no automation. The driver can be assisted by warning systems.
- *Level 1*: driver assistance. The driver is assisted in steering, accelerating or braking.
- *Level 2*: partial automation. In specific driving conditions steering and/or accelerating/decelerating is automated. The driver carries out all other dynamic tasks and can overrule the system.
- *Level 3*: conditional automation. In specific driving conditions the vehicle is fully driven by the system; the system reverts to the driver for certain interventions.
- *Level 4*: high level of automation. Similar to level 3, the difference being that the system does not need to revert to the driver.
- *Level 5*: full automation, in all driving conditions.

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	Monitoring of Driving Environment	Fallback Performance of Dynamic Driving Task	System Capability (Driving Modes)
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 Assistance	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* perform 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

Figure 4. *Levels of automation (SAE, 2014).*

2.4. Technological developments

2.4.1. *'Sensor-based' versus 'connectivity-based' technology*

There are developments in two important technologies that enable automation of the traffic system : 'sensor-based' and 'connectivity-based' technology (Timmer & Kool, 2014). Sensor-based technology is in fact what the current Google-car uses: sensors that observe the environment are used to take

over the driving task from the driver and the vehicle can move independently in the (current) traffic. Connectivity-based technology uses the wireless network to communicate real-time with other vehicles and with the infrastructure. Connectivity-based technology uses the wireless network to communicate real-time with other vehicles and with the infrastructure. *Figure 5* shows the different ways in which the technologies function.

Both technologies are in full development. Sensors are becoming smaller and smarter and allow better observation and understanding of the environment. To make connectivity-based systems possible there is consultation between car manufacturers and governments to agree on a joint protocol.

2.4.2. *Fusion of technologies*

By combining sensor-based and connectivity-based systems, the advantages of both technologies can be used and the restrictions are reduced (Wallace & Silberg, 2012). This so-called 'converged solution' (*Figure 5*) would be the strongest solution; it is likely to have the best performance, will require less expensive sensors and fewer vehicle-road side-investments, and has sufficient overlap so that in principle the system will always work.

Sensor-Based Solution Only
- Cannot sufficiently mimic human senses
- Not cost-effective for mass market adoption
- Lack of adequate 360° mapping of environment in urban grids

Connected Vehicle Solution Only
- DSRC does not currently work with pedestrians, bicyclists, etc.
- DSRC-based V2I might require significant infrastructure investment
- V2V requires high market penetration to deliver value reliably

Converged Solution
- Convergence will facilitate adequate mimicking of human senses
- Convergence will reduce need for an expensive mix of sensors and reduce the need for blanket V2I investment
- Convergence will provide the necessary level of functional redundancy to ensure that the technology will work 100 percent of the time
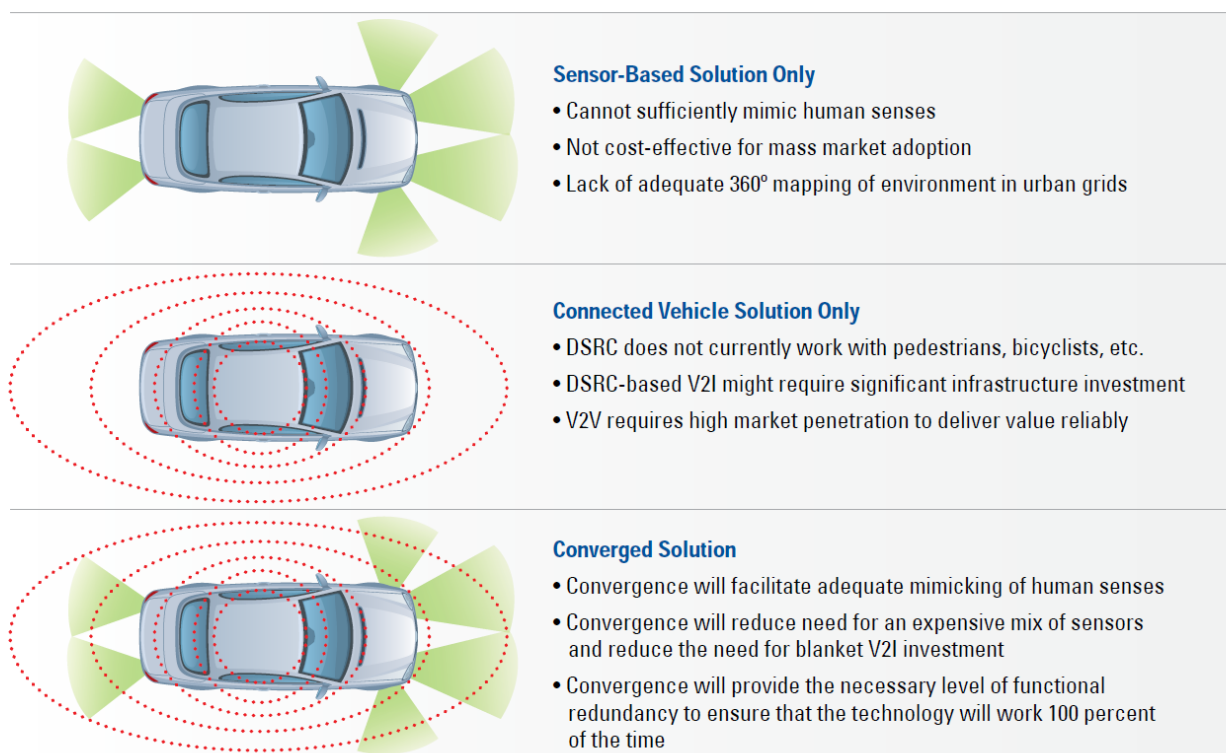
Figure 5. *Diagram of the operation of sensor-based and connectivity-based technology and the combination of these two technological developments (from Wallace & Silberg, 2012, Figure 5, p. 14). DSRC: Dedicated Short-Range Communication; V2V: 'vehicle to vehicle'; V2I: 'vehicle to infrastructure.*

2.5. Roadmaps for automation

The different steps in the automation of the traffic system and the expected developments in technology are presented in so-called roadmaps. The roadmaps developed by the European Road Transport Research Advisory Council (ERTRAC) in cooperation with the industry (EUCAR), two renowned umbrella organisations, are widely supported. These roadmaps provide a schematic representation of expected future developments. They provide insight in the expected timeline for the transition towards automated driving and make a forecast regarding the order in which the different systems are introduced.

ERTRAC has developed different roadmaps for passenger cars, commercial vehicles and public transport. In these roadmaps the different systems that are presently on the market and those yet to be developed are classified by the SAE-level of automation (first dimension). The second dimension is the timeline indicating when the systems are expected to be available in the market.

