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CAVs and road safety

Synthesis

SE 52

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Synthesis SE 52

CAVs and road safety

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Disclaimer

This text is based on a variety of external sources and comments and feedback from the members of the working group. In some cases, use is made of or reference is made to existing knowledge or experience gained during pilot projects. Many theses are merely a reflection of expectations or estimates based on the knowledge of the members of the working group and other literature. There is no conclusive proof for any of these assumptions today, in the current state of science. In any case, we will have to wait and see how the technology of self-driving vehicles will evolve and what impact this will have on the organisation of transport in general and on infrastructure in particular. Consequently, neither the members of the working group nor BRRC can be held liable in any way for decisions taken on the basis of this text.

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Message to the reader

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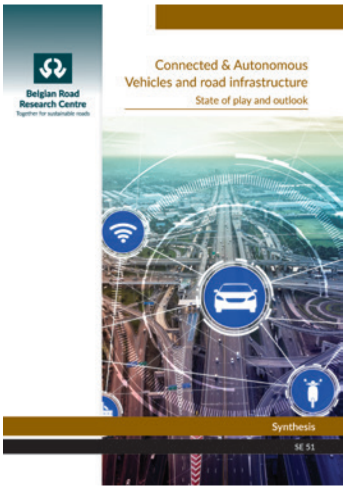
Chapter 1
Introduction

A road system consists of a number of elements (human beings, vehicles and infrastructure). The introduction of Connected & Autonomous Vehicles (CAV) further adds to the importance of the digital dimension (which is already present, in the form of navigation systems and Cooperative Intelligent Transport Systems (C-ITS)). The quality of the interactions between the elements in the system (with additional support from digital functionality in some cases) largely determines how the transport system works, and it also determines the associated **road safety**.

Physical **road infrastructure** is obviously part of the traffic system on public roads. Until recently, not enough research had been carried out into the role of road infrastructure in the development of autonomous transport. Road authorities rightly wondered what investments could help to encourage and guide the safe development of autonomous vehicles, and whether any types of investment might slow that development.

The BRRC studied this area in detail, with a working group including external experts that was set up for this purpose. A literature review and discussions within the working group resulted in the paper "Connected & Autonomous Vehicles and road infrastructure - state of play and outlook", published in 2021 (Redant & Van Geelen, 2021) and available on the BRRC website.



This document also addressed the subject of road safety, but that was not the main focus of the report.

Following publication of the report and the feedback that was received, the working group has continued its activities. As an independent knowledge institution focusing on road safety and physical road infrastructure, the BRRC decided it would be useful to conduct a **more in-depth review** of the topic of road safety.

Figure 1.1 – *BRRC Synthesis Report – CAVs and road infrastructure, state of play and outlook, 2021 (Redant & Van Geelen, 2021)*

This report is the result of research in the area of road safety. Are advanced vehicles really safe? What is the role of road infrastructure? We made an effort to gain more insight into the aspects that influence this, while still maintaining a focus on the road infrastructure as a component.

The report starts with relevant background information (Chapter 2). Chapter 3 then looks at aspects of research and testing. Road safety policies and policy objectives are discussed in Chapter 4. In Chapter 5 we seek to provide more insight into the infrastructure component, with discussions of SAE levels, ADAS and ADS. Finally, we wrap up with a conclusion (Chapter 6).

Chapter 2
Background information

2.1 Potential road safety benefits

Reducing the number of traffic fatalities is an **important rationale** for the focus on autonomous vehicles[1]. Several factors play a role in both the cause and the ultimate consequences of road accidents. Analysis of these accidents shows that the driver plays a prominent role (the human factor plays a part in over 90% of road traffic accidents, and one-third of these are related to excessive speed)[2], so many developments are focused on systems that simplify or take over (some of) the driver's tasks. In the most far-reaching perspectives, this actually results in vehicles operating without human intervention (SAE L4 and SAE L5).

At first glance, it seems that the gains from replacing the human factor by an "infallible" machine would be huge.

Systems in autonomous vehicles are focused on performing several tasks simultaneously (observing the immediate environment and simultaneously detecting potential conflict situations, receiving information from external sources, rapidly processing information, etc.). At present these systems mostly complement the human driver. As their reliability and functionality increase (and with safety always as an absolute requirement), they could potentially one day replace the human driver.

A machine:

- is not distracted by a mobile phone (10% to 30% of accidents are caused by distractions);
- does not drive under the influence of alcohol (a quarter of accidents in the EU are alcohol-related);
- does not exceed the official speed limit (speed is a factor in 30% of fatal accidents) (European Automobile Manufacturers Association [ACEA], 2019a).

It should be remembered that the impact of preventing an accident goes beyond those directly involved; the suffering of large numbers of family members and friends is also prevented.

To illustrate the **potential** for making traffic safer by using autonomous vehicles: research in the Netherlands found that 10% of all car accidents are caused by phone-related distractions. The bottom line is that autonomous vehicles could theoretically prevent 13,000 accidents per year, including about 2,500 involving injuries and 79 that turn out to be fatal (de Boer, 2021).

On the other hand, the human factor does not always relate to the driver of a vehicle and/or this "variable" human factor cannot always be replaced through automation (it is not yet possible to automate the behaviour of pedestrians and cyclists in traffic).

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[1] A review of the literature shows that the main drivers for the development of - and transition to - autonomous vehicles are: improving road safety, economic prosperity, reducing congestion, mobility, use of space, energy efficiency and environmental friendliness, and road capacity (Redant & Van Geelen, 2021).

[2] The percentage referred to above (the involvement of the human factor in road traffic accidents) is based on the number of reported incidents; what is unknown or less well known is exactly how many near-incidents are prevented by humans (Islam et al., 2019; Treat et al., 1979).

2.2 New risks

Clearly there is potential for considerable gains in terms of road safety. There seems to be a perception that autonomous vehicles could bring about a breakthrough in drastically reducing the number of road traffic accidents and could help to achieve the road safety goal of zero accidents by 2050.

However, transferring driving tasks from a human to a machine, leads to **new risks for the traffic system**. Unforeseen situations that human drivers can usually anticipate appropriately can sometimes be challenging for the algorithms operating self-driving cars.

The transition to fully autonomous vehicles brings new challenges, with a mix of automated and human-driven vehicles interacting in traffic, while some people will take even more risks due to the assumption that the automated vehicle will see them and react to avoid potential collisions (International Transport Forum [ITF], 2016).

Especially in **urban environments**, developments are still needed to allow driving support systems and automation to improve road safety for all road users (including pedestrians and cyclists), whether or not these are automated or connected.

Correct and timely estimation of the intentions of cyclists, pedestrians and micro-mobility users and interaction with these road users are all very demanding aspects for driving support systems (in advanced driver assistance systems, detection by sensors and correct interpretation by algorithms cannot yet be taken for granted).

Analysis of rear-end collisions involving self-driving vehicles has shown that the driver of the conventional vehicle is often surprised by the braking behaviour of the self-driving vehicle in front (Pokorny et al., 2021). Not all vehicles are equipped with AEB (Automatic Emergency Braking) or ACC (Adaptive Cruise Control), which can help to prevent rear-end collisions.

Pilot projects involving shuttles and robotaxis (particularly in the United States) suggest that it is possible to handle new types of interactions without generating significant safety problems (conflict situations and accidents). Clear understanding of these interactions should help with systematic mitigation of potential risks. Several pilot projects (mainly outside Europe) may help to improve the operational reliability of self-driving vehicles in complex urban environments.

2.3 Complexity

One of the advantages of cars is that they are very well suited for safely travelling relatively long distances in very different environments. Autonomous vehicles, however, have the **additional challenge** that they must do at least as good as human drivers today at making the choices that are safest for everyone in all situations. The conditions under which this must be done are very diverse and often far from optimal. The context is different in every case: there are differences concerning the types of road users, the road layout, types of road profiles and the crossings available, objects at the roadside have a variety of functions and must also be recognised correctly.

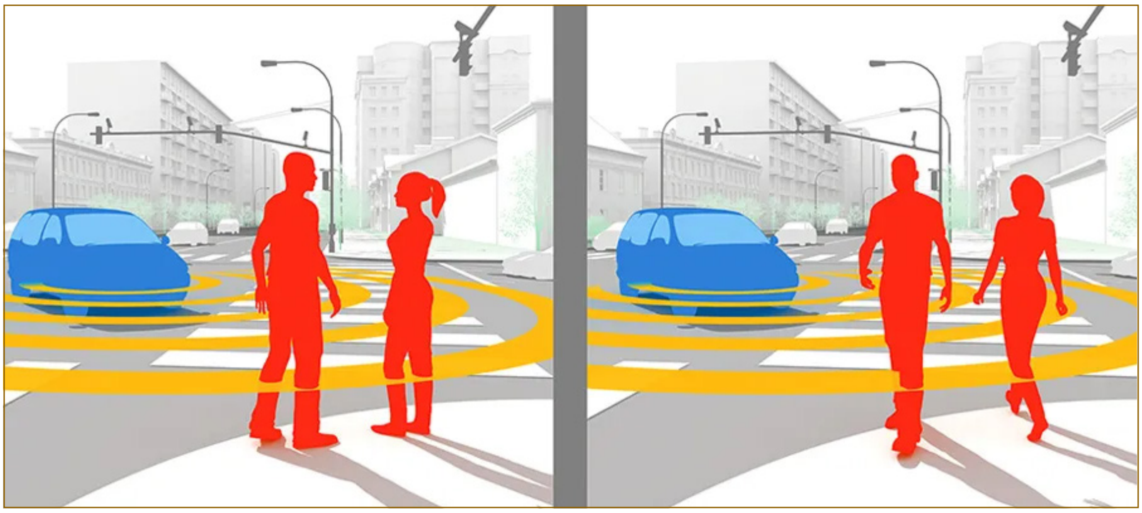

Figure 2.1 – *Illustration showing the interpretation of human behaviour by a self-driving vehicle. Are these two people just having a chat, or are they about to cross the road? (Brooks, 2017)*

The increasing complexity of systems leads to a greater risk of **errors**. These errors can result from multiple causes (Wang et al., 2020):

1. **Perception error**: malfunctioning hardware, bugs in software algorithms or errors in communication between hardware and software can cause situations to be misjudged.

2. Based on the information received by the vehicle, a decision has to be made; at present this is usually done by a human driver, but later on the decision will increasingly be made by the system itself. If the information is wrong, arrives too late or if situations occur that are not anticipated by the algorithm handling the process, wrong decisions can be made (**decision error**).

3. Even if traffic situations are assessed correctly and the correct decision is made by a human being or algorithm, mechanical hiccups on the part of the vehicle or incorrect execution by humans (e.g. due to a decline in driving experience) (**action error**) can still cause situations where accidents are not successfully avoided.

2.4 Automated driving systems (ADS) versus advanced driver assistance systems (ADAS), SAE levels

Driving automation refers to both Advanced Driver Assistance Systems (ADAS) and Automated Driving Systems (ADS). ADAS functions in a vehicle are intended to **support the human driver**, while ADS may eventually be able to **control a vehicle without human intervention**. The industry has identified six levels of driving automation, which can be found on the Society of Automotive Engineers International (SAE) website (ADS Team, s.d.).

- ADAS-functions (levels 0-2) are available in new cars (or as aftermarket module) that are currently on the market. These include automatic emergency braking and adaptive cruise control. When used correctly[3], these features can improve the safety of the driver and passengers (as well as other road users) and prevent collisions;
- ADS technology (SAE levels 3-5) that can control a vehicle under well-defined conditions is currently under development.

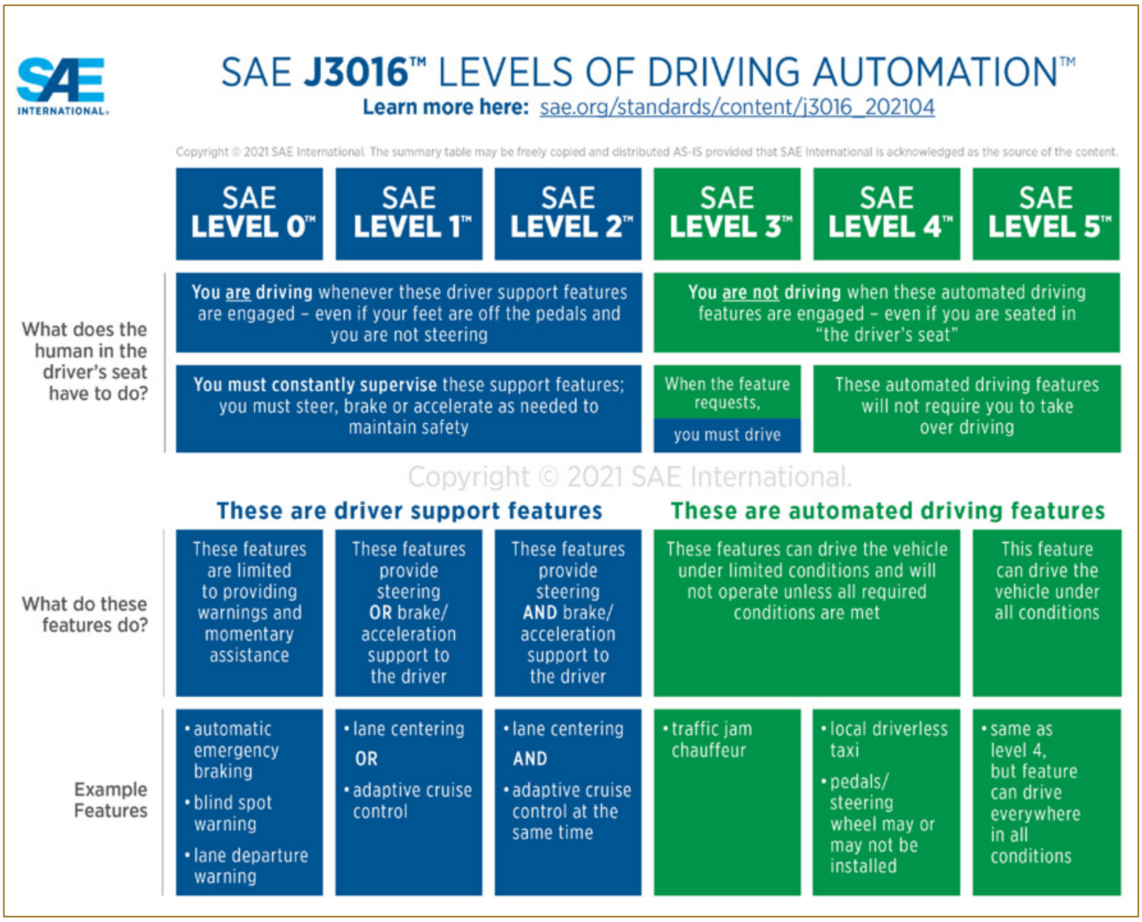

Figure 2.2 – *SAE-levels (SAE International, 2021a)*

[3] § 2.5 Operational Design Domain.

There are not yet any fully **self-driving consumer vehicles** available on the market. New cars do come equipped with a variety of systems that support the driver in various aspects of driving (ADAS – Advanced Driver Assistance Systems), but these do not yet amount to ADS (Automated Driving Systems). The driver still needs to be attentive. Even the most advanced vehicles on the market today (SAE L3) still expect a human driver to be able to resume control in critical situations. Regulation (EU) 2019/2144, 2019 is systematically making these driving support systems compulsory as a condition for homologation of new vehicles. So far these systems are limited to providing information to the human driver or possibly intervening in emergency situations (e.g. AEB[4]). The **human driver** remains in control.

Meanwhile, mobility solution providers are organising pilot projects in various locations (including the US and China) involving publicly accessible **self-driving robotaxis** (both with and without a backup driver). The vehicle is mostly self-driving and intervention by the backup driver in the vehicle or a remote operator is only required in conflict situations.

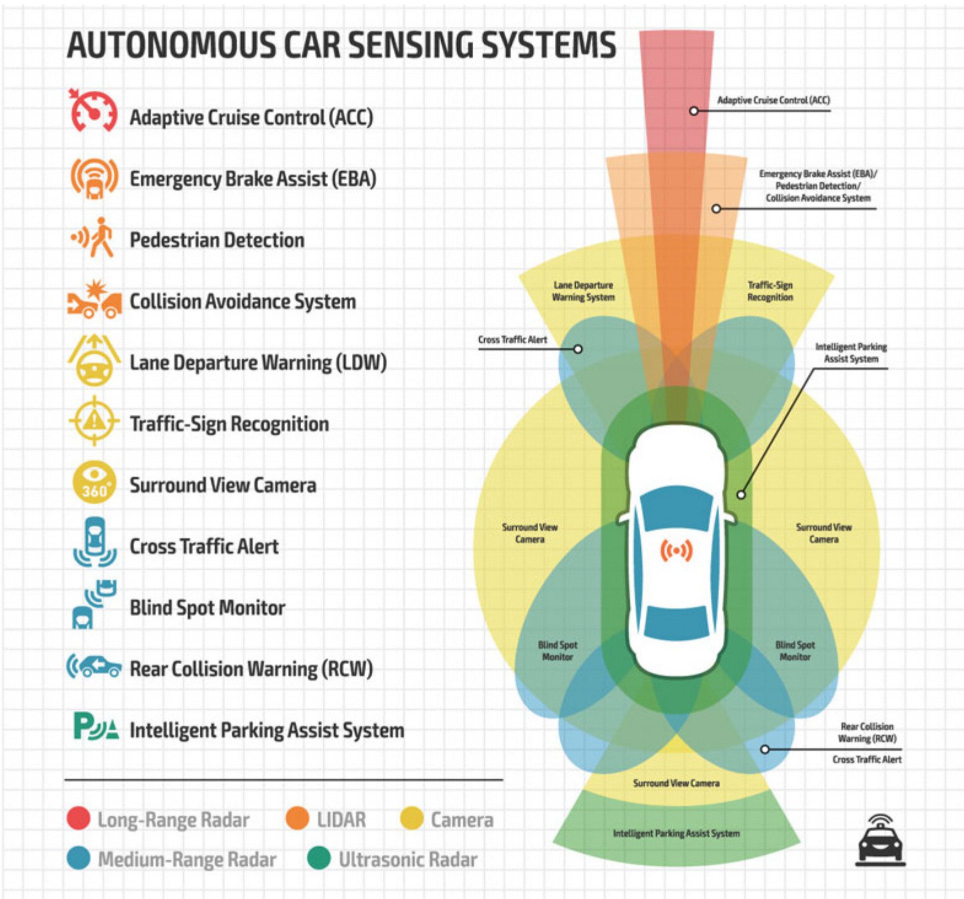

Figure 2.3 – *Sensors in automated vehicles (Viasnoff, 2022)*

[4] AEB: Automatic Emergency Braking. Different designations and abbreviations are used to describe many functions, and these are often specific to the car manufacturer. Automatic Emergency Braking (AEB), Auto(nomous) Emergency Braking (AEB), Emergency Brake Assist (EBA) are different names for the same function.