2.5.1. *Automation of passenger cars*
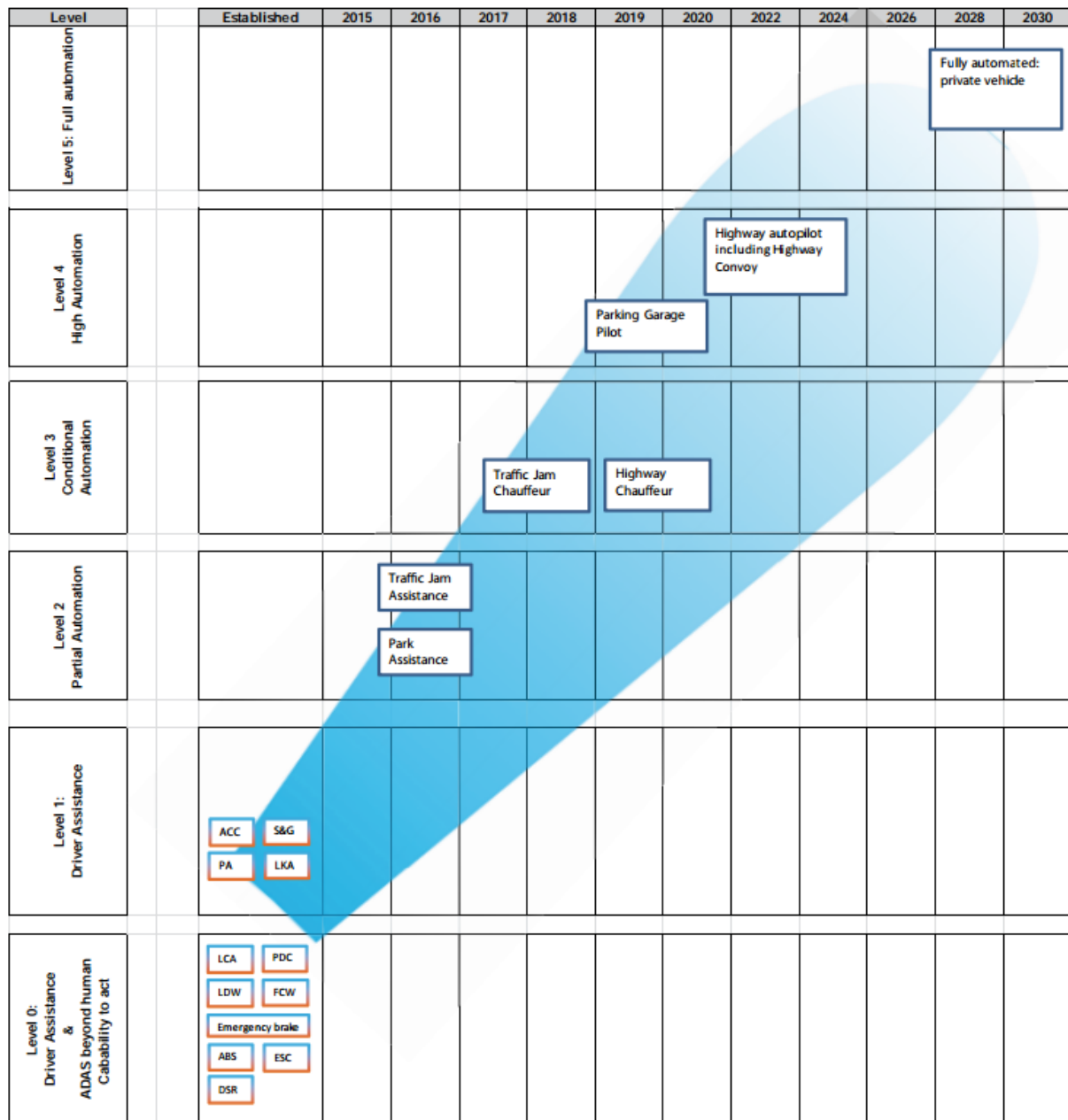
The roadmap for passenger cars is shown in *Figure 6.*

Level	Established	2015	2016	2017	2018	2019	2020	2022	2024	2026	2028	2030
Level 5: Full automation											Fully automated: private vehicle	
Level 4: High Automation						Parking Garage Pilot	Highway autopilot including Highway Convoy					
Level 3: Conditional Automation					Traffic Jam Chauffeur	Highway Chauffeur						
Level 2: Partial Automation				Traffic Jam Assistance / Park Assistance								
Level 1: Driver Assistance	ACC, S&G, PA, LKA											
Level 0: Driver Assistance & ADAS beyond human capability to act	LCA, PDC, LDW, FCW, Emergency brake, ABS, ESC, DSR											

Figure 6. *Roadmap for automation of passenger cars (ERTRAC, 2015).*

Level 0 focuses on systems that assist the driver by giving a warning, e.g. if a potential danger is nearby (Lane Change Assist), if the driver with his vehicle is getting close to objects (Park Distance Control), if the driver with his vehicle is unaware of leaving his lane (Lane Departure Warning) or if the driver with his vehicle is approaching the vehicle ahead (Front Collision Warning).

The systems in level 1 go a step further than just warning the driver. When using Adaptive Cruise Control (ACC) the driver sets the desired speed and distance to the vehicle ahead; ACC then keeps the distance to the vehicle ahead at that set value. A second example is Park Assist, in which the car itself parks and unparks by taking over steering from the driver while the driver operates the brake and accelerator. The Lane Keeping Assist corrects

the position of the vehicle if it nearly leaves the lane. Because this system only works at higher speeds, the driver is given a warning to take action himself at lower speeds.

Level 2 comprises systems that automate part of the driving task. Two examples are Park Assistance and Traffic Jam Assistance. When the driver uses Park Assistance the car drives in and out of the parking space automatically. The driver does not have to be inside the car, but he must constantly monitor the process and intervene if necessary. The Traffic Jam Assist is a function that controls the longitudinal and lateral position of the vehicle at low speeds.

The third level concerns conditional automation. On main roads the 'Traffic Jam Driver' can be switched on in traffic jams with speeds lower than 60 km/h. The system detects the vehicle ahead and controls the vehicle's longitudinal and lateral position. Once the system is activated, the driver does not need to monitor, but he can overrule the system or switch it off. The Highway Driver is a somewhat similar system, but can be used at speeds up to 130 km/h on main roads and even during overtaking, merging or exiting. The system can ask the driver to take back control of the vehicle.

At level 4, the systems have a high degree of automation. With the Highway Pilot vehicles drive automatically and they can drive in platoons, depending on co-operative systems that can communicate with other vehicles, the infrastructure and/or the traffic control centre. The Parking Garage Pilot drives the vehicle into and out of a parking space while the driver does not need to be inside the vehicle ('valet parking' without driver). After the system has been activated, the driver is not required to monitor the progress.

The highest level is fully automated driving where the driver no longer needs to do anything. The driver, however, can overrule or turn off the system at all times. Although in the roadmap the fully automated driving is indicated around 2030, there are some reservations. No realistic estimate can be made of when the fully automated driving system will actually be available (ERTRAC, 2015).

2.5.2. *Automation of commercial vehicles*

The automation developments are not limited to passenger transport. ITS applications like intelligent blind spot detection and signalling systems have been and will be developed for the professional transport sector also. There will also be more applications in the field of dynamic traffic management, such as parking guidance systems or systems aimed at promoting the traffic flow. Below some examples of systems for commercial vehicles are presented.

Many systems that were mentioned above for passenger cars, are also available for commercial vehicles, sometimes customized for commercial transport (see *Figure 7*). For example, a system specifically for commercial vehicles is C-ACC Platooning (level 1). This means that the vehicles drive in a small convoy, a 'train' or platoon, while they are linked through cooperative ACC. The system ensures sufficient distance to the vehicle ahead; the driver is responsible for the other parts of the driving task. 'Truck platooning' is

another example of a system specifically for commercial transport. The vehicles drive in convoy and can thereby save fuel (level 3).
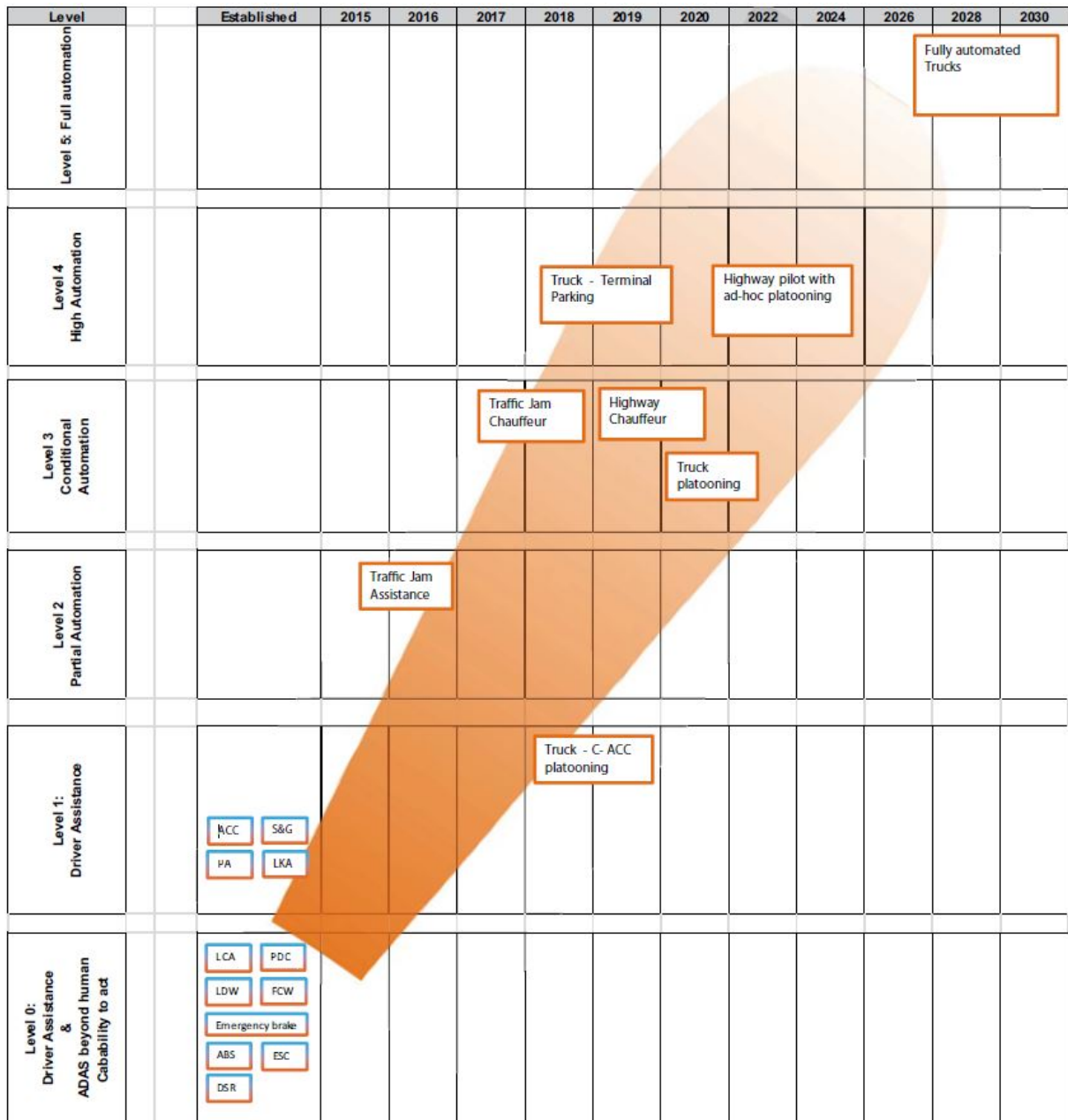

Figure 7. *Roadmap for the automation of commercial vehicles (ERTRAC, 2015)*.

2.5.3. *Automation of public transport*

Also for public transport developments are ongoing. *Figure 8* shows that these devopments mainly concern the higher levels of automation. There are two types of transport concepts: 'cybercars' for individual transport, and automated buses or Personal Rapid Transit (PRT) for the transport of smaller and larger groups.