The **reliability** of these systems is constantly being improved, new functions are being added to cars and driving tasks are being transferred from the human driver to the vehicle, until a situation where vehicles can drive almost autonomously and the human driver is only required to intervene in special situations[5]. This can be described as the human supporting the machine.

Initially these systems only function when all boundary conditions are taken into account (within a defined ODD[6], e.g. Highway Pilot) but it is intended that they will function under all driving conditions eventually.

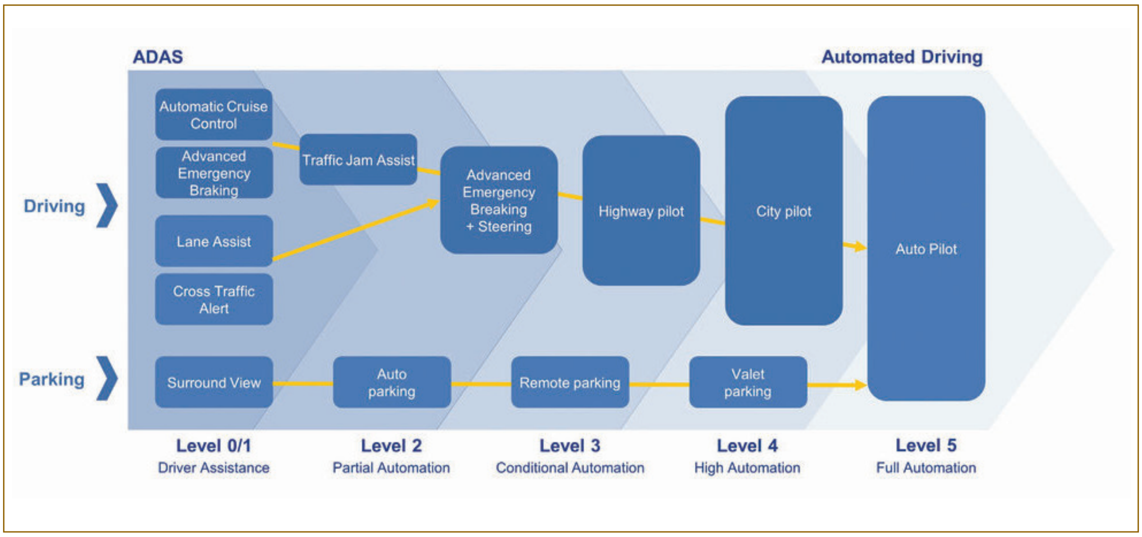

Figure 2.4 – *Functions for different levels of automation (Pinton, 2020)*

According to the SAE classification, ADAS includes **SAE levels 1 en 2**, the levels where the vehicle is already able to provide limited support to the driver (e.g. Adaptive Cruise Control) or intervene in potential conflict situations (e.g. Automatic Emergency Braking).

Starting from SAE level 3 (the lowest level of ADS), automated vehicles are capable of handling certain driving tasks on their own when certain conditions are met, based on their perception of the driving environment (SAE International, 2018). However, a driver must always be present and as soon as the vehicle requests it, the driver must be able to take control of the vehicle (e.g. Traffic Jam Pilot).

SAE levels 4 or 5 vehicles should basically be able to perform all aspects of driving autonomously. In the case of **SAE level 4** (functional under certain conditions), automation systems must allow a vehicle to detect and handle conflict situations autonomously or come safely to a stop. SAE level 5 vehicles must be able (so far only hypothetically) to operate safely under all conditions.

[5] § 5.2 Taking control (disengagement).
[6] ODD: Operational Design Domain, § 2.5

SAE level 3 is seen by some as problematic (Torchinsky, 2022). SAE L3 functions are currently only allowed to operate under limited and very specific driving conditions and a human driver must be able to take over the controls at any time. However, the specification is still vague about when and how control should be transferred from the vehicle to the human driver. That can result in some dangerous situations. For this reason, some people are advocating a transition from SAE L2 directly to SAE L4 (e.g. Litzler, 2019).

Optimal use of ADAS systems also requires drivers to familiarise themselves with the functionality and its limitations to ensure safe operation[7].

The process of evolution that has been outlined here assumes vehicles that function autonomously. A variety of sensors in the vehicle scan the environment and act on the basis of these observations and processing algorithms. At lower levels of automation, the resulting action usually means simply providing information to the driver. As the level of automation increases, more and more active interventions in the vehicle's behaviour are also possible (e.g. in Advanced Cruise Control the vehicle's speed is adjusted to match the speed of the vehicle in front and the preset distance).

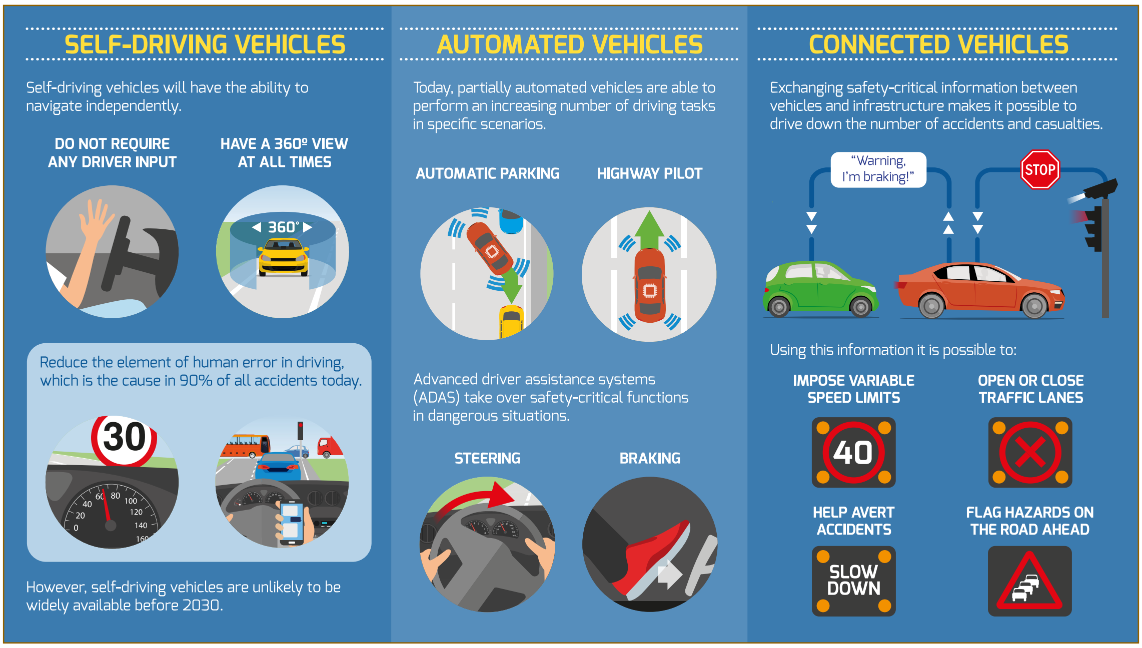

Figure 2.5 – *Road safety by vehicle type (How can automated, s.d.)*

[7] The Flemish Foundation for Traffic Knowledge (VSV) is organising training on these systems for driving instructors (Vlaamse Stichting Verkeerskunde [VSV], 2023) In 2022, the VRT television channel dedicated an episode of **Kijk Uit** (Look Out) to car safety systems (Belgian Federal Police, 2022).

2.5 Operational Design Domain (Hillen, 2020) (ODD)

The advanced driving assistance systems fitted to vehicles that are currently on the market usually function only within a set of specific boundary conditions known as the **Operational Design Domain**[8]. These may include a wide range of parameters (location, speed limits, weather conditions, traffic density, road surface, traffic signs, local customs and rules, etc.).

A lot remains to be done before vehicles can be fully automated to handle all road and environmental conditions that a human driver can manage (Figure 2.6).

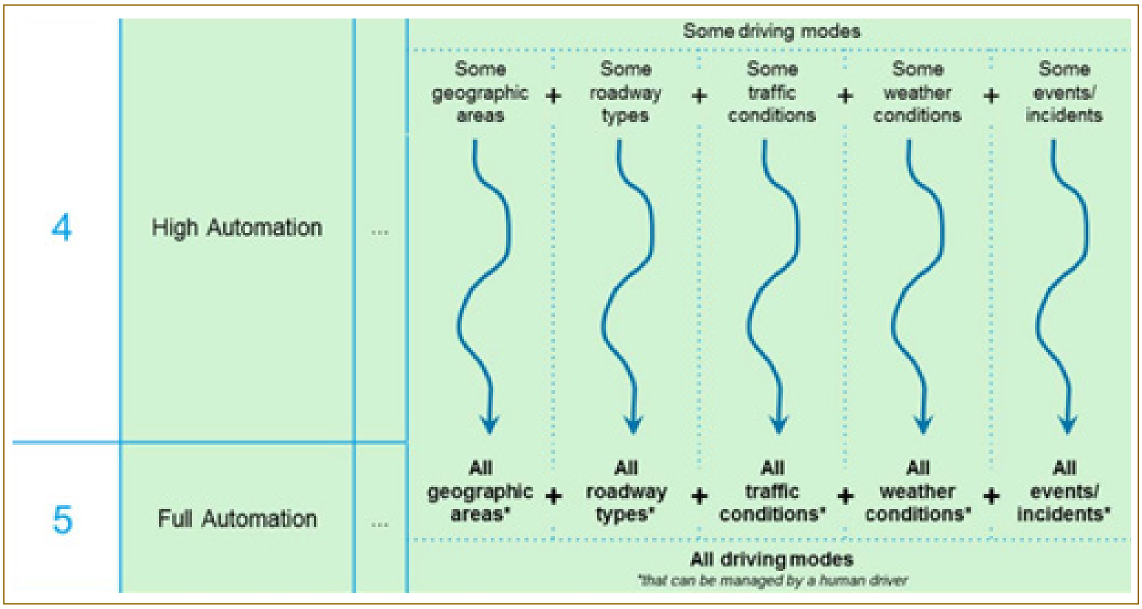

Figure 2.6 – *Transition from high to full driving automation in different contexts (ITF, 2015)*

It is challenging for vehicle manufacturers to develop systems that will function reliably under the widest possible range of conditions. On the other hand, users of vehicles with advanced driver assistance systems should be aware that these systems will not function reliably under all conditions, and that it is even recommended to disable these systems if boundary conditions are exceeded.

[8] SAE J3016 (2021), the Operational Design Domain (ODD) for a driving automation system is defined as "Operating conditions under which a given driving automation system, or feature thereof, is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics." (SAE International, 2021b).

For example, a warning sign has been installed in the Western Scheldt Tunnel (Figure 2.7), following reports of vehicles braking suddenly in the tunnel (Adaptive cruise control, 2021).

Figure 2.7 – *Traffic sign recommending disabling ACC (Western Scheldt Tunnel, Netherlands (Adaptive cruise control, 2021)*

So far **there are no formal agreements** in place on which parameters are decisive for the ODD. How an ODD is defined is largely up to vehicle manufacturers.

Road authorities, however, need a uniform approach. If the operational limitations of a specific function can be **standardised,** road authorities will be able to to take them into account when designing roads.

Road authorities may recommend disabling an **ADAS system** in some circumstances when road safety could be compromised by the use of such a system.

The Dutch Safety Board sees the introduction of systems that are under development or immature on the road as a necessary step in order to develop these systems further. After extensive research, the Board has stated that this is a **black box** situation. When approving new cars, the government does not have sufficient oversight of how new systems will operate under various conditions. The Board also states that for some driver assistance systems, the effects of the systems on road safety is not clear, and there is a lack of proper monitoring and evaluation of these systems (Dutch Safety Board, 2019).

While awaiting the introduction of international regulation, the German government passed legislation in July 2021 that allows fully autonomous driving (SAE L4). This legislation is not a general admission, but it does allow road authorities to allow activation of self-driving systems within a defined area or on a specific road, only - of course - for vehicles that have this functionality (New autonomous driving law, 2021; Pingol, 2021).

The table below illustrates the various boundary conditions required for optimal operation of a lane-assist system as shown in the manual for a number of existing vehicle models.

	Car 1	Car 2	Car 3	Car 4
Speed	65-180 km/h	from 65 km/h	from 60 km/h	60-180 km/h
Action, warning	Steering correction	Steering wheel vibration	Steering correction + steering wheel vibration	Steering correction, buzz from speakers, visual
Operation is disrupted by	Absent, non-visible or multiple markings (in con-struction areas)	Other objects may be recognised as markings	Poor road surface, absent lane marking, other objects, road works, crest curves and sag curves	Non-visible markings (on at least one side), camera obstruction,
		Sudden manoeuvres	Dynamic driving styles	Traffic conditions (e.g., other vehicles in traffic that are not aligned with your vehicle, vehicle trav-elling across or in the opposite direction in the same lane, tight bends)
	Limited distance from vehicle in front			Appropriate distance from vehicle in front
		Difficult weather conditions	Bad weather conditions	Unsuitable visibility conditions, (heavy rain, hail, dense fog, heavy snow, formation of ice layers on the wind-screen)
	Narrow roads, curvy roads	Narrow roads	Sharp bends	Roads that are not straight, roads with tight bends
				Direction indicator active

Table 2.1 – *Operational design domain for Lane Keeping Assistance (LKA) in four different cars*

2.6 Social concerns

The first experiments with driverless cars were conducted 100 years ago. It is only since the turn of the century, however, that a number of organisations have been actively engaged in developing technology for self-driving vehicles, for a variety of reasons and with varying degrees of success. In many cases technological progress is accompanied by **social concerns**.

Any study of autonomous vehicles and road safety, particularly when the focus is on the road infrastructure, must include an awareness of the big picture. The development of autonomous vehicles is only one of the many changes in mobility that need to be taken into account. Mobility policy, sustainability, urban development and digitalisation all have a part to play. At the same time, various social aspects also have to be taken into consideration when developing autonomous forms of transport (e.g., the **sharing economy**, **environmental issues** and the **enforceability of measures** related to accessibility of cities).

2.7 Ethical concerns

For automobile manufacturers, self-driving vehicles are not an end in themselves. The main impetus for research and development in the domain of self-driving vehicles comes from the desire for safer and more environmentally friendly vehicles. Quite often, meaningful innovations are implemented (on a voluntary basis) by the whole automotive industry and/or anchored in legislation and made compulsory for all vehicle models. Passive safety systems are now virtually universal. Active safety systems and self-driving vehicles, whether private or shared, seem to be the most comprehensive approach in order to achieve this; the aim is to build safer vehicles by reducing or eliminating the unpredictability of the most uncertain factor (human beings).

Dilemmas can arise that also involve **ethical** considerations (Wittock & Wittock, 2021):

1. How do you program an ADS algorithm to act in the event of an unavoidable accident? Is the impact of the accident on the vehicle occupants given a higher importance than the impact on other road users?

2. Should the technology be made mandatory if it really does improve safety?

3. How do different investments of public funds compare? What priority should be given to private autonomous transport, in comparison with public transport (whether autonomous or otherwise)?

4. How much decision-making power should be given to an autonomous vehicle? Could human beings lose certain skills if they only have to be ready to take control of the vehicle in an emergency?

The first ethical dilemma raised seems to be becoming less relevant as **artificial intelligence** finds its place in autonomous vehicles. The algorithm will then control the car based on millions of miles of road behaviour, copying positive behaviour from other drivers to new situations[9].

The third dilemma does require some explanation. This seems to be a contradiction between autonomous private transport and non-autonomous public transport. This ignores the fact that public transport is also becoming at least partly autonomous. The robotaxis already driving around in some cities are proof of this. So it would be better to describe the dilemma differently: "What priority should be given to investment in facilities for **private autonomous transport versus public autonomous transport**"?

2.8 Dynamics

The development and roll-out of autonomous vehicles is a dynamic process. For quite some time, there will be a situation where there is a **mix of vehicles** with different levels of automation, while other road users are in vehicles that have few or none of the new technologies installed.

The composition of this mix will change over time, but it is not clear how quickly the transition to autonomous vehicles with higher SAE levels will occur. From road safety perspective, this requires a holistic approach to road safety for all types of road users: from conventional and unconnected (e.g. pedestrians, vintage cars) to hyper-connected (SAE Level 5 autonomous vehicles). It will be crucial to **monitor what is safe** for each mode of transport, both separately for each individual type and also between types.

In terms of **infrastructure**, the approach is to develop autonomous vehicles that can use **existing roads which are not always in an optimal condition**. In principle the systemic change to autonomous mobility does not result in the building of special roads. There is no single physical standard for a road that is ready for autonomous cars.

A general consensus has, however, emerged that **road maintenance will become more important** with the deployment of autonomous vehicles. The most advanced vehicles with self-driving functionality are becoming less and less dependent on road markings. However, bad weather conditions are not conducive to reading road markings correctly. Despite the technological advances that are taking place, there is agreement that clear and **uniform signage** (road signs and road markings) can contribute to the more reliable functioning of new vehicle technologies. This will be helpful for all the vehicles and road users in the mix[10].

However, it remains important that the development of self-driving vehicles takes into account real-world situations and infrastructure elements that do not meet the predetermined standards. At lower SAE levels, it is still possible to take control of the vehicle. At levels SAE L4 and L5, the vehicle should also be able to operate under these non-ideal driving conditions.

There is still an **urgent need** to improve road traffic safety in general. The target of zero traffic fatalities and serious injuries by 2050 must be attained in the coming decades, and attention should go to all possible measures. Statistics show that there is a tendency for stagnation of the number of deaths and serious injuries due to road traffic accidents (or even to increase, as in the United States). (National Highway Traffic Safety Administration [NHTSA], s.d.; World Health organization [WHO] & United Nations [UN] Regional Commissions, 2021).

[10] § 5.3 on the relevant working group (EGRIS sub-working group on road markings & signs).

In Europe there is a strong commitment to the Safe System Approach, and in Belgium the federal and regional governments are committed to All for Zero[11]. Meanwhile, the ARTS 2022 symposium (Highlights, 2023) showed that in the United States, which is usually seen as a leading country in the field of autonomous vehicles, there is a growing awareness that:

- automation is **not a panacea** being handed to us on a silver platter by the industry. Instead, automation is a **potential tool** that can be used to address the increase of traffic fatalities;
- federal policies are needed to avoid a patchwork approach to regulation;
- it is necessary to coordinate the performance of human and Automated Driving (AD) to optimise strengths, rather than expecting human monitors to consistently resolve difficult AD situations;
- there is growing focus on infrastructure support for automated driving (digital support, sensors, physical separations, etc.).

[11] § 4 Policy objectives concerning road safety.