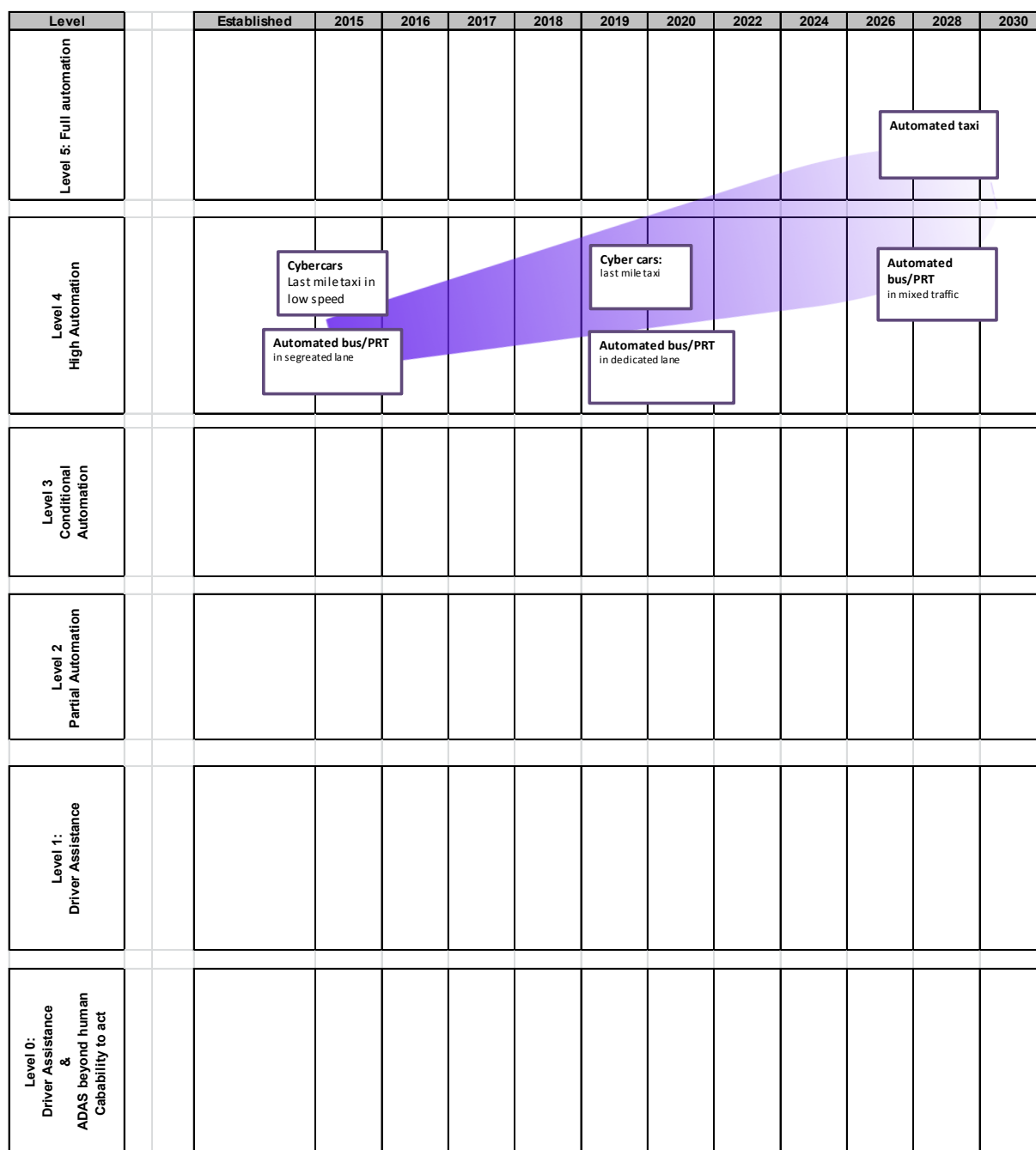| Level		Established	2015	2016	2017	2018	2019	2020	2022	2024	2026	2028	2030
Level 5: Full automation											**Automated taxi**		
Level 4 High Automation			**Cybercars** Last mile taxi in low speed / **Automated bus/PRT** in segreated lane				**Cyber cars:** last mile taxi / **Automated bus/PRT** in dedicated lane				**Automated bus/PRT** in mixed traffic		
Level 3 Conditional Automation													
Level 2 Partial Automation													
Level 1: Driver Assistance													
Level 0: Driver Assistance & ADAS beyond human Cabability to act													

Figure 8. *Roadmap for the automation of public transport (ERTRAC, 2015)*.

2.6. The development cycle of a new system

Every system that is included in the roadmaps will go through a development process before it is placed on the market. This usually starts with the development of a technology, followed by product development via testing in a laboratory environment, to testing on a closed road and finally testing on public roads. When the system is fully developed it can be marketed. This development process is shown schematically in *Figure 9*.
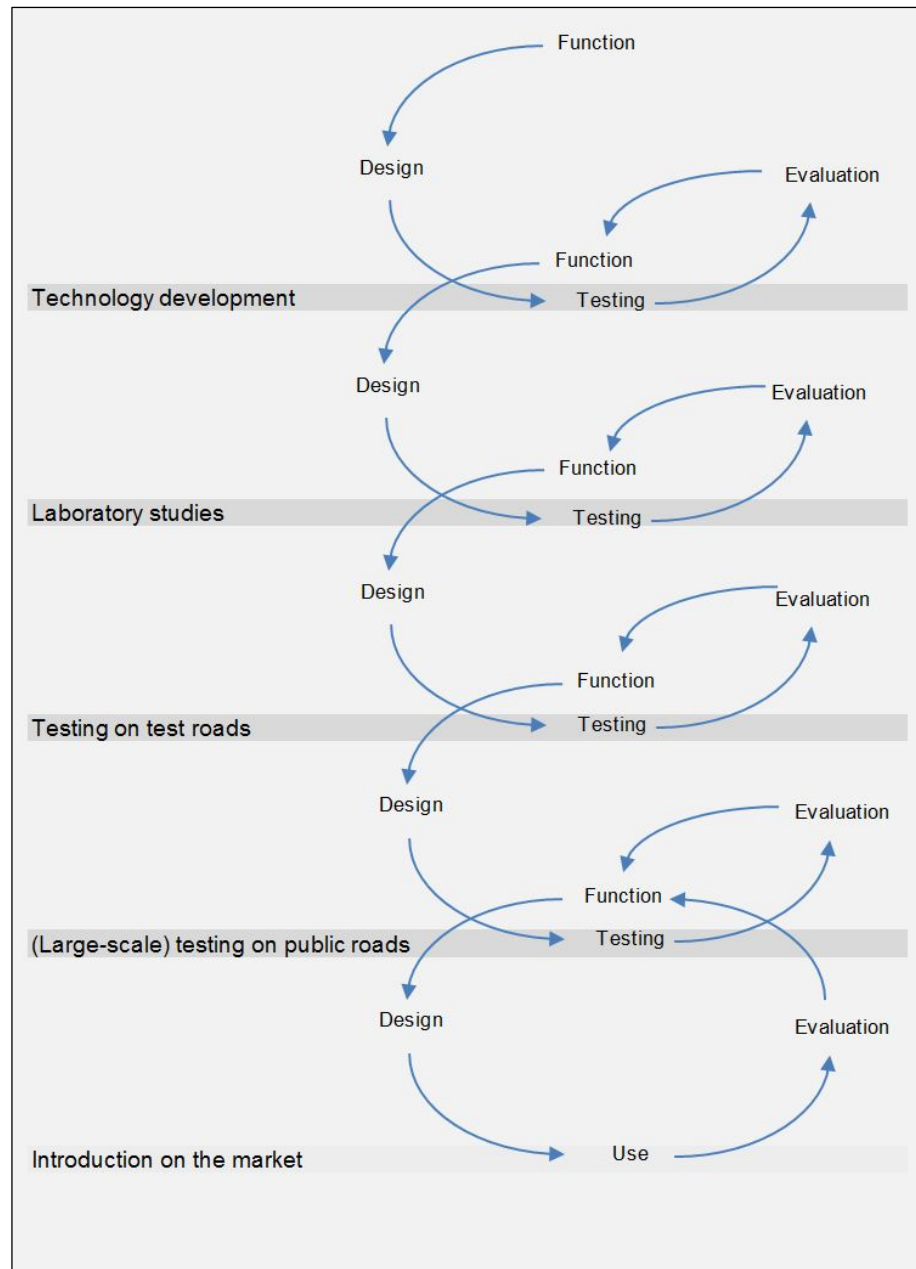

Figure 9. *Diagram of product development and testing new systems.*

Many systems are first introduced for the more expensive vehicle models, and later also for the other models. Thus, the new technologies gradually find their way into traffic while the fleet of vehicles is replaced. Aftermarket

systems that can be installed in a vehicle outside the factory, can significantly accelerate the penetration of new systems on the road.