Chapter 3
Aspects of research and testing

To understand the potential of the solutions, it is first of all necessary to have a good understanding of the nature of the problems. The second step is to conduct research into possible solutions, while the third will be to implement the solutions so that they can prove their usefulness in practice.

Specifically with regard to the transition to autonomous vehicles, knowledge of accident causes is the basis of the process to effectively reduce the number of accidents:

- What are the existing causes of accidents and how are the causes evolving?
- Which causes of accidents can be remedied by an autonomous vehicle?
- How can this be tested in practice?
- How can you scale it up?

In Chapter 2 we mentioned the road safety potential and also the fact that new risks are also emerging. Expert analysis will be needed in order to make the right investments and appraise the role and value of infrastructure correctly.

Road safety is usually assessed on the basis of the number and severity of road traffic accidents and the number of road traffic fatalities. **In-depth analysis** of accidents makes it possible to identify the main causes of an accident. The causes are classified into three main categories: human causes, vehicle-related causes and environmental causes.

3.1 Root cause analysis (Oorzaakanalyse, s.d.)

The primary goal of cause analysis is to determine the **root cause** of a problem or event.

In many cases, there are multiple factors that have a role in causing road traffic accidents. Analysis of accidents shows that in nine out of ten cases the human factor causes or contributes to the consequences of a road traffic accident. In about 60% of cases, the accident is caused by human factors alone. Consequently, actions to improve road safety (driver education, speed and alcohol checks, etc.) often focus on this crucial human factor.

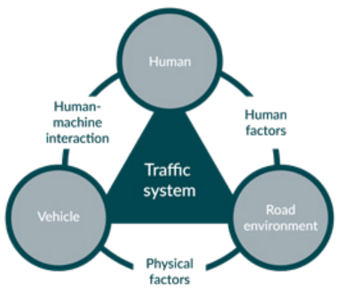

Figure 3.1 – *Components of road safety*

The second aim is to fully understand how these root causes can be eliminated or how to compensate for them so that they no longer cause accidents (or that the compensations help to mitigate the effects of an accident), or to learn about the problems underlying the root cause.

For accidents whose cause is primarily attributable to human factors, it may be a combination of **underlying factors** involving various components and combinations between them (e.g. interaction between human factors and the vehicle/Human Machine Interface (HMI)). Part of the solution (reducing or eliminating human causes of accidents) may then be to improve these interactions through changes in the HMI or through user training. It will also require research into measures that could remedy or compensate for (mitigate) the problem, cf. forgiving roads.

Here is one example of a combination of factors that might emerge from examination of an accident report: the driver's speed was 150 km/h, at a speed limit of 120 km/h. The road surface was slippery due to rain, the driver was distracted by a mobile phone message on his on-board computer, and he was driving under influence (of drugs).

An autonomous vehicle has the potential to be a solution for all the factors mentioned:

- *Driving speed: the AV can be configured so that the vehicle does not exceed the speed limit.*
- *Slippery road surface: the AV analyses the skid resistance of the road itself and adjusts its driving behaviour accordingly.*
- *Distraction by mobile phone: with fully autonomous driving, this risk no longer exists. At lower levels of autonomous driving the driver needs to keep their attention on the road, and it is still possible that the driver will be distracted by their mobile phone. Nevertheless, both vehicle behaviour (e.g., LKA) and driver behaviour (e.g., Advanced Driver Distraction Warning) are monitored by advanced driver assistance systems and the risk of crashes due to distractions is still lower compared to a conventional vehicle.*
- *Driving under the influence: in fully autonomous driving this risk no longer exists; it may still be a problem at lower SAE levels, even though some vehicles can test the driver's fitness to drive.*

The third aim is **to learn from this analysis** and act systematically to prevent future problems or repeat successes. That means looking for links between different accidents, with the emphasis on preventing further similar accidents. Something then needs to be done with this analysis. Changing processes and system-related issues can prevent problems from arising in future.

3.2 How to evaluate the safety of automated and self-driving vehicles?

With increasing levels of automation, vehicles are increasingly taking on the role of a human driver. At present, **driving skills** are initially evaluated during driver training, taking local rules and customs into account. The driver's ability then continues to be assessed on an ad-hoc basis through checks, automated monitoring systems, observed infringements etc. The **vehicle's roadworthiness** is evaluated according to the requirements for homologation and subsequently also via regular roadworthiness (MOT) testing. Both a homologation certificate and a positive roadworthiness inspection are required before a vehicle is allowed to drive on public roads. For ADAS systems, an important focus seems to be the ongoing monitoring of their operation, rather than periodic checks. It is also best for ADAS systems to be accurately calibrated after a collision or damage to the bodywork or windows.

One way of evaluating passive vehicle safety is through (voluntary) **Euro NCAP crash tests**, which provide an indication of the potential consequences of a collision for both occupants and other road users. Euro NCAP crash tests are a voluntary initiative by the car industry. The industry sponsors a series of tests on popular vehicle models every year. Car manufacturers are also free to conduct tests on their own vehicle models. The organisation does not have the capacity to test every possible vehicle model and variant.

As in-vehicle systems become more and more mandatory and increasingly take over the role of human drivers, there will be a need to evaluate the **functionality and reliability** of these systems and possibly test them against minimum requirements before allowing them to be used in cars.

So far, however, **there is no standardised method** for evaluating whether a self-driving vehicle is safe to operate.

Evaluations may be based on testing of individual components or functions. Regulation (EU) 2019/2144, 2019 requires car manufacturers to equip new vehicles gradually with a number of advanced capabilities (LKA, AEB, drowsiness detection, ISA, etc.) **as standard**. It must be demonstrated that the reliability of these systems meets predefined criteria. In the case of ISA, for example, the premise is that speed limits must be recognised correctly in 80% of cases.

Euro NCAP has added a **Safety Assist** component to its ratings. In this assessment, the availability and operation of a number of safety features is evaluated using a number of standard scenarios in a test set-up that also includes suboptimal conditions. For example, the assessment of LKA systems also includes how the system operates when edge markings are missing. The Safety Backup assessment looks at system malfunctions, driver intervention and collision avoidance.

Evaluation of the safety gains achieved by AVs through **analysis of real accidents** also does not seem to be a conclusive solution. The reality is that road traffic accidents are relatively rare. It would take a very long time to demonstrate from accident data that an AV is safer than a conventional vehicle[12].

To demonstrate statistically that autonomous motorised vehicles have a similar fatal crash rate as current road traffic, a total of 440 million km would have to be travelled without a single fatality. That would take years of testing with a limited number of vehicles. **Test driving** alone cannot provide sufficient evidence to prove the safety of autonomous vehicles. Developers of this technology and third-party testers will need to develop innovative methods to demonstrate the safety and reliability

[12] 390 road traffic accidents per 1^{E}09 km travelled (0.00004 %) (De Bruyne, 2021) / Google car in California (US) period 2000-2015: 11 accidents per 2.7^{E} 06 km travelled (0.0004% / 10 times higher) (according to Pritchard, 2015) – also a lot of (the same) info in (ITF, 2018).

of the vehicles. Even when these methods are used it may not be possible to determine with certainty exactly how safe autonomous vehicles are[13].

Safety is a major concern in **pilot projects**. Prior demonstration of how conflict situations will be handled without compromising the safety of road users is required. During this process, increasingly difficult scenarios are included.

During testing on public roads, accident reporting and transfers of control to the human driver (**disengagement**) can be used as a measure to evaluate the functioning of advanced driver assistance systems (Petrovič, 2020; Wang et al., 2020).

However, using the disengagement indicator also encounters resistance (Yoshida, 2019). If it is used in this way, AV developers might be tempted to configure systems to be more tolerant. Disengagements and information on why control was transferred to the human driver are useful, however, to identify the limits of reliable functioning for both ADAS and ADS and to systematically increase the reliability of these systems in these edge cases.

Studies on the effects of ADAS are therefore also based on **simulations** in a design environment. Driving simulators imitate a driving environment, and this can be used to analyse the behaviour of an autonomous vehicle or driver (e.g. by changing the driving environment and comparing the resulting behaviour). A similar research method can also be used in transitional situations, when an autonomous vehicle transfers control to a driver. Developing and simulating a design environment of this kind is also not very obvious (Feng et al., 2021). The existing simulation methods are based on "statistical averages". Car manufacturers use very sophisticated simulation models which are highly complex and include considerable variation, but it has turned out to be extremely difficult to simulate the **complexity of a real road environment** with multiple random events occurring.

3.3 Design environment versus testing on public roads?

More and more **pilot projects** involving autonomous vehicles are being conducted worldwide. Particularly outside Europe[14], these are large-scale tests in which a fully automated taxi service is offered in a city or district. In Belgium, pilot projects are currently limited to testing shuttles on a fixed route (Louvain-La-Neuve, Terhills, Mechelen, etc.) or conducting experiments on individual vehicles (Detroz et al). As more experience is gained from these pilot projects and the total distances travelled by these vehicles increases, more knowledge about road safety is becoming available.

However, physically evaluating all the possible scenarios (combinations of different environments, vehicles and driver attention) is impossible. Estimating the safety of autonomous vehicles requires a **combination of simulations and pilot projects**. The use of simulations or pilot projects alone would be too one-sided to obtain a comprehensive view of the safety potential. Test conditions, for example, are not always representative of the unpredictable behaviour of road users on public roads.

[13] That would require 12.5 years of testing with 100 autonomous motor vehicles driving 365 days a year, 24 hours a day at an average speed of 40 km/hr (Kalra & Paddock, 2016).
[14] United States, China, etc.

Waymo pilot project - United States (Bellan, 2022).

Since 2016, Waymo has been testing self-driving taxis (ride-hailing services) in a specific neighbourhood of Phoenix, Arizona. Initially there was always a safety-driver as a backup in the vehicle. Since 2020 these have even been operating without the backup driver. In 2022, the area in which these vehicles operate was enlarged to include a number of other neighbourhoods and Phoenix airport. Until recently, only employees were allowed to use these services. Development of the project accelerated in 2022 and 2023. In 2022 the vehicles were made available for use by a wider group of users. In 2023, the test areas were expanded further (Phoenix, Los Angeles and San Francisco), which resulted in approval being given for commercial applications.

Mobileye pilot project - Germany (Mobileye kicks off, 2023).

The green light given to Mobileye by TÜV SÜD in early 2023 to deploy autonomous vehicles across Germany allows Mobileye to intensify its MaaS pilot projects in Darmstadt and Munich. Robotaxis and autonomous shuttles need to be equipped with Mobileye technology, which requires in-depth testing. Initially, there will still be a back-up safety-driver in these vehicles. If the necessary approvals and permits are obtained for this, the system will then also be tested without this backup.

The advanced driving assistance system is known as "Mobility SuperVision™". This contains technological building blocks that have been tested, validated and adopted by leading car manufacturers. By incrementally adding computing power and active sensors to the system, Mobileye is working towards providing autonomous vehicles for consumers.

[15] MaaS involves planning, booking and paying for all the available transportation using apps. Examples include shared bikes, cars, scooters, trains, trams and (water) taxis. Privately owned cars or bicycles are included as well. In most cases combinations of all these types of transportation are used (Ministerie van infrastructuur en Waterstaat, s.d.).

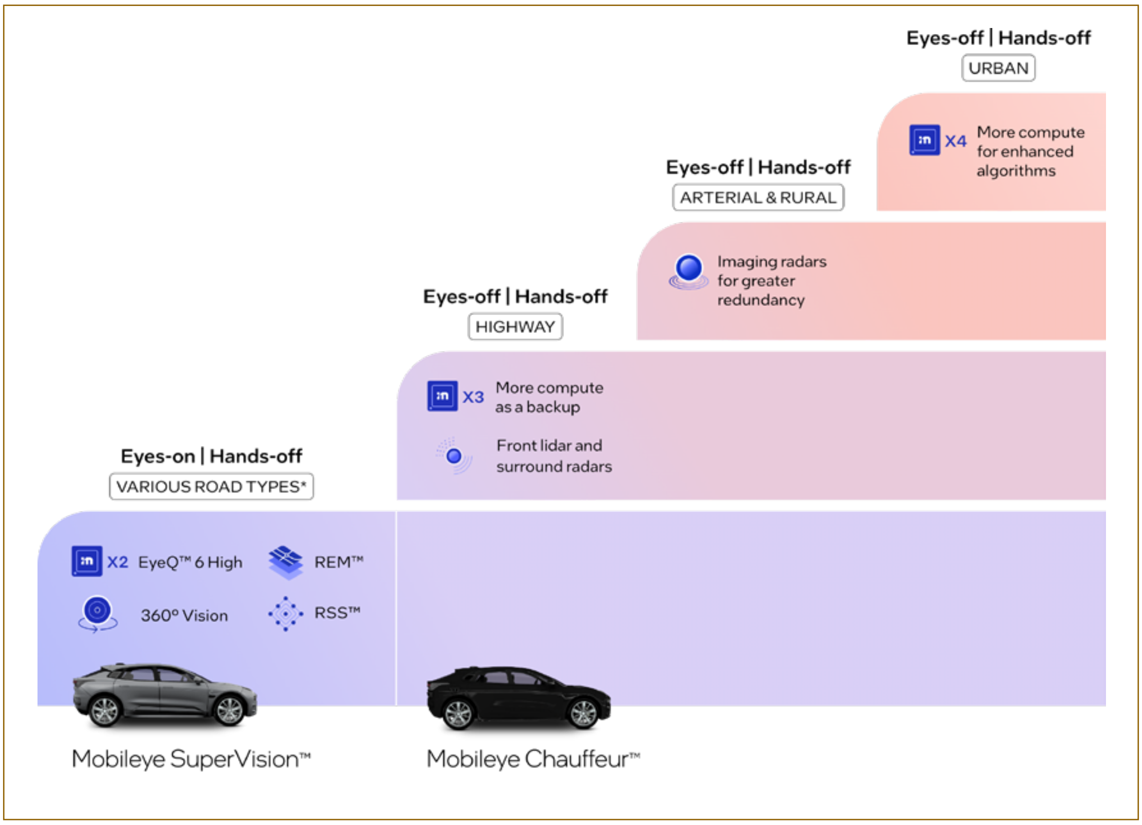

Figure 3.2 – *(Mobileye SuperVision, 2023)*

3.4 Consumer confidence in autonomous vehicles

It is not so obvious to make any comment on the effects of vehicle automation on road safety. Accidents involving self-driving vehicles receive an above-average level of attention, possibly creating a rather negative image. There seems to be a growing awareness that autonomous vehicles, like human drivers, can make mistakes when driving. On the other hand, while driver errors are perceived as inevitable, errors by autonomous vehicles are (almost) never seen as acceptable.

Experiments with self-driving vehicles that are evaluated positively are necessarily limited in both time and geographical scale, so it is not possible to generalise from these. Nevertheless, it does appear that **consumer confidence** in the safety of self-driving vehicles is improving (Figure 3.3).

Figure 3.3 – *Why autonomous vehicles need a large-system approach to safety (Sun et al., 2021)*

Testing vehicles on public roads is **closest to reality** to demonstrate vehicle safety. This does not necessarily require the use of a full self-driving mode. Tests with a human driver where the algorithm observes human behaviour and compares it to the actions it would take itself (in so-called **shadow mode**) can also provide a lot of useful information. This also allows adjustments to be made to the algorithm.

For example, objective data can help to dispel public scepticism about the safety of autonomous vehicles. Negative reports can then be seen in a different light.

An assessment by **Euro NCAP** is another approach that can help to build consumer confidence. Euro NCAP tests originally involved assessing the passive safety of vehicles using crash tests with dummies representing the driver. Later, assessments of the impact of an accident on other occupants and on vulnerable road users involved in a collision were also added. Euro NCAP now also assesses vehicles for their (active) **assistance systems** (2020 assisted driving tests, 2020; Euro NCAP, 2020).

3.5 Connectivity and communications

Experts generally agree that connectivity **can help** self-driving vehicles to operate more reliably, efficiently and safely. For example, car manufacturers now seem uncertain whether ISA systems based solely on speed limit recognition by vehicle sensors are reliable enough (Van Doorselaet, 2022). To achieve an acceptable level of reliability, other sources of data must also be used (crowdsourcing, digital maps, etc.) and this info somehow has to get into the vehicle.

On the other hand, the need for connectivity is challenged by experiences gained through pilot projects with robotaxis (US, China). In these projects, connectivity is apparently not critical to safety and all decisions are made inside the vehicle. Connectivity is available to allow the traffic centre to intervene when requested by the vehicle and for customer support.

As a result there is disagreement on whether or not safety should be dependent on this type of connectivity. However, there is a wide spectrum of variants between "dependent on" and "contributing to".

In any case, it is important to establish clear standards for connectivity, operational reliability and security (both cybersecurity and reliability). Standards are being developed within CEN/TC278 (Road Transport and Traffic Telematics), ISO/TC204 (Intelligent Transport Systems) and ETSI TC Intelligent Transport Systems on aspects including data exchange[16].

The now mainly visual communication that takes place between vehicle drivers, pedestrians and cyclists is difficult to capture in algorithms and automated systems. The vehicles used in pilot projects maintain wide safety margins and are virtually never involved in accidents with pedestrians or cyclists. In many cases current systems[17] can intervene correctly in near-miss situations. On the other hand, sharing information to assess behaviours and respond to them appropriately without acting abrupt is a separate challenge. Studies suggest that pedestrians and cyclists may (involuntarily) alter their behaviour when interacting with AVs or they may need training to take this into account. Obviously, if the behaviour of cyclists and pedestrians is changing, it will be extremely difficult to automate systems based on such changing behaviour.

When vehicles are **connected**, there are additional factors that must also be considered. It is conceivable that communication could be lost or that erroneous information could be uploaded - either maliciously or otherwise. As in other applications (aviation, energy), it therefore seems better **not to make** the operation of safety-critical functions **dependent** on this type of connectivity.

[16] For example European Committee for Standardization, 2018-2022: data exchange specifications for various ITS services

[17] More info about AEB pedestrian and AEB cyclist (AEB pedestrian, 2023)

3.6 Belgian code of conduct for testing (Heyndrickx, 2016)

FPS Mobility and Transport has consulted with partners to produce a **code of conduct** for testing in Belgium. This sets out a framework that defines the roles and responsibilities of those involved.

This code of conduct provides guidelines for organisations wishing to carry out tests with technologies for drivers assistance systems and automated vehicles on public roads or in other public places in Belgium. This Code of Conduct is intended for the following applications:

- Testing driver assistance systems and partly or even fully automated vehicle technologies on public roads or in other public places in Belgium;
- Testing a wide range of vehicles, from smaller, automated pods and shuttles to more conventional road vehicles such as cars, vans, buses or trucks.

An application form must be completed before conducting tests on public roads or in other public places. This forms the basis for the FPS Mobility and Transportation's assessment prior to granting approval to prototype vehicles.