2.7. Transition: safety is crucial

The transition towards an automated traffic system and the pace at which this happens, will not only be determined by technological developments such as presented in the roadmaps (Section 2.5). As automation does not only bring new opportunities, but also new risks, the safety aspect is also crucial for (the pace of) the transition. Each step must be taken in a responsible and the safest possible way, so that (serious) crashes are prevented as much as possible. It is important that new systems are sufficiently safe and that the foreseen and unforeseen effects are observed.

Safety is crucial to the pace of the transition. Safety is also an important factor in social acceptance, which is also crucial for the pace of the transition. If serious crashes involving automated vehicles occur, this could reduce the acceptance and slow down the pace of the introduction. Especially when such crashes get much media attention. This will not only greatly affect the social acceptance of automation, but also the political support and therewith delay the necessary development of legislation and liability.

The next chapter will take a closer look at the possible consequences for road safety and other social consequences.

3. What does this mean for road safety?

The various systems that are becoming available in vehicles not only provide opportunities to improve road safety but also bring new risks. The new technology can fail and it is, for example, uncertain whether the driver always understands the technology and uses it as intended. It is therefore important to secure the safety of the entire traffic system during the transition to higher levels of automation.

Whereas the previous chapter mainly discussed the new possibilities, this chapter will discuss the new risks that may arise from the introduction of new systems in the transition towards higher levels of automation. *Figure 10* gives an overview of the various factors that could play a role in the framework of the chain approach. In the sections below, the various factors are explained, from near-crash to macro factors.
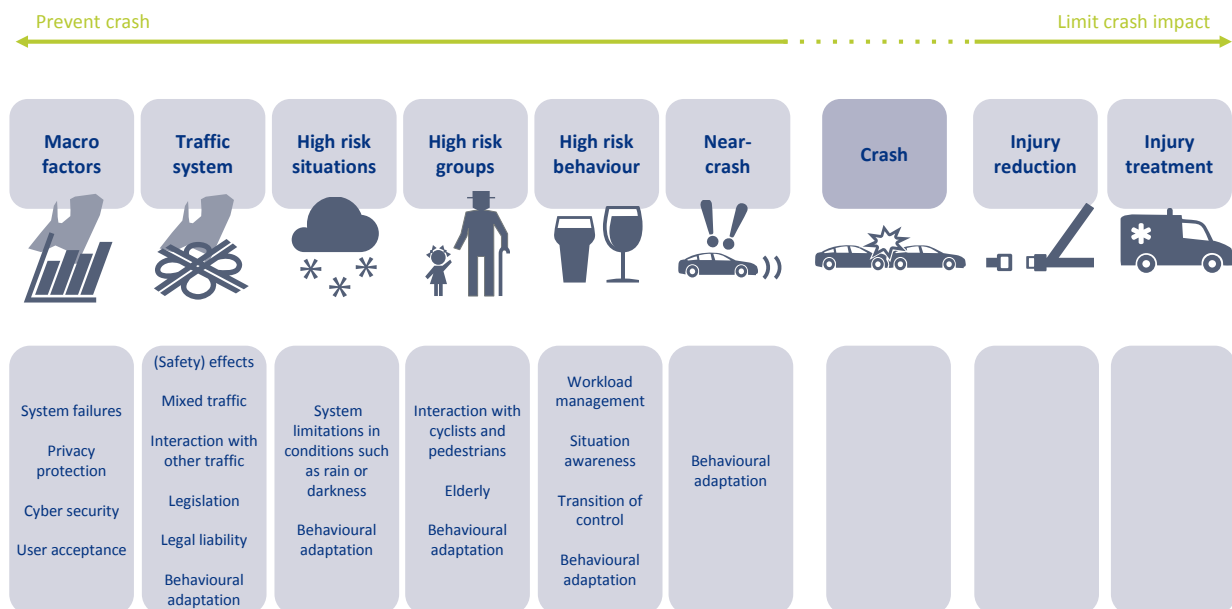

Figure 10. *Overview of new risks that may arise with the introduction of new systems.*

3.1. Behavioural adaptation

New systems often lead to a form of behavioural change. Behavioural adaptation means that the driver adjusts his behaviour to the new (driver assistance) technology. This can result in the intended safety effect being reduced, sometimes being annihilated wiped out, or even the opposite effect. If the opposite effect is attained, for example when a driver over-relies on a system and does not pay sufficient attention anymore, this is known as rebound effect.

An example of behavioural adaptation is that drivers adjust their driving habits when they have a Lane Departure Warning system (LDW) installed. The

driver is confident he will get a warning when necessary and therefore takes more freedom to perform secondary tasks which increases the risk. Another form of behavioural adaptation seems to occur after platoon-driving. Simulator studies, for example, have shown that drivers who have driven in a platoon – with short headway distances –, persist in short headway distances after having left the platoon (Skottke et al, 2014).

Behavioural adaptation can play a role at all levels of interaction: interaction of the driver with the new technology, interaction of the (partially) automated vehicles with other (vulnerable) road users, and interaction with smart infrastructure. When designing new systems, it is necessary to anticipate behavioural adaptation to prevent negative safety effects as much as possible. Also in the evaluation of the effect of new systems, possible behavioural adaptation must be considered.

3.2. Workload management

Gradually, an increasing number of driver support systems will become available during the transition to partially or fully autonomous vehicles. Initially these will be systems that warn the driver in specific situations. In this phase it is important that information is prioritized, to avoid distraction by less important signals. In this way it can be prevented that the workload gets too high and the risk of errors increases (Cantin et al., 2009). Furthermore, it is important that the warning is given in the right manner. Depending on the situation, the driver can be warned by an auditory signal, a visual signal, a haptic signal (such as a vibration of handlebars or seat), or a combination of signals.

During the transition period, the driving task will be taken over step by step, until the task is taken over completely during (part of) the journey. We know that driving a car is primarily a mental task (Gabaude et al., 2012). This means that partially taking over task leads to a reduction in the driver's task load (Timmer et al., 2013). When the task load is too low, the performance goes down and the risk consequently goes up (De Waard, 1996). Because the driving task will change from driver to 'supervisor', the task load will also reduce. It is therefore important to examine the effects of this task load reduction on the execution of the driving task, and on road safety.

Although the purpose of automation is to facilitate the driving task, it paradoxically also sets requirements that people do generally not meet well. A few decades ago, Bainbridge (1983) already wrote the article '*The irony of the automation*' in which he states that people are going to make more errors through automation. After all, people may lose certain skills through automation and may be less careful if they only have to pay attention to devices that nearly always function well.

3.3. Transition of control, situation awareness and hazard perception

If vehicles can drive autonomously, for full trips or (part of) the trip, the driver will be able to do other things while traveling (Wallace & Silberg, 2012), such as working, sleeping, reading or making phone calls. Until the vehicles are fully autonomous, the driver must at some point during the journey surrender the driving task to the vehicle and take it back. This is also known as 'transition of control'. If the driving task is passed to the vehicle, the driver can temporarily

'get out of the loop'; when the driver takes over the driving task again he must 'get back into the loop'. These are challenging processes. After having been 'out of the loop' the situational awareness (awareness of what is going on around you going on) must be rebuilt. This takes time. The temporarily limited situational awareness leads to, among others, less effective hazard perception and anticipation. Endsley & Kaber (1999) showed that highly automated system are responsible for people to some extent losing their situation awareness. Vlakveld et al. (2015) and Wright et al. (2016) investigated the time needed to build up situational awareness and to identify potential hazards and concluded that the hazard perception performance is much better with a take-over time of 6 seconds than 4 seconds.
In the case of partial automation people often find it difficult to understand the boundaries of the system, making it difficult to intervene in good time if necessary.

A recent literature review (Vlakveld, 2015) shows that little is yet known about how well and quickly the driver can take back the operational driving task and about the time required rebuild the 'situation awareness' and to perceive (latent) hazards. Another question is how the driver can best be assisted in this.

3.4. Interaction between the elderly and new technology

New systems can keep the elderly and the disabled mobile longer. This is a great contribution to the mobility and therewith independence of these groups. On the other hand, here the new technology also brings challenges. The elderly in particular may have problems understanding and using the new systems. It is important to take into account the comprehensibility for all users in the development of the systems.

Interpersonal differences
It would be good to tailor support systems to the user as much as possible and to cater for interpersonal differences. To this end, one could consider to tailor systems to certain groups, such as elderly or younger drivers, or to make systems adaptive. The system can for example be designed to (automatically) adjust to the preference of a driver, for example a smooth or rather a sportive driving style based on continuously monitoring of the driving style. The more a system is tailored to the personal needs and style, the greater the acceptance, and the (safety) effect can also be greater.

3.5. Interaction with vulnerable road users

Several pictures of future traffic systems assume a large degree of urbanization, which will cause many different types of traffic to mix. It is crucial in the development of new systems to take into account the interaction between (partially) automated cars and vulnerable road users such as pedestrians, cyclists and motorcyclists. It is important that (partially) automated vehicles recognize vulnerable road users and predict their intentions and behaviour to be able to anticipate (Vissers et al., 2016). It is at least as important that the behaviour of the (partially) automated vehicles is understandable and predictable for the vulnerable road users. The infrastructural design is also important; clarity about the designated place on the road for all modes of transport and about the locations where they can interact is very important.

The intelligent bicycle

Following the ITS applications for vehicles and the infrastructure, a next challenge is to also develop ITS applications for bicycles. The bicycle is an increasingly used mode of transport in cities around the globe. Over the past years an increasing numbers of pedelecs and speed pedelecs have entered the roads and their number is expected to increase further in coming years. Pedelecs offer more possibilities for the implementation of ITS systems than regular bikes as they already are powered. ITS on bikes offers plenty of opportunities, e.g. 'connectivity' (communication between vehicles) offers the possibility to increase the virtual visibility of cyclists for drivers, and as a result increases their safety, especially in low visibility conditions.

Powered two-wheelers

The question is which developments are to be expected regarding ITS on powered two-wheelers. The safety of motorcycles and scooters could also increase if they could communicate with other vehicles and with the infrastructure. This offers opportunities to improve their (virtual) visibility for other road users.

3.6. Mixed traffic

In the transition towards the self-driving car we have to deal with so-called 'mixed traffic', this refers to a traffic system in which vehicles with different levels of automation drive simultaneously. This can be confusing and risky because road users will not know to what extent another vehicle is automated, and what behaviour is therefore to be expected, and how they must anticipate and interact.

For the effect of some systems the penetration rate – the percentage of vehicles or roads that is equipped with a system – is relevant to achieve the intended effect. Especially for cooperative systems, the quality of the system depends on the number of cars and/or roads that are equipped with this technology. Many cooperative systems are only effective if sufficient cars (or infrastructure) are equipped with that system . A 'critical mass' needs to be attained. It will require some time to achieve this critical mass. The vehicle fleet is gradually replaced and will gradually include a greater number of (more) intelligent vehicles (Sivak & Schoettle, 2015). This makes the introduction of new systems difficult, because the user cannot take advantage of the functionality until sufficient other road users also have it. The safety effect of such systems also depends on their penetration rate.

Interaction with non-users

When a share of the road users do have a particular system, and another share do not, this could affect the safety of road users. A system such as ACC or LDW influences the behaviour of the vehicle. During the transition road users do not know which systems other vehicles are equipped with and what behaviour to expect.

3.7. Legislation and legal liability

The developments towards self-driving vehicles brings forward the new issue of who is legally 'the driver' if the vehicle has (partially) taken over the driving task. Another legal issue is the liability in case of damage or injury when the traffic system is (partially) automated. In addition, the law must – to

begin with – permit the future vehicles with their technology on public roads. This permission is crucial for the pace of the transition and is in the hands of the legislators in individual countries, continents and worldwide. Cross-border traffic could be troublesome if the transition legislation between countries is not synchronous or if different technologies are used that do not work together. Therefore, it is important to cooperate between states, between countries and at the global level.

3.8. Acceptance

Acceptance is crucial to the pace of the transition to higher levels of automation. This concerns not only acceptance by the users and the general public, but also the political support among Ministers and (public) bodies that are responsible for changing legislation and permitting (partially) automated vehicles on public roads.

Subjective safety plays a role in this acceptance: a system can be safe, but can be experienced as being unsafe or vice versa. In addition, serious (but also less serious) incidents with the new technology in its early days can affect the acceptance and slow down or even stop the acceptance process. This not only applies to the testing phases, but also to the actual introduction.

3.9. Ethical issues

In the transition to higher levels of automation ethical issues also play a role. According to Timmer et al. (2013) ethically tricky considerations will need to be made, for example in the programming of the software.