In addition, a **regional permit** from the regional road authority is also required to use the infrastructure, and this sets out under which conditions this is allowed (traffic volume, weather conditions, during rush hour or not, etc.).

The **infrastructure component** is only mentioned in the Code of Conduct in the "Competent Authorities" section:

- "Any specific infrastructure requirement that is considered necessary in the context of the tests, such as road signage, must be put in place as agreed with the road authorities".

Before vehicles can be tested on **public roads** or in other public places, organisations must demonstrate that the vehicles and/or technologies have been previously and adequately tested on **private roads** or test tracks. These tests must have produced sufficient results to allow tests to be carried out on public roads or other public places without putting road users at additional risk.

The vehicle's sensor and control systems must be sufficiently developed to **respond** appropriately **to all types of road users** that may be encountered during the relevant test. In particular, the organisations must pay special attention to the most vulnerable road users, such as people with disabilities, people with visual or hearing impairments, pedestrians, cyclists and moped riders, motorcyclists, children and people on horseback.

If the situation requires it (for example due to the weather, but also for **infrastructure-related** reasons), the driver should be able to take the steering wheel again. The "Process for transitioning between automatic and manual modes" section does not address these situations or the infrastructure in detail.

It does state that managing the transition from manual control to automatic mode is an important safety aspect in automated vehicle testing and also says that ensuring minimal transition periods between manual and automatic modes, while also keeping risks to a minimum, is an important part of the vehicle development process and the design of the intended tests. The text ends with these words: "this aspect must therefore obviously be **developed and tested on closed roads** or test tracks before testing takes place on public roads or in other public places."

3.7 Geneva Convention

The Geneva Convention on Road Traffic (Geneva Convention on Road Traffic, 1949) is an international treaty aimed at facilitating international road traffic and improving road safety through the adoption of uniform traffic regulations. It includes agreements on aspects such as traffic regulations, mutual approval by the parties of vehicles from other treaty states and (inter)national driving licences.

On July 14, 2022, **Article 34 bis** of the Vienna Convention on Road Traffic, 2022, which allows self-driving vehicles to operate on roads in Europe, came into force. This may lead to a faster pace of research once the member states have transposed it into national legislation. The relevant article allows the driver to release the steering wheel during SAE Level 3 autonomous driving. However, the driver has to keep his eyes on the road, and must be able to take control of the vehicle at any time. Several conditions must also be met: there must be a physical separation between the two carriageways, a speed limit of 60 km/h applies and there must be no pedestrians or cyclists on the road[18].

Mercedes Drive pilot

In December 2021, Mercedes-Benz became the first car manufacturer in the world to meet the stringent regulatory requirements of international UN Regulation 157 (United Nations, 2021) for a Level 3 system that makes conditionally automated driving possible.

Mercedes is therefore allowed to offer this feature (hands-free driving at speeds up to 60 km/h) on the German market, where the use of certain SAE L3 features is allowed on various (parts of) the motorway network (a total of 13,191 km). The vehicle uses multiple sensors to make this possible.

2016 saw a breakthrough in **automated driving technologies** with the entry into force of an amendment to the Road Traffic Convention that allows to transfer driving tasks to the vehicle, provided that these technologies are compliant with the United Nations regulations on vehicles or can be overridden or disabled by the driver (50 years on, 2018).

[18] On May 30, 2022, even before Article 34 bis came into force, it was already being proposed to raise this speed limit to 130 km/h if the vehicle is also able to change lanes safely at speeds above 60 km/h (United Nations Economic Commission for Europe (UNECE), Inland Transport Committee, Working Party on Automated/Autonomous and Connected Vehicles, 2022).

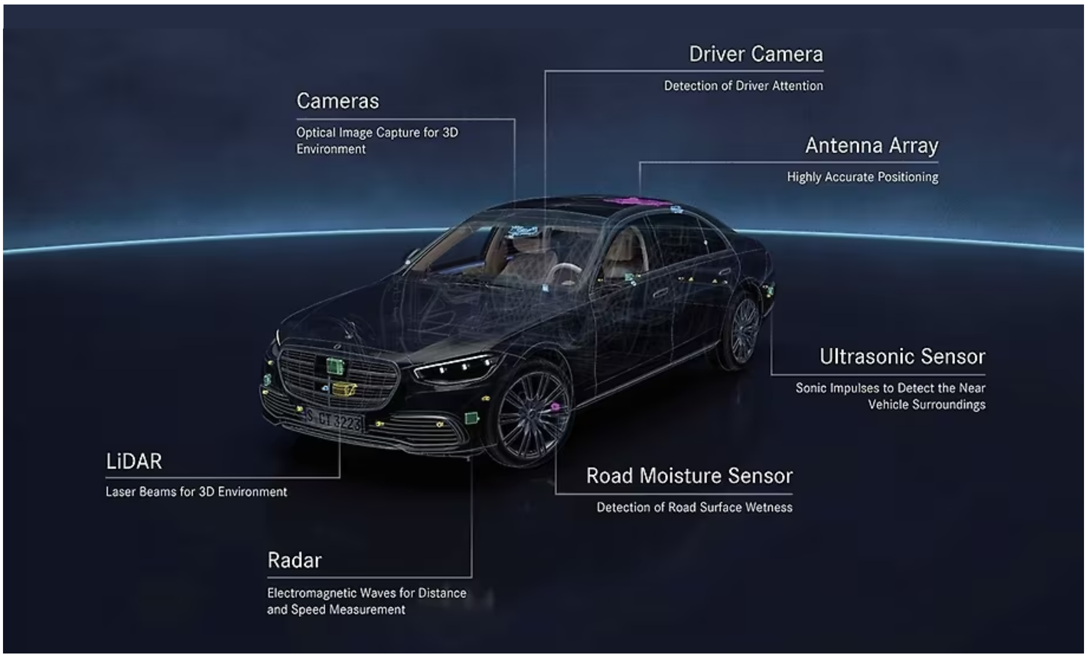

Figure 3.4 – *Drive Pilot's sensors (Mercedes-Benz Group, 2023)*

The permission that has been granted is very similar to the terms of Article 34 bis of the Vienna Convention on Road Traffic (Vienna Convention, 2022): it is permitted to release the steering wheel on motorways at below 60 km/h (Beeckman, 2021). The system is mainly useful for acquiring experience and as a demonstration that the system can operate safely. After all, the system is only limitedly applicable: the maximum speed of 60 km/h is only applicable in situations where there is congestion[19].

3.8 Vienna Convention on Road Signs and Signals

The Vienna Convention on Road Signs and Signals, 1968, signed by more than 60 countries in the world (including Belgium) prescribes a **harmonised system** of road signs and signals, based on the use of shapes, colours and symbols. It also contains requirements relating to road markings and defines the different types of markings and the colours used.

In recent years, many countries have introduced new traffic regulations and road signs. The Expert Group on Road Signs and Signals[20] is working on an update of the 1968 Convention; this is intended, among other things, to systematically eliminate the discrepancies that have arisen as far as possible. The Treaty is also being amended to take account of **new road safety needs**.

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19 Since 1978, and based on normal conditions (no congestion, no road works), the ***Autobahn*** has had an advisory speed of 130 km/h and a minimum speed of 90 km/h on the middle lane and 110 km/h on the left lane.

20 See UNECE/Road Traffic Safety/Global Forum for Road Traffic Safety (WP.1)/Expert Group on Road Signs and Signals. *https://unece.org/transport/road-traffic-safety*

3.9 What do the figures say?

It is not yet possible to arrive at firm conclusions based on statistics, due to the limited amount of numerical data available. As more autonomous vehicles are tested and monitored, more data will become available. Comparing figures only makes sense if the comparison is contextualised, for example in terms of technological progress.

Articles in 2019 and 2020

Figures from articles published in 2020 (Petrovic, 2020; Wang et al., 2020) based on data from 2014 to 2018, indicated the following:

- that self-driving vehicles are **involved in more** accidents than non-self-driving vehicles;
- that most accidents, moreover, occur when the self-driving vehicle is in “automatic” mode;
- that in most accidents, the **cause** was **not the self-driving vehicle** but the other non-automated road user (vulnerable road user (VRU) or non-automated vehicle);
- that the **severity of accidents** involving self-driving vehicles is lower than average; that analysis of the type of collisions shows that self-driving vehicles are involved in more **rear-end collisions** on average (in which the non-automated vehicle collides with the automated vehicle);
  - this may be explained by drivers' unfamiliarity with the conservative driving behaviour of self-driving vehicles (entirely in accordance with traffic regulations);
- that automated vehicles are less involved in **side-on impacts or accidents involving pedestrians**. Self-driving vehicles tend to approach potential conflict situations cautiously, so they are thought to be more capable of avoiding these types of accidents.

Research from China

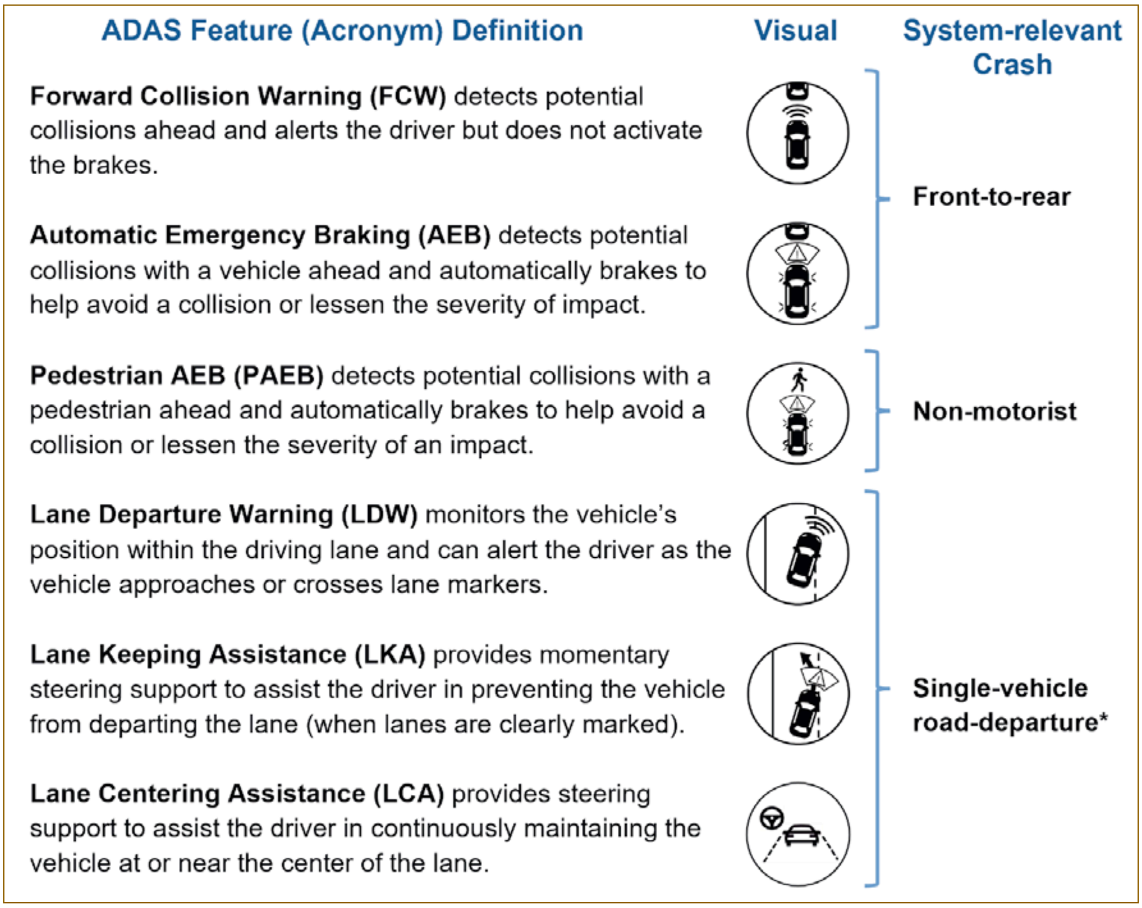
Research in China in 2022 has resulted in the compilation of different accident data with more recent statistics (Ren et al., 2022). Multiple factors affecting the severity of crashes were studied (environmental, road-related and vehicle-related variables).

- The presence of **cycle lanes** increases the probability of high accident severity (due to the higher average severity of accidents involving cyclists) compared to roads with motorised traffic only. On the other hand, the advanced sensors and algorithms of autonomous vehicles appear to be better at detecting cyclists in a timely manner than human drivers of conventional vehicles, so (the increase in) the probability of a collision is lower between a cyclist and an AV than between a cyclist and a conventional vehicle.
- **Rain, mixed land use and night driving** are reported to cause high injury severity in "autonomous mode", but their effects were not significant in "conventional driving mode”.
- **Larger numbers of lanes** are reported to increase the probability of a serious accident in conventional mode due to incorrect decisions by human drivers. Autonomous vehicles can effectively prevent such errors.
  - A larger number of lanes increases the risk of a serious accident because it usually means higher speeds.
  - Due to the advantages of autonomous vehicles, such as the avoidance of driver errors and more appropriate speeds, they outperform human drivers in the multiple-lane scenario.
- Serious accidents are 27% more likely to occur on roads with a **crossing** on both sides, compared to lanes without a crossing or roads with only one crossing at the roadside.

    - Extensive research on interactions between pedestrians and autonomous vehicles has shown that autonomous vehicles are not yet fully able to detect, understand and respond appropriately to pedestrian reactions.
    - When there is no communication between pedestrian and driver (e.g., eye contact), pedestrian behaviour becomes more unpredictable.
- The impact of **daily vehicle flow** (DVF) on crash severity was lower in autonomous driving mode than in conventional mode.
    - Autonomous vehicles equipped with advanced sensing devices can perceive objects at greater distances and are better than humans at recognising specific targets (e.g., face, text, etc.).

PARTS study

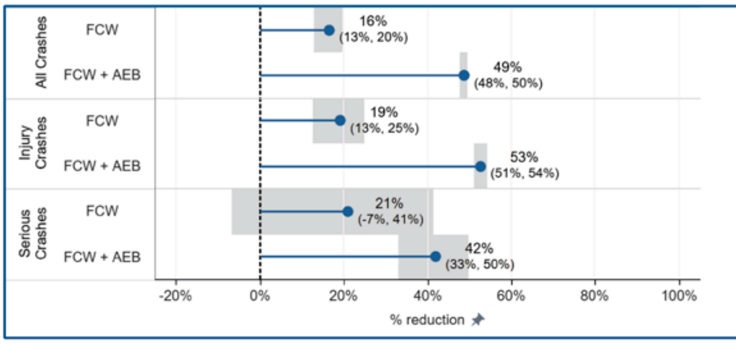
An analysis of accidents involving ADAS was also conducted in the context of PARTS (Partnership for Analytics Research in Traffic Safety [PARTS], 2022).



ADAS Feature (Acronym) Definition	Visual	System-relevant Crash
Forward Collision Warning (FCW) detects potential collisions ahead and alerts the driver but does not activate the brakes.		Front-to-rear
Automatic Emergency Braking (AEB) detects potential collisions with a vehicle ahead and automatically brakes to help avoid a collision or lessen the severity of impact.		
Pedestrian AEB (PAEB) detects potential collisions with a pedestrian ahead and automatically brakes to help avoid a collision or lessen the severity of an impact.		Non-motorist
Lane Departure Warning (LDW) monitors the vehicle's position within the driving lane and can alert the driver as the vehicle approaches or crosses lane markers.		Single-vehicle road-departure*
Lane Keeping Assistance (LKA) provides momentary steering support to assist the driver in preventing the vehicle from departing the lane (when lanes are clearly marked).		
Lane Centering Assistance (LCA) provides steering support to assist the driver in continuously maintaining the vehicle at or near the center of the lane.		

Figure 3.5 – *Study of ADAS in the PARTS study (PARTS, 2022)*

In particular, vehicles equipped with FCW (**Forward Collision Warning**) + AEB (**Automatic Emergency Braking**) showed a substantial reduction of about 50% in the number of accidents of all types. The reduction in the number of accidents involving injury was slightly higher than the reduction in the total number of accidents. When only serious accidents are included, FCW + AEB also offer an estimated 42% reduction. FCW alone still reduces the number of serious accidents by 21%.



		System Relevant	Control
All Crashes	Neither	171,409	251,957
	FCW	5,769	12,893
	FCW + AEB	39,297	137,157
Injury Crashes	Neither	41,440	251,957
	FCW	1,289	12,893
	FCW + AEB	8,598	137,157
Serious Crashes	Neither	1,918	251,957
	FCW	67	12,893
	FCW + AEB	440	137,157

Figure 3.6 – *Safety gains from FCW and AEB (PARTS, 2022)*

This PARTS study found no statistically significant results for Pedestrian Automatic Emergency Braking.

When combined with LDW (Lane Departure Warning) ADAS active lane management features (LKA – Lane Keeping Assistance and LCA – Lane Centering Assistance) reduced the probability of all accidents by about one-tenth.

Two **scientific organisations in the United States**, the Highway Loss Data Institute (HLDI) and the Insurance Institute for Highway Safety (IIHS), jointly studied the real-world benefits of crash avoidance technologies (Insurance Institute for Highway Safety [IIHS] & Highway Loss Data Institute [HLDI], 2023).

They saw high relative safety gains from automatic braking when driving in reverse and from forward collision warnings. They quite logically argue that these technologies can only be effective if they are used, and that appropriate driver responses and acceptance of the technologies are crucial to their success.

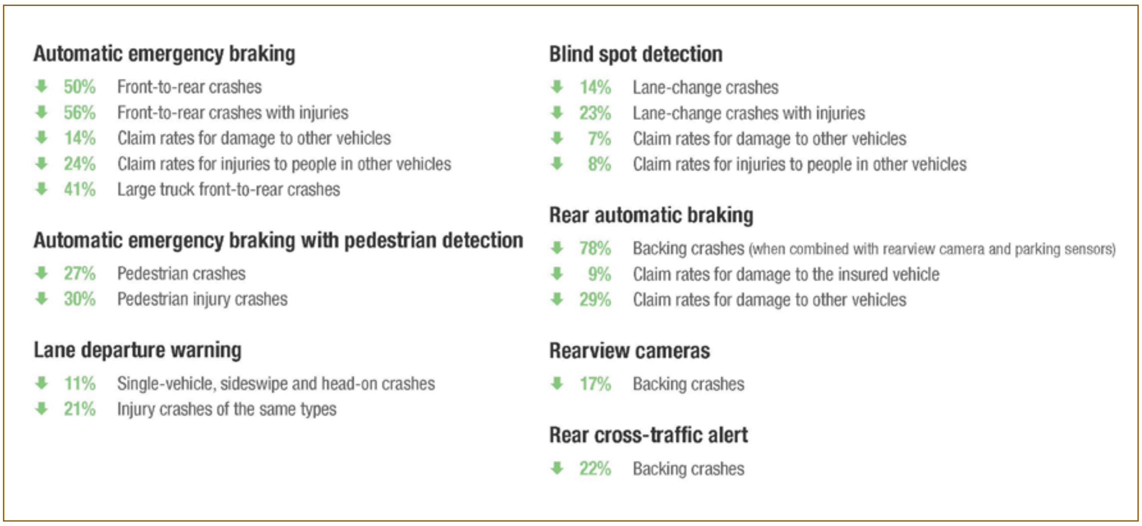


Figure 3.7 – *Real world benefits of crash avoidance technologies (IIHS & HLDI, 2023)*

However, IIHS states that crash data did not show similar benefits for the **Level 2 partial automation systems** on the market. On the contrary, IIHS research has shown that at least some of the designs could make the roads more dangerous by increasing driver complacency when driving (Drivers let their focus slip, 2020; IIHS president, 2023).

Finally, **French simulation research (Pilet e.a., 2021)** shows that an approximately 60% reduction in accidents involving injuries and fatalities can be expected if all LVs (light vehicles) on France's roads are replaced with AVs. There are differences depending on the active road user involved: the effect was lower for crashes between LVs and cyclists and motorised two-wheelers, and higher for crashes between LVs.

The tables below distinguish the **level of replacement** by autonomous vehicles (10%, 50%, 100%). Two values are given in each case: when experts disagreed, the study gives averages of low (unfavourable expert response, UF) and higher (favourable expert response, F) percentages of accidents that could potentially be avoided.

Table 1 Average percentage* of avoided injury crashes by configuration

Replacement level	Confidence interval	Crash configurations				
		LV/Pedestrian (%)	LV/Cyclist (%)	LV/M2W (%)	LV/LV (%)	LV/Truck (%)
10% AV	UF mean	6.6	3.2	2.7	8.5	4.3
	F mean	6.8	4.8	7.3	10.9	
50% AV	UF mean	33.0	15.5	13.9	40.0	21.5
	F mean	34.1	23.9	37.4	48.5	
100% AV	UF mean	66.2	31.2	27.5	72.6	43.7
	F mean	68.5	47.7	75.0	82.6	
	UC UF	14.5	20.8	12.6	15.1	20.14
	UC F	14.5	24.5	13.1	14.3	

AV, Autonomous Vehicle; LV, Light Vehicle; M2W, Motorized-Two-Wheeler; UF, Unfavourable; F, Favourable; UC, Uncovered
*% on 100% injury crashes within each configuration

Table *3.1 – Average percentage of* ***accidents involving injury*** *prevented for each configuration (Pilet e.a., 2021)*

Table 2 Average percentage* of avoided fatal crashes by configuration

Replacement level	Confidence interval	Crash configurations				
		LV/Pedestrian (%)	LV/Cyclist (%)	LV/M2W (%)	LV/LV (%)	LV/Truck (%)
10% AV	UF mean	6.4	3.4	2.8	10.4	6.4
	F mean	7.0	4.2	7.4	11.7	
50% AV	UF mean	31.8	15.4	13.9	47.8	31.9
	F mean	34.8	19.6	37.1	53.0	
100% AV	UF mean	63.3	30.8	27.8	85.2	63.8
	F mean	69.3	39.6	74.0	92.1	
	UC UF	17.5	7.5	2.1	2.5	8.80
	UC F					

AV, Autonomous Vehicle; LV, Light Vehicle; M2W, Motorized-Two-Wheeler; UF, Unfavourable; F, Favourable; (here results are the same for F and UF); UC, Uncovered
*% on 100% fatal crashes within each configuration

Table *3.2 –Average percentage of* ***fatal accidents*** *prevented for each configuration (Pilet e.a., 2021)*

Chapter 4
Policy objectives concerning road safety

We saw in the previous chapter that the causes of accidents can be wide-ranging and that they often involve a combination of factors. More and more vehicles are equipped with advanced driver assistance systems (ADAS). Eventually this could lead to drivers being replaced by a self-driving system (ADS).

However, it will be a long time before a fully systemic change to autonomous mobility can take place and bring about the hoped-for improvements in road safety. Gradually, policy documents setting out longer-term goals will have to shift towards a greater focus on connected and, subsequently also on fully autonomous vehicles. In situations where autonomous self-driving systems are not yet reliable enough, remote driving may be an interim solution, as long as a reliable connection is available[21].

However, the development of autonomous vehicles cannot be seen in isolation or separate from the transport system as a whole. Now the entire system must be considered in order to understand the causes of road traffic accidents.

The term currently used in policy documents for the **integrated approach** is **Safe System approach**, where previously there was the Human Error approach. In the Safe System approach, the function, design, layout of roads and their speed limits are coordinated in such a way that human error does not result in deaths and serious injuries. This approach is based on the assumption of shared responsibility.

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[21] Remote driving is part of what is known as "teleoperation". Teleoperation is a catch-all term that encompasses monitoring, assisting and controlling of autonomous vehicles by a teleoperator from a remote location (How does remote driving work?, 2022)

Safe System Approach (ITF, 2016)

The Safe System Approach brings together four principles that guide thinking and policy to ensure design and operation of the road network in a way that ultimately avoids fatalities and serious traffic injuries caused by road traffic accidents (Figure 4.1).

A Safe System for road traffic encompasses four principles:

1. People make mistakes that can lead to road traffic accidents.
2. The human body has a limited physical ability to tolerate impact forces before physical injury occurs.
3. There is a shared responsibility between those who design, build, manage and use roads and vehicles and those who provide post-accident care to prevent accidents resulting in serious injury or death.
4. All parts of the system must be improved in order to multiply the resulting effects. If one component fails, road users are still protected.

A safe system requires a holistic understanding and management of the complex and dynamic interactions between speeds, vehicles, road infrastructure, and the behaviour of road users. Unlike some approaches, a Safe System does not, in principle, accept a trade-off between road safety and other priorities, nor does it view traffic fatalities and serious injuries as a price to be paid.

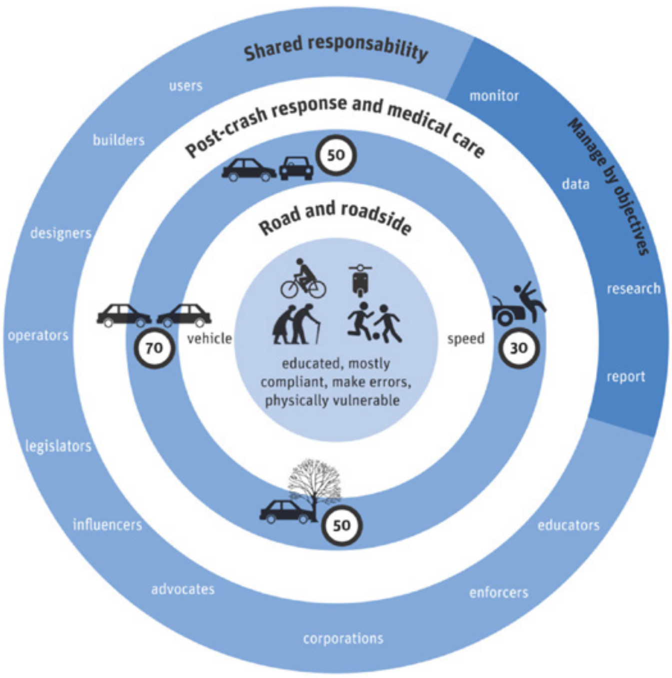

Figure 4.1 – *Graphical representation of the Safe System Approach (ITF, 2016)*

In the centre of Figure 4.1 are a number of road users who deserve special attention because they are physically vulnerable and because it must be assumed that human beings do make mistakes.

The second circle represents the relationship between speed, roads, roadsides and vehicles, encouraging users to behave safely in traffic and take action to ensure that an accident does not result in a serious injury. These two outcomes are achieved through interactions between the physical design, the layout and operating conditions of the road and roadside area, and vehicles, to permit safe operating speeds, safe vehicle operation and safe outcomes. Safe System vehicles use **active technology** (e.g., smart speed assist or collision avoidance systems) to help the driver to take action (or intervene if he does not), as well as secondary collision protection for both vehicle occupants and people outside the vehicle.

The third circle represents the second Safe System-principle that the human body has a limited physical ability to tolerate impact forces. A safe system attempts to reduce the risk of serious injury by anticipating possible causes and controlling the three components in the second circle and the interactions between them to prevent collisions with impact forces above dangerous levels.

The fourth circle in the Safe System-diagram concerns medical care after an accident. Health outcomes for accident victims depend on the ability of the emergency medical response system to locate first responders who can provide medical assistance, stabilise the victim and then transport the person to the appropriate emergency hospital treatment.

Together, the second and fourth circles illustrate the third principle of a safe system, which is that every part of the system must be strengthened to multiply their effects; if one part fails, road users are still protected.

The fifth and outer circle of the diagram illustrates the fourth principle of shared responsibility for a safe system: responsibility is shared between those who design, build, manage and operate roads and vehicles and those who provide after-care to prevent accidents resulting in serious injury or death.

Specifically, in an **accident in which a vehicle leaves the road on a bend**: a driver may have been travelling too fast because the appearance of the road suggested doing so.

- In that case the cause (driving too fast) is not purely the driver's fault but but also due to the environment. The **Safe System** approach takes into account the fact that human drivers make mistakes.
- Vehicle-related measures (e.g., ISA/LKA) and infrastructure measures (e.g., modified road layouts) are intended to reduce the likelihood of errors (driving too fast). If an accident still occurs despite these measures, other interventions (a forgiving roadside design) can help to mitigate the consequences of the accident.
- Even in this integrated approach, the **human** factor continues to play an important part. New technology is being used in an attempt to reduce the impact of the human factor, or at least to compensate to some extent for the unpredictability of human behaviour.
- At present mainly vehicles are being equipped with **new technology**. In future, however, the environment will also be equipped with new technology to ensure that the various components of the system work together as safely and reliably as possible.

4.1 Toward zero traffic fatalities

More and more policy documents are including an ultimate goal of **zero traffic fatalities by 2050.** This represents a break with the past; previously targets were set that "accepted" a number of traffic deaths as collateral damage from the road system. Now the idea is that the traffic system can and ultimately should be organised in such a way that no more traffic deaths occur.

Similar policies have been initiated in countries that were early to identify road safety as a very high priority. The Swedish policy, which bears the very clear title **Vision Zero** and was first introduced in 1994, is seen as the first and most important inspiration for road safety policies in many countries and in umbrella organisations such as the World Health Organization (WHO), the United Nations (UN) and the European Union (EU).

4.2 The World Health Organization and the United Nations

In September 2020, the UN General Assembly adopted Resolution A/RES/74/299 "Improving Global Road Safety" (UN General Assembly, 2020), declaring the Decade of Action for Road Safety 2021-2030, with the ambitious goal of **preventing at least 50% of road deaths and injuries by 2030**.

WHO and UN Regional Commissions worked with other partners in the UN road safety collaboration to develop a global plan for the decade of action, which was published in October 2021.

The plan includes a section on new technologies entitled Adapting technologies to the Safe System (WHO & UN Regional Commissions, 2021). The elements mentioned are quite general and the reasoning is closely linked to the automotive technology and safety systems used.

The reasoning is that **automotive technology** is changing at an unprecedented rate.

- While there is debate about the **potential of emerging technologies**, advanced driver assistance systems, including electronic stability control, lane change alerts and automatic emergency braking are already saving lives in many countries. Future functions of automated vehicles are being developed that may save even more lives.
- **V2V and V2I communications** can also contribute towards making mobility safer and more sustainable. In particular, this possibility may improve the safety of pedestrians, cyclists and powered two-wheelers. Similar technology may also allow route planning to reduce congestion, reduce emissions and optimise safety.
- Promoting the development of safety technology that can cope with a wide range of environments is one part of the challenge.
- The other aspect involves managing the technological revolution and its potential positive and negative impacts on road safety. Increasing connectivity and other mobile technologies are creating **new opportunities and challenges**, requiring policies, regulations and traffic laws to be evaluated and updated.

Particularly in the area of **infrastructure**, aspects are outlined that are really important (including minimum standards for basic features). Comments about the road safety aspects of autonomous vehicles and infrastructure are reserved until the end of the section on new technologies (WHO & UN Regional Commissions, 2021).

- Minimum technical infrastructure standards are mandatory, to improve the safety of pedestrians, cyclists, motorcyclists, vehicle occupants, public transport users, freight carriers and other mobility users.
- These standards should include basic features such as vertical and horizontal signage (traffic signs and road markings); footpaths; safe crossings; cycle lanes; motorcycle lanes; bus lanes; safe roadside areas; separation of different modes of transport; median separation for high-speed traffic; intersection design; and appropriate speed limits for the location, the desired facility and the type of traffic.
- **Physical and digital infrastructure requirements** for advanced driver assistance technologies and **autonomous vehicles** need to be **specified**.

4.3 European Union policy

The European Union (European Parliament resolution P9_TA[2021]0407, 2021) incorporates a wide range of considerations in its road safety policy, such as:

- the existence of new trends and challenges in the field of **automation** which could have huge implications for road safety;
- the need to address the growing phenomenon of distraction by mobile devices;
- the presence in the near future of vehicles with a wide range of **automated/connected** components alongside conventional vehicles in blended traffic, posing a new risk, particularly for vulnerable road users like motorcyclists, cyclists and pedestrians;
- the fact that technological progress, connectivity, automation and the sharing economy are creating new opportunities for road safety and for addressing congestion, particularly in urban areas;
- developing synergies between safety and sustainability measures and the continuing modal shift towards sustainable modes of public transport and active mobility, which can reduce CO_2-emissions, improve air quality and promote the development of more active, healthier lifestyles.

Policy considerations of this kind have resulted in the EU Road Safety Policy Framework 2021-2030. This includes the following striking **objectives**:

- to achieve a figure for the number of deaths and serious injuries on EU roads that is **close to zero** by 2050 at the latest (Vision Zero);
- medium term: to reduce the number of deaths and serious injuries by 50% from 2020 to 2030;
- to define outcome targets by 2023 using the Safe System approach and an EU-wide harmonised methodology for the use of Key Performance Indicators (KPI's).

The same policy framework also includes a number of **requests** that may be relevant to autonomous vehicles, such as:

- A request to the Commission and Member States to accelerate their work on **EU specifications for the performance of road signs and road markings** to pave the way for greater vehicle automation[22].

  - The Parliament reiterates the importance of the performance of road signs and road markings, including their placement, visibility and reflectivity, particularly for the effectiveness of driver assistance systems such as intelligent speed assistance and lane keeping assistance.

- The Parliament emphasises the importance of using infrastructure, so that the roads that are built are self-explanatory, **enforce correct driving behaviour** and are "forgiving" to improve safety for all road users, especially in hazardous areas or in areas with a significant number of vulnerable road users.
- A request to the Commission to propose a new, **harmonised regulatory framework for automated cars**, using comprehensive testing including real-world driving conditions, to ensure that automated cars operate in a manner that is completely safe both for their drivers and for other road users, particularly regarding their interactions with conventional vehicles and vulnerable road users.
- A request to the Commission to meanwhile assess the road safety risks of the **existing advanced driver assistance systems**, such as excessive dependency and driver distraction.
- A request to the Commission to consider introducing a requirement to equip drivers' mobile and electronic devices with a "safe driving mode" and consider the installation of other technological tools by default to reduce distractions during driving.
- The Parliament emphasises that external factors and emerging societal trends are posing unprecedented challenges for road safety in the context of the EU's strategy for 2030 and beyond.

  - It notes that the EU has to clear the way for **connected and automated vehicles to be introduced at the right times** and must assess the potential risks of combining these vehicles in blended traffic with both conventional vehicles and vulnerable road users.
  - It asks the Commission to thoroughly assess the impact of the increased number of automated vehicles on traffic in urban areas and on the environment.
  - It emphasises that it may be necessary to **upgrade infrastructure** to ensure that automated and semi-automated vehicles can operate safely, while also improving the safety of conventional vehicles, leading to benefits for all road users.

[22] EC Expert Group on Road Infrastructure Safety (EGRIS): *https://ec.europa.eu/transparency/expert-groups-register/screen/expert-groups/consult?lang=en&do=groupDetail.groupDetail&groupID=3686*

4.4 Belgium: All for zero[23]

The inter-federal plan All for zero (All for zero, 2021) is the joint vision and commitment of the regional and federal governments to introduce road safety measures eventually intended **to achieve zero road traffic deaths**. This common vision builds on existing regional and federal goals and action plans.

Table 1. Targets for 2030 and 2050

	Current value (2019)	Current value (2030)	Current value (2050)
Number of traffic deaths	644	< 320	0
Number of seriously injured in traffic (MAIS3+)	3600	< 1800	< 360

Figure 4.2 – *Targets for 2030 and 2050 in Belgium according to the inter-federal plan All for zero (All for zero, 2021)*[24]

Alongside the existing areas of concern, this plan also identifies "**new challenges** for road safety". It is noticeable that the problem of road safety in regard to autonomous vehicles is described only in terms of problems with alertness, risks of system failure and cybersecurity. The wording is as follows: "increasing **automation of certain driving tasks** which can lead to reduced alertness; eventually problems could also result from system and cybersecurity failures."

The plan also states that **new technologies offer opportunities**, stating, among other things, that the "evolution toward 'smart' roads (that can be read by automated vehicles) and Intelligent Transportation Systems (ITS) and Smart Mobility can help to improve road safety."

Based on the Safe System approach, the various governments are committed to working, within their own remit, towards the ten **general goals**.

[23] Interfederal, shared vision "All for zero: a shared vision of road safety in Belgium" (Staten-Generaal 2021, 2021)

[24] MAIS: Maximum Abbreviated Injury Scale: The Abbreviated Injury Scale (AIS) severity score is an ordinal scale from 1 to 6 (1 indicating a minor injury and 6 being maximal). A casualty that sustains an injury with a score of 3 or higher on the AIS is classified as clinically seriously injured (MAIS3+).