An example is programming an avoidance manoeuvre and the priorities that may possibly need to be set. The choice may need to be made in favour of one or another, between the own safety or that of another road user, or between the one or the other road user. Such ethical dilemmas should be technologically avoided. Any injury should be prevented by tuning the speed to the situation and secure sufficient stopping distance.

The political and societal support, but also the acceptance of new systems will play a role in this type of ethical issues and, vice versa, the ethical discussion will influence the political and societal support.

3.10. Quality assurance: system errors and cyber security

Security will also be a challenge in a (partially) automated traffic system. It must be prevented that unauthorized parties have access to the system and could abuse it, resulting in possible threats to the safety of its users. The systems can be designed in such a way, that information is collected by the manufacturers, for example the locations where the car drives, how fast it goes et cetera. This data could be of great value, but is also vulnerable for misuse. Additionally, more sources than just the road administration are available for traffic information. The law will need to be adapted to allow the collecting and using traffic data. Standards should be designed for an accessible and reliable supply of traffic information (Timmer et al., 2013).

With the increasing automation much more data will be available to monitor and regulate the traffic flows. For the security of the system it is very important to prevent system errors. There must be serious attention for the quality of available software and products (Timmer et al., 2013). That quality, for instance good security of the control of the vehicle, must be guaranteed. Considerations will need to be made about the conditions under which systems and services can be brought on the market and which parties have the legal liability.

3.11. Protection of data and privacy

The large amount of data to monitor and regulate the traffic flows contains privacy-sensitive information; they indicate who is or was where at what time. It is important that the privacy of the individual is protected,that this data is properly secured and is not used for other purposes. Insufficient protection of privacy could affect the acceptance, but it could also cause delay in bringing these technologies on the market because they do not meet the law or other requirements (Timmer et al., 2013).

4. Research challenges

The previous chapter provides an overview of the main new risks that have been identified for the transition towards higher levels of automation of the traffic system. That overview is not exhaustive and progressive insight or developments may also bring additional risks. To ensure road safety in the future, it is important to carry out scientifically correct and practically applicable research to continue to identify new risks and to develop new knowledge to limit or prevent the risks with appropriate designs and measures.

This chapter presents a research agenda indicating the most relevant research topics to ensure a safe and smooth transition. The agenda focuses on risks related to infrastructure, behaviour, and the interaction between man, vehicle and road. This concerns the following risk factors: task load, transition of control, situation awareness and hazard perception, elderly, interaction with other road users, interaction with vulnerable road users, acceptance, mixed traffic, smart infrastructure and behavioural adaptation.

The remaining risk areas are as important but not within the SWOV's specific expertise. We encourage other (research) organisations that have expertise in these areas to take these topics further: system errors, cyber security, protection of data and privacy, ethical issues, legislation and legal liability.

The research topics mentioned above can be clustered into three groups:
1. interaction of the driver with the new technology in the vehicle;
2. interaction of (partially) automated vehicles with other traffic;
3. smart infrastructure and traffic system.

To study those research areas in breadth and in depth, it is necessary to use different research methods that complement one another, such as driving simulators, instrumented vehicles, Naturalistic Driving data, in-depth research, instrumented bicycles, and microsimulation models. Additionally, the development and testing of new systems requires field trials with (partially) self-driving vehicles.

4.1. Interaction of the driver with the new technology

It is important to develop knowledge about the impact of systems on the driving task and the road safety consequences. The introduction of new systems and the higher levels of automation influence the drivers' task load, the situational awareness and the degree of hazard perception. With increasing automation, it is important to ensure that the drivers' task load is neither too low, nor too high, so that their performance, and thus safety, is optimal. Also the transition of control between vehicle and driver in partly automated vehicles are a challenge.

Below we present a number of concrete ideas for relevant and feasible research in this area are presented. The list is certainly not exhaustive. On the basis of progressive insight and in cooperation with other parties these ideas can be developed further.

Task load

Simulator research has already shown that drivers take more risks when the driving task is automated to a large extent (Skottke et al., 2014). In a literature study into the behaviour of drivers in largely but not yet fully automated vehicles, De Winter et al. (2014) conclude that although automation releases mental capacity, the drivers' attention for the driving task lessens and drivers pay less attention to the traffic.

It has not yet been thoroughly investigated how the task load can be measured in the real traffic. There is also still limited understanding of the range of the optimal task load, if and how drivers regulate this themselves and how the car could regulate this. It is important to acquire a better understanding of this to ensure road safety during the transition to further automation. It is important to perform research into the changing task and task load of drivers due to the introduction of new systems and into ways to manage this task load during the transition.

Currently, SWOV is doing research into the physiological measuring of the task load while driving. This research offers insight into the variation of the task load while driving in different situations. The next step is to take this further and develop a proxy for task load in Naturalistic Driving data. Naturalistic Driving-data could provide insight in the natural behaviour and reveal if and how the task load varies, whether it is levelled within certain limits (self-regulation), and if so, how the driver does this and what those limits are.

Follow-up questions are:
1. Which parts of the driving task contribute more and less to the total task load?
2. When part of the driving task is taken over, how do you ensure that the driver's task load is within the optimal performance window? (not too high or too low)
3. When the task load is too low but the driver must remain alert, how do you ensure that he will not perform activities other than driving task-related ones?

Transition of control, situation awareness and hazard perception

It is expected that initially only parts of the car journey will be automated before the entire journey can be made in automated mode. The question is how the hand over from automated to manual driving (transition of control) can best be carried out from the road safety and HMI point of view. It is not yet known how capable drivers are in hazard perception immediately after they take back control and operation of the vehicle. Horswill & McKenna (2004) define hazard perception as situational awareness for potentially dangerous situations in the road and traffic environment. Endsley (1995) defines situational awareness as being able to perceive and understand the existing situation and being able to predict how potentially dangerous situations may develop into real dangers. In this case hazard perception is being able to detect and recognize potentially dangerous situations, and predict how these potential hazards can develop into situations in which a crash can no longer be avoided.

SWOV has expertise in hazard perception research. Recently, research has been done into how well drivers perceive dangers directly after having taken

over the driving task from an independently driving car. The analyses show that after transition significantly fewer potential hazards are identified (Vlakveld et al., 2015). It was also found that the ability to perceive dangers after transition shows the strongest decreases at hazards that are harder to spot. The follow-up research now conducts a simulator study in which the driver has to take over the driving task again after a period of automated driving. This study examined whether drivers observe the latent hazards in the traffic environment and also how well they perform on the driving task.