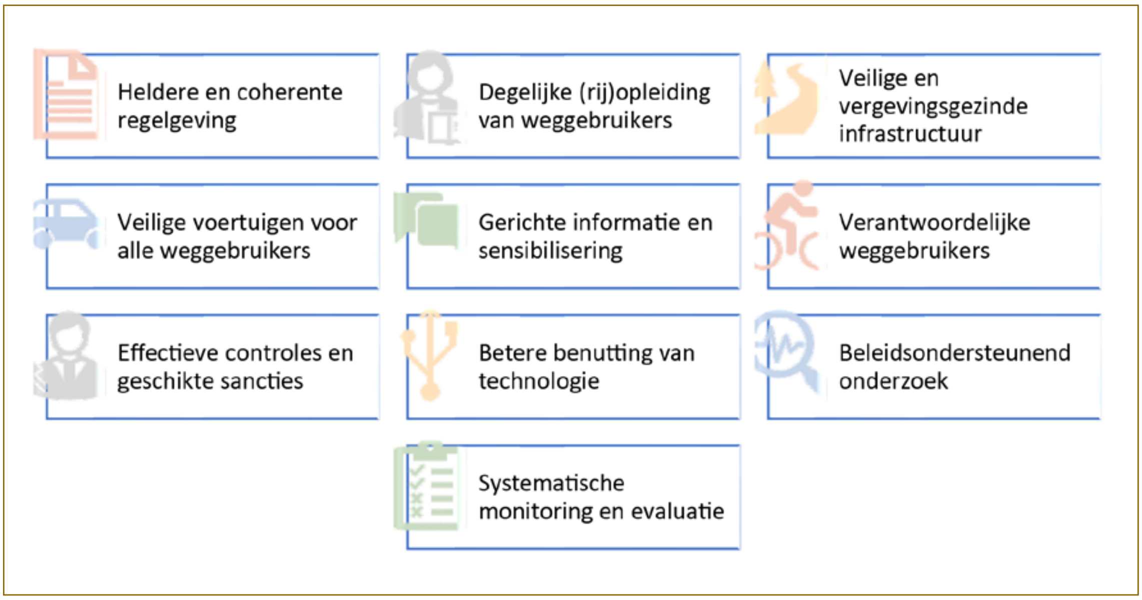

Figure 4.3 – *Ten general objectives of the inter-federal plan (All for zero, 2021)*

It is clear that some elements of the development towards **autonomous vehicles** are included in the general objectives of All for zero, but putting them into practice will mainly be the responsibility of the regions[25].

[25] The FPS Mobility and Traffic's code of conduct for testing autonomous vehicles will be used as a framework (§ 3) (Federale Overheidsdienst Mobiliteit en Vervoer [FOD Mobiliteit en Vervoer], 2016)

4.5 Regulations

In the Roadmap for the deployment of automated driving in the EU (ACEA, 2019b), ACEA (Association de Constructeurs Européens d'Automobiles)[26] outlines the steps it considers to be **relevant and necessary** for the deployment of autonomous vehicles. Apart from the technological developments and steps required to work towards a more uniform infrastructure, the existing regulations at the international, European and national levels are very diverse; the areas covered include vehicle functionality, cybersecurity, rules relating to driving and rest periods but also regulations governing traffic, road infrastructure and road safety.

Chapter 5 of Connected and Autonomous Vehicles & road infrastructure, state of play and outlook (Redant & Van Geelen, 2021) lists relevant regulations for the roll-out of intelligent transportation systems and self-driving vehicles. The most prominent infrastructure-related aspects are:

- striving to create a connection between road infrastructure and the vehicle including through data sharing agreements (Directive 2010/40/EU, 2010; Commission Delegated Regulation 2022/670, 2022);
- Commission Delegated Regulation (EU) 2015/962, 2015 (Real Time Traffic Information - RTTI) makes a distinction between static road data (speed limits, the road layout, restrictions on certain types of vehicles, etc.), dynamic road information (road works, accidents, road surface in poor condition, etc.) and traffic information (traffic flows etc.);
- Commission Delegated Regulation No. 886/2013, 2013 (Safety Related Traffic Information - SRTI) focuses on communication of a series of conditions or events that compromise road safety;
- Directive (EU) 2019/1936, 2019 (Road Infrastructure Management - RISM) calls for a specific focus on the recognisability of road markings and road signs for both human drivers and automated systems. According to this directive, the desirability of European recommendations regarding the visibility of these facilities is also examined;
- Regulation (EU) 2019/2144, 2019 covers the homologation of new vehicles. Under this regulation, driver assistance systems should be enabled by default. Nevertheless, the regulation allows these systems to be **disabled** (either manually or automatically) if the available infrastructure is not adequate to allow these systems to function reliably. For ISA in particular, the regulation indicates that speed information used in the vehicle may come from observations made on **infrastructure** or from other data sources. Experience has shown, however, that traffic signs are not enough by themselves to allow ISA systems to function reliably (ITS.be, 2022).

[26] The European Automobile Manufacturers' Association (ACEA), brings together Europe's 16 major car, truck, van and bus manufacturers. https://www.acea.auto/about-acea/

Chapter 5
The role of infrastructure in road safety aspects relating to autonomous vehicles

In Chapter 1 we looked at the different **SAE levels** that exist in regard to autonomous driving. The lower levels are classed as advanced driver assistance systems (ADAS), while the higher levels are referred to as autonomous driving (ADS). It is important to maintain this distinction in order to grasp the road safety aspects of semi-autonomous and fully autonomous driving. Supporting functions (ADAS), eventually leading to autonomous driving (ADS) can contribute towards improvements in road safety.

The technology is progressing at lightning speed. Car manufacturers and developers of advanced driver assistance systems are increasingly successful at integrating their systems into vehicles. Sensors are becoming more reliable, cheaper and more readily available, allowing them to be incorporated more widely into new vehicle models. As a result, special adaptations to infrastructure seem to be less and less of an **absolute requirement** for the deployment of self-driving vehicles. Nevertheless, as in the case of conventional vehicles with human drivers, infrastructure still **contributes** towards allowing advanced vehicles to function properly and deliver smooth, comfortable and safe travel.

5.1 Connectivity, CCAM, Communication

As well as developing sensing systems and improving decision-making algorithms, experts anticipate considerable benefits from the addition of **connectivity** (between vehicles and between vehicles and infrastructure) to cars.

Even the best sensors currently available can only see a maximum of 250 m ahead. Travelling on a motorway at a speed of 120 km/h, visible situations can therefore be detected 7 to 8 seconds in advance. Enabling vehicles to receive real-time information from other vehicles or from road infrastructure and use that information as a data source for driver assistance systems will mean that action can be taken more quickly (informing the driver or active intervention by the vehicle). Road infrastructure and road users will then function like **remote sensors**, informing other road users and providing information that can be used to optimise road traffic (in terms of safety, mobility and the environment).

5.2 Transferring control (disengagement)

In the **transitional period** from advanced driver assistance systems to fully self-driving vehicles, the role of the human driver in the existing systems continues to be vital[27]. Even when the vehicle is operating autonomously within the existing operational design domain - in the case of SAE L3 - the human driver must remain alert and able to take over the controls if conditions require this[28]. During the transitional period, as the driver's input gradually decreases, it is possible that levels of driving experience will decrease (**deskilling**) to the point where it is not adequate at times when it is needed most; i.e. in complex situations when the vehicle's automated functions disengage. It is only at SAE levels 4 and 5 that vehicles are fully autonomous in most circumstances (SAE level 4) or in all situations (SAE level 5).

If the vehicle detects a situation it cannot handle, it will transfer control to the driver (**disengagement**). Depending on the driver's level of awareness of the environment (**situational awareness**) and numerous other parameters, it can easily be a few seconds[29] before the driver is sufficiently aware of his driving environment and has appropriately taken back control of the vehicle.

The system must be designed to be fail-safe so that the vehicle will stop safely if the driver does not respond to a transfer request. The driver's **response time** that is needed before they can resume control of the vehicle depends on what the driver is doing, such as listening to music, reading an article or talking on the phone (NDR tasks[30]). Response time also varies with driving experience and age (Benam, 2021).

An admittedly limited experiment in a **driving simulator** showed that older drivers are generally better at taking back control of a self-driving vehicle. This experiment also showed that about half of the participants did not see the visual cue to take back control and three-quarters of the participants accelerated after taking control rather than slowing down as expected (Favaro et al., 2019).

The transfer of control should ideally be as seamless as possible. Simply requesting a transfer is not enough. It is necessary to verify that whoever is now responsible for driving (either the human driver or the system) **actually has control** of the vehicle. If this resumption of control is inadequate or does not occur at all, the system must be able to take appropriate action (slow down or come to a safe stop).

It is likely that questions will be asked in future about **where** the single occupant of an autonomous vehicle can sit. If it must be possible to take the wheel of the vehicle at any time, there will still be a "driver's seat". In other cases, the vehicle will have to stop effectively so that the occupant can move to the correct seat.

Problems with the infrastructure (e.g. visibility of signs or defects in the road surface) and problems with the environment more broadly (e.g. road works) may cause a self-driving vehicle to request

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[27] For now, passenger cars that routinely take control from a human driver still need the driver to be able to resume control. There are, however, also some pilot projects in which self-driving vehicles operate without a human driver within a well-defined environment.

[28] Transfers of control can be initiated either by the vehicle or by the driver.

[29] Research has indicated that the required transition time (from vehicle to driver) is eight to ten seconds (De Bruyne, 2021, Hoofdstuk 5, Deel 5).

[30] NDR-tasks: Non-Driving Related Tasks

operator intervention. Based on the available information, however, infrastructure or the environment are not the main **reasons for disengagements**. Most transfers of control are initiated by the driver due to infrastructure or environmental problems, not because the system cannot handle them.

The graphical representations below indicate that the number of disengagements initiated by the (vehicle) system is moving in the right direction and vehicles appear to be increasingly capable of handling all kinds of situations appropriately.

Moreover, the situations that result in a human operator taking control do not necessarily constitute safety hazards.

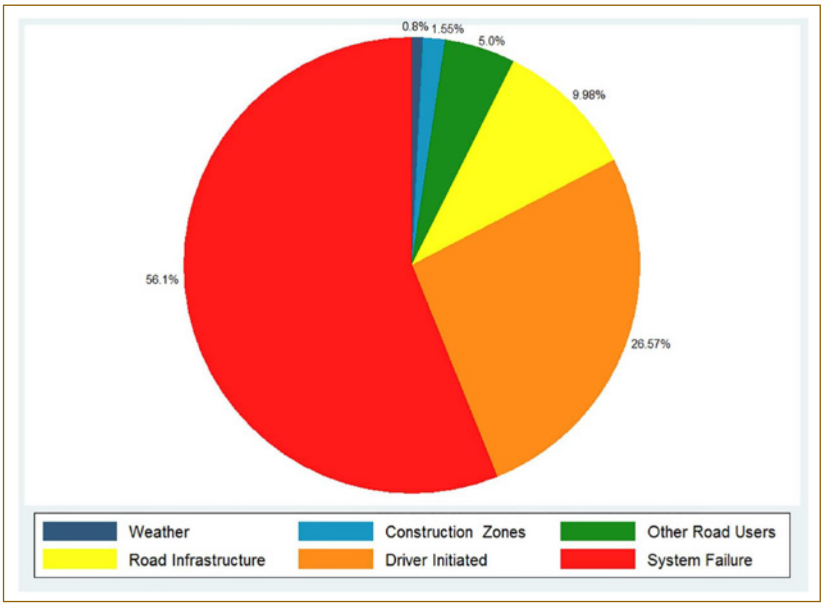


Figure 5.1

Reasons for disengagement, based on public road testing in California (09/2014-11/2015) (Dixit et al., 2016)

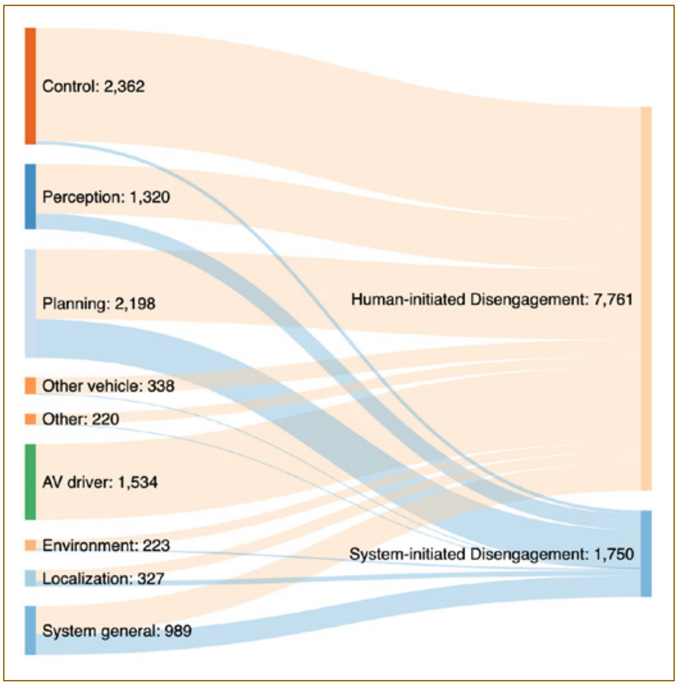


Figure 5.2

Reasons for disengagement, based on tests on public roads in California, 2021 (Zhang et al., 2021)

Figures 5.1 and 5.2 do, however, also suggest that as vehicle systems function more reliably and occupant confidence also increases, other factors (including infrastructure) may begin to play a larger role.

Artificial intelligence applications, or AI for short, can be designed to inform the driver about the current or upcoming traffic situation (Benam, 2021).

- An AI-based system can communicate with the driver in a "human" way instead of alerting them via a warning light or vibrating steering wheel. Voice messages improve the safety and reliability of the entire system.
- AI applications enable drivers to be ready before a hazard arises. That can lower their response times in the case of a possible transfer.
- AI applications can monitor previous transfers and adjust the way future transfers are guided, based on driver characteristics such as age, experience or response time, or other time-related parameters or situations that have occurred simultaneously. The transfer time of about 10 seconds can therefore be adjusted and increased or decreased, as long as doing this is not contrary to any safety goals.
- Driver personalisation by AI systems can improve the availability and safety of the system.

5.3 Road signs and road markings

Just as road signage affects the driving behaviour of human drivers, it can also **help** ADAS and ADS to operate more appropriately and reliably.

Research in Australia (Marr et al., 2020) on the capabilities and limitations of current machine vision systems for recognising road markings has generated a number of observations:

- recognising markings is more difficult during the day than at night;
- contrast between the markings and the road surface is an important factor;
- the colour of the markings has only a limited influence;
- unclear configurations will confuse automated systems too;
- bright sunlight and shade are difficult;
- dashed markings are usually less easy to identify than continuous markings. Sufficiently wide markings and good visibility features then become even more important.

Manufacturers of both cars and driver assistance systems currently appear to need clearly visible and **uniform traffic signs and road markings** for the operation of ISA and LDW (Lane Departure Warning) / LKA (Lane Keeping Assist).

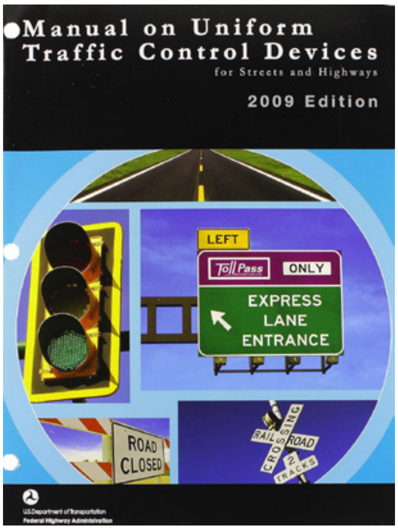
More advanced road marking **detection systems** based on LIDAR technology can also identify the edge of the road based on changes in the surface or a difference in level. One disadvantage, however, is that ghost markings (covered markings) or joints may - because they cause surface changes - be falsely identified by LIDAR systems as the edge of a traffic lane.

For optimal performance, it is still important for markings to be sufficiently visible. In the case of LIDAR detection systems, retroreflection also facilitates better detection during the day. Markings are also more visible to camera-based and LIDAR-based detection systems if the edges of the marking are more clearly outlined and if there is a greater contrast between the marking and the road surface.

Following the revision of the RISM Directive (EU) 2019/1936, 2019, Europe is considering whether it is advisable to introduce European **specifications** for the visibility and recognisability of road markings and road signs, for the benefit of both human drivers and self-driving vehicles[31].

The United States Federal Highways Agency (FHWA), in the updated version of their Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD), focuses on **markings for the benefit of self-driving vehicles**[32].

MUTCD



(US Department of Transportation [US DOT], Federal Highway Administration [FHWA], 2023)

MUTCD defines the recommendations for road authorities nationwide concerning the installation and maintenance of traffic control infrastructure on all public roads, highways, bicycle lanes and private roads that are accessible to passenger traffic. This is a compilation of the national recommendations for all traffic control infrastructure, including road markings, highway signs and traffic lights. The document is updated periodically to reflect the country's changing transportation needs and to address new safety technologies, traffic control tools and traffic management techniques.

The May 2023 edition includes the updates required to support safe testing of automated vehicle technology and all the necessary preparations for safe integration of automated vehicles on public roads.

31 In the EGRIS working group (Expert Group on Road Infrastructure Safety)
32 https://mutcd.fhwa.dot.gov/

A subgroup of the UNECE/Global Forum for Road Traffic Safety (WP.1) has launched an initiative to harmonise the various types of road signs, partly to improve the functional reliability of advanced driver assistance systems.

Figure 5.3 – *A few variants of the "dangerous descent" sign*[33]

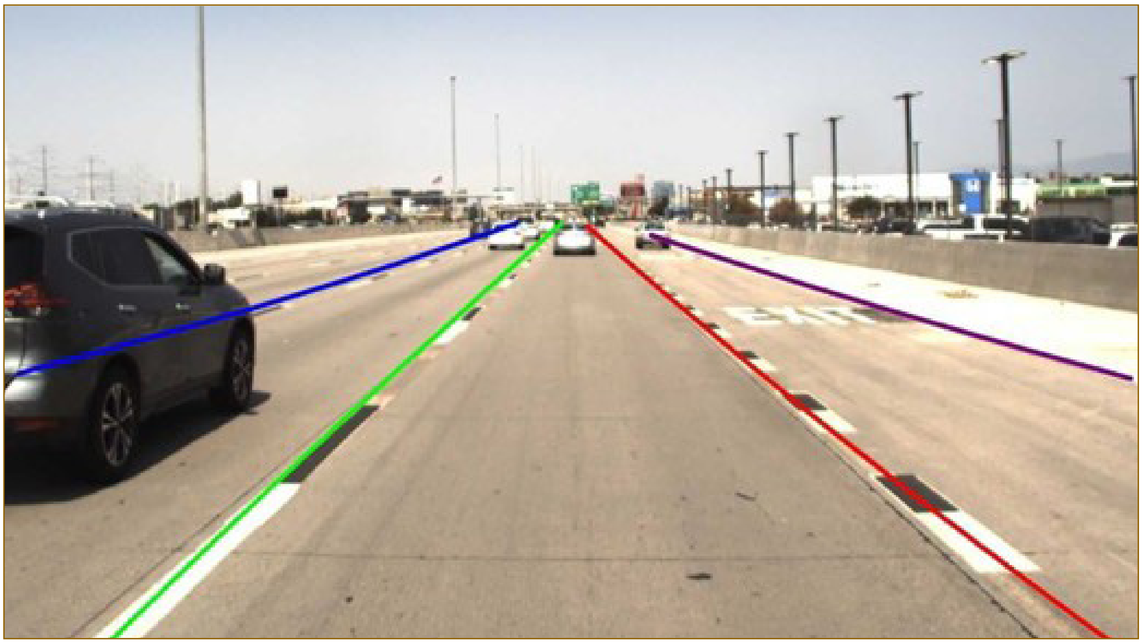


Figure 5.4 – *Contrast lane markers improve the reliability of LKA (Lane Keeping Assistance) and LDW (Lane Departure Warning) systems, particularly against light-coloured road surfaces and in bright light (VSI Labs, 2021)*

33 5.3a (Verkeersbord SB250 A3, 2023); 5.3b (Finnish Transport Infrastructure Agency, s.d.); 5.3c (Roadsigns in Norway, 2023); 5.3d (National Driving School, 2023)

Recognition of speed limits by relying solely on detection of traffic signs has been found not to be sufficiently reliable[34]. Degradation of signs, weather conditions and insufficient visibility of signs due to other obstacles mean that sensors are not always able to recognise traffic signs correctly. In situations where there are different speed limits on two adjacent roads, there is also a chance that the applicable speed limit may not be recognised correctly. In quite a few cases, the speed limit is also determined in ways other than by road signs alone.

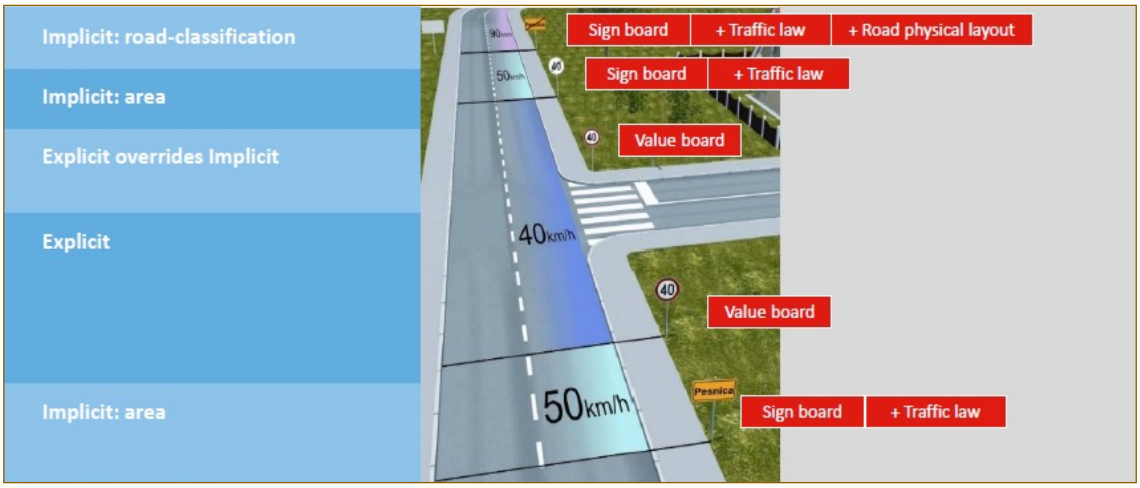


Figure 5.5 – *Illustration of elements that determine speed limits (ITS.be, 2022)*

Figure 5.6 – *Different speed limits on a main road and parallel road (Klem, 2022)*

Regulation 2019/2144 also allows ISA and LDW/LKA to operate on the basis of data sources (crowdsourcing, digital maps, etc.) rather than relying solely on observations by in-vehicle sensors. At present it seems that including information from these other data sources is the only way to ensure sufficiently reliable operation of ISA and LDW/LKA systems.

34 According to ACEA, ISA systems based on cameras alone detect the applicable speed limit correctly in only 50% of cases (ITS.be, 2022)

5.4 Road surface and obstacles

Human drivers are usually good at detecting obstacles on the road surface or defects in good time and either avoiding them or adjusting their driving behaviour so that they ultimately have only a limited impact on traffic.

Road surface defects are currently difficult for autonomous vehicles to interpret. They will pass control back to the driver for reasons of caution, if this is warranted. Information about **transfers of control** must be timely and clear, and the driver must have sufficient skill to operate the vehicle[35].

Limited experience with self-driving shuttles in Belgium suggests that these vehicles are not always able to handle obstacles correctly. Due perhaps in part to the conservative configuration of this shuttle (which is designed to err on the safe side), stationary vehicles, small obstacles and overtaking vehicles that re-enter a lane too quickly can cause the **vehicle to stop**, sometimes abruptly, requiring action by the human operator to get the vehicle moving again[36].

The self-driving shuttles currently being used in pilot projects in Belgium appear to be reasonably good at distinguishing obstacles, but they still have **difficulty avoiding** them. Pilot projects with more sophisticated self-driving vehicles in other parts of the world (and, after 2022, probably in Europe as well) indicate that obstacles of this kind will not necessarily restrict the operation of these vehicles for very long.

5.5 Emergency refuge area (Xue et al., 2022)

In situations where the occupant is unable to take control of the vehicle when requested and the self-driving vehicle is unable to handle a situation, the vehicle must be able to stop safely on all road types[37]. The question arises of whether it is safer for cars to stop on the hard shoulder, or whether they should use an emergency refuge area.

35 § 5.3 Transferring control (disengagement)

36 Initial experience gained from pilot shuttle projects in Waterloo (VIAS) and Louvain-La-Neuve (TEC + Ville de Louvain-la-Neuve) has shown that obstacles regularly caused the vehicle to stop. Operator intervention was then needed to get the vehicle moving again (Mertens, 2022).

37 UN, 2021 speaks of a Minimum Risk Manoeuvre; this means coming to a controlled stop within the traffic lane and activating hazard warning lights.

5.6 Classification of roads

In many cases, advanced driver assistance or self-driving functions in vehicles only work under well-defined conditions. If advanced driver assistance functions work on a given road for a particular vehicle, that does not guarantee that the same functions will work on a different vehicle model. **Classification of roads according to their readiness** to support certain functions could be a step towards harmonisation. When developing advanced driver assistance systems, companies can focus on this classification and the associated infrastructure features. For road operators, the classification would provide them with a guide to the level at which specific infrastructure elements should be maintained to support ADS and ADAS (regardless of the vehicle).

The INFRAMIX project (Infrastructure categorisation, 2017) included a proposal for a classification to indicate the extent to which the available infrastructure supports both automated and conventional transport; particularly during the transitional period when both types are sharing the road. The classification, known as **ISAD levels** (Infrastructure Support Levels for Automated Driving), provides information on the extent to which a road is equipped with connectivity support and prepared for future automated traffic.

	Level	Name	Description	Digital information provided to AVs			
				Digital map with static road signs	VMS, warnings, incidents, weather	Microscopic traffic situation	Guidance: speed, gap, lane advice
Digital infrastructure	A	Cooperative driving	Based on the real-time information on vehicles movements, he infrastructure is able to guide AVs (groups of vehicles or single vehicles) in order to optimize the overall traffic flow	X	X	X	X
	B	Cooperative perception	Infrastructure is capable of perceiving microscopic traffic situations and providing this data to AVs in real-time	X	X	X	
	C	Dynamic digital information	All dynamic and static infrastructure information is available in digital form and can be provided to AVs	X	X		
Conventional infrastructure	D	Static digital information / Map support	Digital map data is available with static road signs. Map data could be complemented by physical reference points (landmarks signs). Traffic lights, short term road works and VMS need to be recognized by AVs	X			
	E	Conventional infrastructure / no AV support	Conventional infrastructure without digital information. AVs need to recognise road geometry and road signs				

Figure 5.7 – *Classification of infrastructure for autonomous vehicles: ISAD levels as proposed in the INFRAMIX project (Infrastructure categorisation, 2017)*

PIARC has built on these ISAD levels with its Smart Road Classification (Garcia Garcia, 2021). The LOSAD[38] level (related to physical infrastructure) is combined with the ISAD level (related to digital infrastructure), resulting in five **Smart Road Levels**. These five smart road levels differentiate the readiness of the road network for autonomous vehicles, with differences in connectivity and in the numbers of disengagements that would be required (Figures 5.8 and 5.9).

38 LOSAD-level: Level Of Service of Automated Driving; indicates the degree to which a section of road is compatible with all, some or no vehicle ODDs (E: not compatible with vehicle ODDs, A: compatible with most vehicle ODDs).

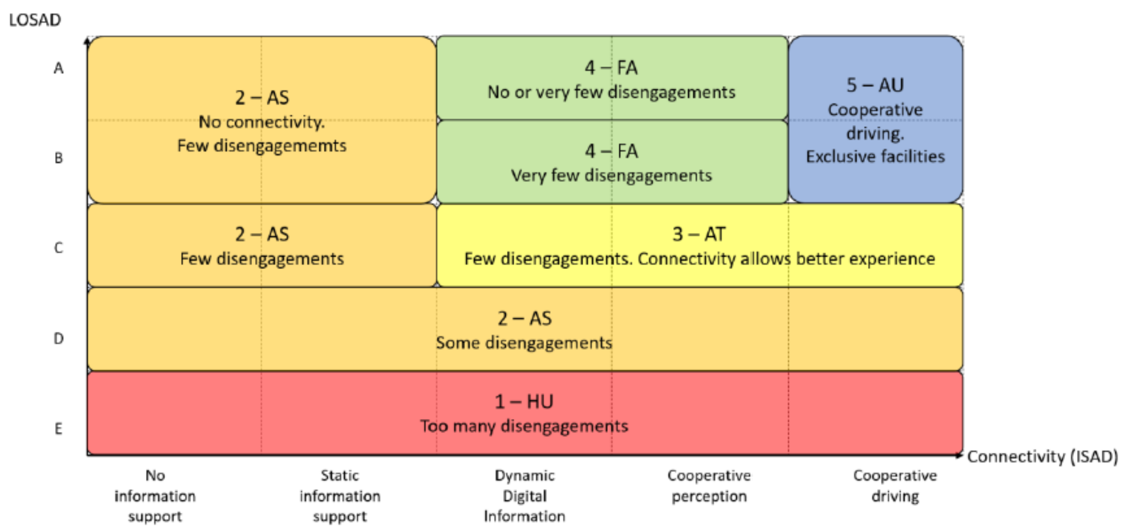


Figure 5.8 – *SRL (Smart Road Level according to PIARC) (Garcia Garcia, 2021)*

Smart Road Level	Description
Human way (HU)	The road segment is not ready to host CAVs, due to the high number of disengagements, and/or the low capability for sharing of digital data to inform vehicles about their ODDs.
Assisted way (AS)	The road segment is adequate to perform autonomously, but this condition may cease to apply due to a variety of factors (not as frequently as in HU segments). Drivers of vehicles with SAE levels 1 to 4 automation should therefore be attentive to the road and to disengagements or takeover requests.
Automated way (AT)	The road segment presents reasonably good connectivity and physical infrastructure capabilities, so the number of disengagements or takeover requests should be quite a lot lower compared to AS and HU roads. Vehicles can match their ODD limitations with the digital information shared by the road segments, so that most takeover requests (SAE levels 3-4) are planned.
Full Automated way (FA)	The road presents a continuous ORS, ensuring ODD compatibility with a large majority of SAE level 3-4 vehicles. Digital information is shared so these vehicles can plan any takeover request. This means that an experience with no disengagements can be attained. SAE level 2 vehicles should experience a very small number of disengagements.
Autonomous way (AU)	In a similar way to FA, the connectivity infrastructure supports cooperative driving, so the infrastructure can receive and transmit tailored instructions to all vehicles, micromanaging traffic performance. This type of road segment is exclusively intended for SAE level 4-5 CAVs. This highest smart level may be designated for specific lanes

Figure 5.9 – *Smart Road Levels (PIARC) (Garcia Garcia, 2021)*

5.7 Digital Twin/Digital Map

Digital twins (Digital twin, 2023) are a **digital representation of a physical** reality, system or process. They are used for simulation, integration, testing, monitoring and maintenance. In addition to the characteristics of physical reality, the representation may include **information about the condition** of that reality or about specific events as they occur.

In the context of autonomous vehicles, digital twins can be representations of the vehicles, including all integrated systems, the traffic environment, and all the events that may occur in that environment.

Digital twins are used at virtually every stage in vehicle development, from prototyping to commercial roll-out of new vehicles. For example, they are used in the development phase to test advanced driver assistance systems and self-driving cars. Meaningful testing requires a correct digital representation of both the **vehicle** (including all its sensors and their behaviour) and the **traffic environment** (taking into account all possible variables such as weather conditions, local traffic rules or customs, sudden events, etc.).

At present, advanced driver assistance systems and automated vehicles rely mainly on observations from built-in **sensors**. In addition to the inherent limitation that detection is only possible within the operating range of these sensors (currently about 250 m), sensors also only allow an object to be detected, recognised and located, with varying degrees of accuracy[39].

In addition to a simple digital representation of the road and the road environment, information in a digital twin can be **augmented** to include characteristics about the objects in the digital twin that are not immediately **visually perceptible** and that are meaningful for both the operation of an automated vehicle and the decisions it makes. These include, for example, information about the roughness of a road surface, the containment performance of barrier structures and dynamic information about other traffic participants or road works.

Some information about the physical reality may also be detected by vehicle sensors and, if it is inconsistent with the data in the digital twin, it can be reported to the road authorities, who can then plan more targeted interventions (e.g. problems with LKA due to markings not being sufficiently visible).

The fact that navigation systems are being built into more and more vehicles as standard gives an idea of the potential of digital twins. To support higher SAE levels, however, these digital twins need to be **updated** in near real-time. Vehicles and infrastructure therefore need to be equipped with appropriate communication capabilities, and this will require the commitment of sufficient resources.

Particularly in regard to **road works**, it is challenging to keep digital information up to date so that vehicles can be aware of conditions. There is a particularly strong awareness of this in the United States, where roadside interaction at construction sites is becoming a national priority (Highlights, 2023).

[39] HERE (a provider of automation vehicle systems) has announced that they are offering digital twins of the road environment (including identification, classification and localisation of objects with a relative accuracy of 2 cm) created from LIDAR sensor data (HERE, s.d.)

Road works constitute a disruption compared with the normal situation: the road markings and/or traffic signs that exist in the "normal" situation are temporarily not applicable. The location and timing of road works must be known in a timely and correct manner. It would be appropriate to include this in **contracts between road authorities and contractors**. Work is in progress to develop standard notifications for road works. The DATEX standard specifies how information about traffic-related events, including road works, can be transmitted in a structured manner[40].

AWV requests that where there are **mobile construction sites**, the Traffic Centre should be informed of the planned work, the actual start of the work and interim relocations (Agentschap Wegen en Verkeer [AWV], 2021). The beginning and end of the work should always be communicated by telephone so that road users can be informed about it and sections of road can be closed if necessary - using dynamic road signs.

Automatic communication of the position of truck mounted attenuators using track & trace data allows sections of road to be closed in a much more targeted manner and reinstated more quickly once the work has been completed. If only the sections of road where work is actually being done are closed, the available road capacity can be used more efficiently and these restrictions will be perceived as more credible and followed more closely by road users.

For information on **permanent construction sites**, AWV promotes the use of the internal application WERF. This system allows information on the use of public land to be entered, made available and updated (Decreet houdende de uitwisseling van informatie, 2014) where the work is being done for AWV or other organisations.

AWV's aim in the **Mobilidata** project is to make information available to road users on mobile lane closures or slow-moving intervention vehicles and road works, as well as information about other risks and hazards on the roads[41]. Data is collected automatically where possible, without the need for (manual) inputting by users. This is currently used solely as a source of information for drivers, but later it will also be a source of data for self-driving vehicles.

40 DATEX II (CEN, 2018-2022) is the electronic language used in Europe to exchange traffic-related data. The standard was created in the 1990s and is currently maintained by CEN/TC 278 (Road Transport and Traffic Telematics). https://www.itsstandards.eu/aboutus/

41 www.mobilidata.be

5.8 Digital infrastructure

It is not yet clear whether data sharing between road users and infrastructure will be a **precondition** for safe operation of self-driving vehicles. Nevertheless, many observers believe that communication can contribute towards the reliability of ADAS[42]. If self-driving vehicles are also going to use data from other vehicles or infrastructure when they are in operation or act as a data source for other road users, the necessary communication hardware and software will in any case need to be in place[43].

It already seems that to achieve acceptable reliability, ISA systems cannot operate solely on the basis of speed limits recognised by vehicle sensors. To meet the reliability levels required for homologation[44], additional information from outside the vehicle will also be needed.

It seems that digital infrastructure will play a larger role. One example is the **Cooperative Forward Collision Warning application**: information about the location and movement of the vehicle and also of nearby vehicles can be used to calculate their trajectories and warn drivers when there is a risk of a collision. Map data can be used to filter and interpret the relative location and movement of nearby vehicles. There are questions about feasibility: what is the (initial) financial feasibility of the system and what about privacy?

- V2V communication: vehicles equipped with this are detected.
- V2I communication: vehicle location and vehicle movements are received by infrastructure and used by road authorities to support a wide range of road safety and mobility applications.
- GPS sensors (within the vehicle) allow detection of approaching hazards (via a location database). Detection of pedestrians can also be included as a feature in these systems.

China: infrastructure as an **enabler** (How USD300bn, 2022)

The development of AI systems is a crucial step towards the highest level of autonomous driving. China has chosen not to focus on the development of AI alone, but it is also strongly emphasising the installation of technologically less demanding **smart roadside units**.

UBS Investment Bank says China is best placed to lead the way in **vehicle infrastructure collaboration (VIC)**. They predict roadside investment in China totalling US $300 billion between 2022 and 2040. They believe the market is overlooking the potential of VIC in regard to AD. Their reasoning is that VIC eliminates technological bottlenecks, making AD easier to achieve than it would be using AI technology.

The idea in China is to create motorways that are ready for autonomous trucks first and subsequently also for passenger cars. To achieve the maximum level of AD, China wants to install a whole package in each km: 50 cameras, 20 millimeter-wave radars and 10 intelligent roadside installations (Gibbs, 2021).

42 ACEA estimates that the reliability of ISA based on recognition of road signs alone is limited to about 50%. The use of other data sources will be essential to achieve an adequate level of reliability (ACEA, 2021).
43 New traffic lights in Flanders are already being equipped with this (the possibility of communication or optional extension).
44 Commission Delegated Regulation (EU) 2021/1958, 2021 requires ISA systems to recognise the speed limit correctly in 90% of cases on average. According to ACEA, systems based solely on recognition of road signs can achieve 50% reliability.

5.9 Communication between AVs and vulnerable road users (Tabone et al., 2021)

A 2021 publication on research on the **views of human factors researchers** on the future of interaction between autonomous vehicles and vulnerable road users made it clear that they are not very clear about the "infrastructure" aspect.