To gain further insight in how the transition from automated to manual driving can be carried out safely, the following questions need to be answered in future research:
1. How much time does the driver needed to get back 'in the loop'?
2. What determines the amount of time the driver needs to get back 'in the loop'?
3. What determines the extent to which someone is able to perceive potential hazards after having been 'out of the loop'?
4. Are there conditions (road and traffic environment) in which the transition from automatic to manual happens faster or better? How can this be done smoothly and fast?
5. How can the system best guide a driver in fully taking back the driving task as quickly as possible?

The elderly
For the elderly automation is of particular importance as it creates possibilities to remain mobile longer. At the same time, especially for the elderly, automation also brings new risks. The question is whether the elderly understand the new technology. This results in two research questions:
1. How can the elderly be supported in the driving task so that they remain mobile longer?
   As ageing increases the society has to deal with a larger group of elderly people. It is of individual and social importance to keep these elderly people (auto) mobile as long as possible. We also know that age comes with physical limitations, such as for example a longer response time and stiffness of the body. It is important to take the specific needs and limitations of the elderly as a starting point to see how ITS systems could support them to remain mobile longer. Which tasks do they especially need to be supported in and how could systems help them? This research should lead to the formulation of specific requirements for the elderly and design solutions tailored to their needs.
2. Are the new systems that are being developed sufficiently suitable for the elderly? To what extent do these systems connect with the older road user? Can they be understood by the elderly?
   It seems that systems are often developed for and tested by the average driver. It is important that the systems are also tested by older people and are developed in such a way that they also benefit this specific group of drivers or in any case does not bother them. Misunderstanding and misuse of systems is a real risk for elderly. By evaluating different systems specifically for the elderly road users (in a driving simulator or with an instrumented car) guidelines can be developed for system designs for the elderly.

4.2.   Interaction with other road users

New in-vehicle systems change driving behaviour. The (partially) self-driving car will sometimes behave differently than we are used to. This can affect the behaviour of other road users as they may respond differently to certain behaviours. There is evidence that people take over the behaviour of the automated vehicles. A recent simulator study of Gouy et al. (2014) shows that the road users adjust the headway distance due to the presence of platoons. It is also possible that the behaviour of the automated vehicle is not understood correctly by the other road users or - the other way around – the automated vehicle is not able to 'understand' the behaviour of other road users.

Vulnerable road users
It is particularly important to do research into the safety of vulnerable road users in a traffic system with fully or partially autonomous vehicles and in the transition towards such a system. Important issues in the interaction with vulnerable road users to a large extent concern the implementation of the (partially) automated vehicle, such as the speed and the position on the road, and the interaction and communication with the vulnerable road user, such as the recognizability of the fact that the vehicle is (partially) self-driving and the predictability of the (partially) self-driving vehicle. Concerning the recognizability of (partially) self-driving vehicles, it is important to realize that this might be different in the initial phase, when the phenomenon is new, then in a later phase, when people are more accustomed to the presence of (partially) self-driving cars and have learned to predict their behaviour. In the later phases the (partially) self-driving cars should also be more used to the behaviour of vulnerable road users (Vissers et al., 2016).

Below some ideas for relevant and feasible research in this area are presented. This is certainly not an exhaustive list; on the basis of progressive insight and in cooperation with other parties these ideas can be developed further.

1. Analysis of crashes and near-crashes with cyclists and pedestrians on the basis of Naturalistic Driving data and on the basis of in-depth studies. This could provide insight in how the driver could be supported, for example by means of ITS systems, in the prevention of such crashes.
2. Analysis of the 'normal' interaction between the truck/car and cyclist/pedestrian in Naturalistic Driving-data. The most critical manoeuvres can be studied, such as the right turn in urban areas, and in particular to the viewing habits of the driver, use of the mirrors, task load of this manoeuvre, position of cyclists relative to the truck, distraction and whether the driver gets 'out of the loop' while waiting for a traffic light. These insights provide directions for if and how the driver can get supported better.
3. Experimental research into characteristics on which pedestrians and cyclists base their expectations about motorized traffic: presence, location, speed and intended manoeuvres. In experiments with manipulated conditions (in a driving simulator, on closed training areas or on public roads) it can be investigated which factors influence expectations. These insights can be used in the development of automatic systems.
4. Research into the developments in the field of ITS for vulnerable road users (pedestrians, cyclists, motorcyclists) to improve the safety of these modes of transport by means of active safety systems.

4.3. Smart infrastructure and effects on the traffic system

The infrastructure is getting smarter and cars will increasingly communicate with each other and with the infrastructure. The lifespan of infrastructure, however, is longer than that of cars. That is why it is important to see how the infrastructure can be prepared for the self-driving vehicles and the transition period.

1. Some ITS systems make certain infrastructural measures less important or unnecessary. For example, Lane Departure Warning systems reduce the need for rumbles strips to indicate that one is crossing the side marking. Given the developments in the field of automation, it is important to plan ahead for new infrastructure and to understand measures will remain important in the long term and what measures may be less important because ITS systems may solve the problem? And in what time frame?
2. 'Roads that cars can read'. On the other hand, the new ITS-systems can make new requirements of the infrastructure. Clear and automatically readable markings and road signs for instance are becoming more important. The infrastructure needs to be prepared for the self-driving vehicle using it. Which infrastructural measures are required for this?

It is important to be able to make an assessment of the safety effects of new systems. Using microsimulations, the safety effects on the traffic system can be studied. Certain systems require a critical mass that uses the system to obtain the intended (safety) effect. For such systems, it is important to know the (safety) effect at various penetration rates of the system. This can be investigated with microsimulations. For running meaningful microsimulations, it is important to use correct variables for the behaviour of the cars in the simulation.

1. Development of good safety indicators for microsimulations.
2. Microsimulations to gain insight in the safety effects of certain systems at various penetration rates.
3. Behaviour research to develop reliable behavioural models to use in microsimulations. Behavioural models could be developed based on experiments and by analysis of Naturalistic Driving data.
4. What information facilities at the roadside can be phased out when vehicles become increasingly smarter? How can this transition from roadside information to in-vehicle information safely be realized? And at which penetration rate can this be realized for all road users in a safe and smooth manner?

4.4. Safety in field trials with (partially) self-driving vehicles

Before new systems are put on the market, they need to be tested. Often this is first done in a laboratory environment, then on a closed off test site and finally in a field trial on public roads (see *Figure 9*).

For a practical test with a (partially) self-driving vehicle on (a specific part of) the public roads, an exemption is necessary. This exemption is to be requested at the National Vehicle Authority, in the Netherlands this is the RDW. After going through the exemption procedure the National Vehicle Authority decides whether or not to grant the exemption. As road safety is an

important precondition in the exemption procedure, SWOV has an advisory role with regard to the safety of testing on public roads in the Netherlands and securing knowledge on this issue(Boele et al., 2015).

There is valuable interaction between this area of research and the three other research areas. That what is found in practice can lead to new research questions. Conversely, knowledge from research can be used in assessing the safety risks of the field trials.

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