In general, the researchers agreed that fully autonomous vehicles will not be introduced quickly and that smart infrastructure and separation of traffic flows are considered crucial but expensive. AR (Augmented Reality) is seen as promising, but it is considered that implicit (non-verbal) communication will remain dominant for the time being and that it will be difficult to replace this solely by using vehicle sensors to detect conflict situations. The use of eHMIs (external human-machine interfaces), messages from the vehicle to other road users, could replace this non-verbal communication between people. At present, however, there do not seem to be any sufficiently well developed concept solutions.

eHMI for self-driving vehicles for the benefit of vulnerable road users are systems that make it possible to inform road users outside the vehicle ("machine").

Figure 5.10 – *Example of a vehicle with multiple information screens for communication with pedestrians (Volkswagen Tiguan) – projection of road crossing (Duff, 2015; Light staging and exterior HMI, 2018)*

Specifically in the area of **uncertainty about road infrastructure**, some of the researchers' comments were telling: they are mostly guesswork (Appendix 3).

5.10 Weather conditions (Hoe beïnvloedt het weer de verkeersveiligheid, 2023; Stichting Wetenschappelijk Onderzoek Verkeersveiligheid [SWOV], 2023)

It is undeniable that weather affects both behaviour on the roads and road safety. Weather conditions influence the likelihood of an accident and also its consequences. This is true for a variety of weather conditions: rain, hail, snow, ice, heat and also low sun. In rain, snow and hail, the **skid resistance of the road surface** is lower and there is an increased risk of a vehicle entering a skid. In fog, visibility decreases but vehicles generally drive closer together. Low incident angle sunshine also reduces visibility, and this effect is compounded if there is water on the road reflecting the sunlight. Wind in particular has an effect on road positioning of tall vehicles.

Depending on the type of weather, people modify their behaviour by using a different mode of transport or exercising caution. For example, motorists generally overtake less in the rain, they drive more slowly and do not drive as close together.

Research shows that the **risk of an accident** may be higher under these conditions than in "normal" weather, despite adjustments in driving behaviour. Research in the Netherlands has estimated that 5% of traffic fatalities are directly linked to weather conditions. It was also found that the probability of an accident on a motorway increases by 35% to 182% in the rain, and by as much as 77% to 245% in icy conditions. As a side note, accidents that occur during precipitation tend to be less severe.

This area offers **considerable potential for improvements in road safety** even in difficult weather conditions. The following questions arise about the performance of autonomous vehicles:

- Do autonomous vehicles with their sensors and warning systems have the ability to correctly detect objects and events in their environment under these more difficult weather conditions?
- Can they use that information to make the right decisions (adjust speed, perform a manoeuvre, stop the car, ask an occupant to take over the controls, etc.)?

Research has been carried out in the United States on how **adverse weather conditions** in different driving environments affect the dynamics and activities of AVs, driver behaviour (specifically disengagements), communication and AV sensor capabilities (Coventry et al., 2022; Neumeister & Pape, 2019).

Performance in bad weather seemed to be a factor in determining the approach to automation to support driver assistance by all the AV models tested over two study periods. Here are some of the findings[45]:

- **Camera-only systems** perform worst in bad weather. Radar and camera systems were still sensitive to rain and ice, but the effects were less than with the vision-only system;
- glare from the sun did not seem to affect the only vehicle that was able to be tested;
- **rain** had a significant effect on high speed lane following for two of the three vehicles. Rain only affected Lane Departure Warning and Traffic Jam Assist in the vision-only system;
- **ice or snow** on the radar and camera disabled the safety systems in all the vehicles. One vehicle was able to operate with the camera covered and another was able to operate with the radar covered. Due to time constraints it was not possible to test the opposite situation for each vehicle.

[45] appendix 1.

In the same study conducted in the United States, the following **limitations** of autonomous vehicles in bad weather were noted during a workshop:

- there is no good method for deciding whether or not to start or continue a trip with automation;
- road authorities (at state and municipal level) are poorly equipped to advise on automation and manufacturers do not advertise the limitations of their products;
- although the ODD must be specified by the vehicle manufacturer, it is not clear who is responsible for determining whether current or predicted conditions fall within the ODD;
- road authorities (at state and municipal level) are concerned that they may be asked to accept a new responsibility for AV operations, such as making decisions on when roads should be closed;
- the weather-related limitations of AVs are not well understood.

5.11 Case study of ADAS and Safe System Approach (human – environment – vehicle)

ADAS (Driver assistance technology, s.d.) stands for advanced driver assistance systems on vehicles. Some driver assistance technologies are designed to **alert** the driver when there is a risk of an accident, while others are designed to **take action** to prevent an accident.

It is essential to understand how the technology works, its limits and how it can protect the vehicle occupants and others. There is a need for **training** for drivers. Research shows that quite a large proportion of drivers do not know and use ADAS well enough (Brown, 2018; Caster, 2021).

Based on practical experience with advanced driver assistance systems, what is the role of physical road infrastructure? How can infrastructure help to ensure that advanced driver assistance systems operate more reliably? To answer these questions, a step-by-step description follows of what happens at the human, environment and vehicle levels in an ADAS system: the **lane keeping assistant** (LKA).

- An LKA uses road markings to analyse the traffic lane (the infrastructure).
- The vehicle signals to the driver as soon as the vehicle is at risk of leaving the lane.
- A visible road marking (infrastructure) supports the human driver (non-CAV), thus contributing towards better driving behaviour and reducing the number of accidents (beneficial for people, vehicles and the environment).
- On the other hand, evolving technology and better functioning LKA are more capable of detecting even less visible road markings. If necessary, the vehicle can signal to the driver to modify his or her behaviour.

These developments seem to suggest that high-visibility markings are becoming less important as more advanced vehicles come onto the market. Nevertheless, for some time to come a mix of vehicles will need to be taken into account, either without advanced driver assistance systems or with very different levels of the technology. Technological advances should therefore not be used as a reason for neglecting conventional infrastructure elements. Aside from this, it is helpful to ask about the limit regarding the minimum requirements for road markings, for vehicles that do have advanced detection technology.

If human beings are taken out of the loop, there are three interrelated elements that will be important. One of these is the physical infrastructure:

- high-quality markings (physical infrastructure);
- a digital twin of the lane (digital infrastructure);
- radars in vehicles (vehicle technology).

A similar analysis can be performed for other systems, such as **speed assistance**, but in that case the physical road infrastructure are the road signs at the roadside. According to the highway code, it are these that are decisive, not a digital twin, if there is one. The question is whether the highway code should take ongoing digitisation into account, to what extent this should take place and whether the physical road infrastructure will still be the decisive factor in that situation.

The same applies to **adaptive speed control**. If a road is in poor condition (e.g. there is a pothole), the vehicle and driver may be forced to slow down or even swerve. Such a situation can then affect other road users (the vehicle behind, a vehicle in another lane, etc.).

Chapter 6
Conclusion

Improving road safety is a significant rationale for policymakers and companies to engage with autonomous mobility. The gradual emergence of autonomous mobility as a valid alternative to more traditional modes of transport is a **challenge**, and it also presents **opportunities** to build a safer traffic system.

A literature review, discussions with experts and monitoring of conferences have shown that vehicle automation is not a panacea, but it can lead to major improvements in road safety. New road safety risks will, however, continue to arise. Reasons for this include:

- there will be vehicles on the road with different levels of automation for a long time to come;
- it can take up to 10 seconds for a human driver to take over the controls, which in many traffic situations can be described as sub-optimal at best;
- taking control in more complex situations can be problematic;
- drivers may gradually lose their driving skills;
- non-verbal communication between human road users is difficult to incorporate in automated systems. eHMI (external human machine interfaces) are not yet well developed and do not yet provide a valid alternative in this context;
- drivers take time to get used to new systems.

The introduction of autonomous mobility is also progressing more slowly than was predicted and promoted a few years ago by some experts and developers of autonomous vehicles. The **reality** has proven **more difficult** in many areas, including ethical and legal debates, social acceptance and economic aspects. The move towards vehicles that generate less pollution is taking up a lot of attention and investment. Autonomous vehicles are at least temporarily less at the forefront of necessary mobility system improvements.

Advocates of autonomous mobility argue that there are no **technological** barriers to allowing autonomous vehicles onto the road network, even in urban contexts. They cite tests outside the EU that have moved beyond the pilot project level.

With regard to **transfers of control** to a human driver, autonomous vehicles are taking the initiative less and less frequently. This suggests that self-driving vehicles are increasingly reliable. Furthermore, the available information indicates that road infrastructure (e.g., visibility of signage or road surface defects) is not the main reason for disengagements.

In **practice**, road traffic accidents involving autonomous vehicles are given a lot of attention in the press. That could have an adverse impact on consumer confidence, but research shows that confidence in autonomous mobility is growing anyway. If the emphasis is placed on the desired road safety gains, confidence is likely to improve further.

One consequence of the press coverage of problems with self-driving vehicles is that policymakers are showing some **reticence** about introducing autonomous vehicles on our roads. Based on an analysis of the limited number of road accidents involving self-driving vehicles, we can say that this is at least partly unjustified: the cause of the accident is often the conventional vehicle and the severity of accidents is usually lower.

There is no single method for evaluating the road safety of autonomous vehicles (or benchmarking them against "conventional" vehicles). To estimate the safety of a system, a **combination of simulations and pilot projects** is the most complete approach, since this avoids giving an excessively one-sided impression of its potential in terms of road safety. Testing on public roads comes closest to reality as a way of demonstrating safety. This can be done in full self-driving mode or in shadow mode, where the algorithm observes human behaviour and compares this with the actions it would take itself. That allows adjustments to be made to the algorithm.

There are not yet any self-driving vehicles on the market for consumers. The most advanced vehicles in this category are SAE Level 3, and these are currently only allowed to operate under limited and very specific driving conditions. Robotaxis are already operating in various places around the world (US and China). For now, large-scale pilot projects seem to be limited to the home countries of the companies organising the trials. In the European Union, there seems to be **reticence** about large-scale testing, partly because of uncertainty about its effects on road safety.

The **EU** wants to ensure that the introduction of self-driving vehicles will be a success. That can be done by making safety an absolute precondition when organising tests or issuing permits for autonomous vehicles. Discussions are therefore also under way about the conditions in which autonomous vehicles can be tested or allowed to operate on the road network.

Car manufacturers only guarantee that advanced driver assistance systems or self-driving functions will reliably work under well-defined conditions; the so-called **Operational Design Domain (ODD)**. So far there are no formal agreements in place concerning the parameters that are decisive for an ODD. Nevertheless, it is clear is that there is no single physical standard that defines a road that is ready for autonomous vehicles. There seems to be a strong consensus that building a dedicated road network for autonomous vehicles will not be necessary, but that they will use **existing roads**. Especially in urban contexts, this is the only logical approach.

There are some road traffic accidents involving autonomous vehicles that can be traced back to **system failures**. These may include perception errors (e.g., due to hardware faults, bugs in algorithms), decision errors (information provided too late, wrong information) and action errors (e.g., mechanical failures by the vehicle, reduced driving experience of the people who have to take over the controls). Further development of algorithms and the use of **artificial intelligence** will be crucial to incrementally reduce these errors to a minimum.

Weather conditions affect the operation of autonomous vehicles. The algorithms used in an autonomous vehicle are programmed to stay on the safe side. Eliminating decision-making by a human driver can be seen as a significant improvement. That is because some human drivers take risks in adverse weather conditions, while the autonomous vehicle will avoid them.

There is a consensus that **clear and uniform signage** (road signs and road markings) can help new vehicle technologies to operate more reliably. On the one hand, autonomous vehicles are increasingly able to cope with poorer quality road markings; on the other hand, existing performance recommendations are not met everywhere. Nevertheless, vehicles with all levels of automation will be continuing to use the existing roads for quite some time. Reading road signs and road markings correctly is challenging under some weather conditions.

Connectivity can help AVs to function better, but it is not an absolute requirement. There is no consensus on whether safety should be made dependent on connectivity. One argument for **not making** the operation of security-critical functions **dependent** on connectivity is the possibility of communication being lost or erroneous information being transmitted, either maliciously or otherwise.

In terms of policy, we see a goal of zero traffic fatalities by 2050. Recent policy documents are linked to the integrated approach called the **Safe System Approach**. One of the principles underlying this system is that responsibility is shared. Human beings can make mistakes, and the system should be configured so that human error and unpredictable behaviour do not result in serious accidents. The same can be said about autonomous vehicles: they can also make mistakes, or their algorithms may not yet be sufficiently developed. Policy in regard to autonomous vehicles, should also aim to **prevent serious accidents**. Specifically, advanced driver assistance or self-driving systems depend on these systems working correctly, but they also require a clearly **readable road environment** and they need communication facilities to operate reliably. The shift towards autonomous mobility therefore further emphasises the importance of positive cooperation between different stakeholders.

Self-driving vehicles are increasingly successful at locating themselves using GPS data.

Insufficient harmonisation among road signs, reduced visibility due to pollution or exposure to weather conditions, specific additional rules displayed underneath road signs and implicit rules (e.g. speed limits after leaving a built-up area) make it difficult for **ISA systems** to identify the correct speed limits with a sufficient level of reliability. Improving the reliability of these systems requires external sources of information (digital maps) and further efforts on speed limits displayed using physical signage.

Finally, road authorities need clear recommendations on infrastructure features that can promote the use of self-driving transportation. This mainly concerns requirements for physical signage components (road signs and road markings), but it may also involve the development of AI systems or smart roadside units.

The **ITS Directive** (Directive 2010/40/EU, 2010) and associated regulations already require some types of traffic information (including information about short-term road work) to be made available to road users. Advanced (connected) vehicles can help to make this information available to all road users more effectively.

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Appendix 1 - Weather conditions (Coventry et al., 2022; Neumeister & Pape, 2019)

The research in the United States consisted of three phases. It became clear that steady progress is being made, but **challenges** still remain. Results in each research phase:

Phase 1 of the study: rain

- All the AVs tested performed well during High-Speed Following (HSF) and most of them also performed well during Low-Speed Following (LSF) in dry conditions, but heavy or persistent rain was a challenge for all AVs.
- All AVs performed well on lane keeping on straight, dry roads and in light rain, but the performance of all AVs deteriorated in heavy or persistent rain.
- The performance of some AVs improved when the traffic lane and road markings were wet (perhaps due to improved contrast with darker asphalt).

In ice and light snow (phase 1 of study)

- When there was ice on the cameras, none of the AVs were capable of lane keeping. One AV even had problems with residual water coverage.
- No AVs are able to detect objects or provide support when there is a thin layer of ice covering the radar sensor. One was capable of lane keeping and LSF with ice on the radar and a clear windscreen camera.
- Light falling snow did not affect manoeuvres, but even a modest amount of snow adherent to parts of a heated radar sensor affected Adaptive Cruise Control (ACC) functions.

Glare from the sun (phase 1 of the study)

- The performance of the AVs in lane keeping tests ranged from no impact to high impact due to glare from the sun at a low incident angle.

Phase 2 of the study: Lane Departure in falling snow and with snow on the road

- AVs seemed to "see" lines marking traffic lanes more quickly in this test phase than in phase 1.
- The levels of support provided by AVs depended on the reliability of their sensors.
- AVs operated the Lane Keeping System with different amounts of information - one required both lane markings to be visible, one could keep to the lane with only one lane marking, and one was able to do so with two or even one line/contrasting edge.
- Light drifting snow did not affect the performance of the AVs.
- AVs performed better with complete, continuous cover than with patchy/sporadic cover.

Following manoeuvres in falling snow, phase 2 of the study

- None of the AVs had much trouble following in falling rain or snow.
- If the vehicle in front deviated from visible lane markings in the snow, this led to one AV continuing to follow the vehicle ahead for short distances (and therefore deviating from the lane as indicated by the markings) (although this was outside the conditions being tested).

Lane Departure with glare from the sun, on a bend, phase 2 of the study

- Some AVs performed well but appeared to turn too tightly.
- Other AVs dropped out and asked to disengage on half of these occasions.

Stage 3, with SAE level 2: lane keeping

- In AVs with a higher level of automation, lane keeping ability was not affected by winter conditions.
- Snowy roads with tyre tracks had a significant impact on the ability of AVs with a lower level of autonomy to detect the edges of the traffic lane and stay within them.
- Ice-covered roads did not affect the performance of this AV.
- Stage 3, with SAE level 2: lane keeping - change in right-hand lane.
- On snowy roads with tyre tracks, AV with higher levels of autonomy experienced an occasional loss of localisation when changing lanes.
- AV with lower levels of driving automation was unable to change lanes in snowy road conditions with tyre tracks.
- Under other winter conditions, both AVs performed the lane change successfully.

Phase 3 test with SAE level 2, green light at intersection with traffic lights (continuing straight on and turning left)

- On snowy roads, AV with a higher level of autonomy experienced an occasional loss of localisation when making a left turn at an intersection.
- Other AV deviated from the lane during all winter weather conditions.

Detection of a stationary car (phase 3, with SAE level 2)

- The AV detected the stationary car and came to a complete stop under all weather conditions without disabling the steering controls.

Appendix 2 – Abbreviations

ABS	Anti-lock Braking System	ITS	Intelligent Transport Systems
ACEA	European Automobile Manufacturers Association	KPI	Key Performance Indicator
AEBS	Advanced Emergency Braking System	LCA	Lane Centering Assistance
ACC	Adaptive Cruise Control	LDW	Lane Departure Warning
AD	Automated Driving	LDWS	Lane Departure Warning System
ADS	Automated Driving System	LKS	Lane Keeping Systems
ADAS	Advanced Driver Assistance System	LOSAD	Level Of Service of Automated Driving
AEB	Autonomous Emergency Braking	LKA	Lane Keeping Assistance
AI	Artificial Intelligence	LSF	Low Speed Following
AR	Augmented Reality	LV	Light Vehicle
ARTS	Automated Road Transportation Symposium	MaaS	Mobility as a Service
AV	Autonomous Vehicle	MUTCD	Manual on Uniform Traffic Control Devices
CACC	Connected Adaptive Cruise Control	NDR tasks	Non Driving Related tasks
CAV	Connected and Autonomous Vehicles	ODD	Operational Design Domain
CCAM	Connected Cooperative Automated Mobility	PARTS	Partnership for Analytics Research in Traffic Safety
eHMI	External Human Machine Interfaces	PAEB	Pedestrian AEB
EU	European Union	RTTI	Real Time Traffic Information
Euro NCAP	European New Car Assessment Programme	RISM	Road Infrastructure Safety Management
FCW	Forward Collision Warning	SAE	Society of Automotive Engineers (US)
FHWA	Federal Highways Agency	SRTI	Safety Related Traffic Information
GNSS	Global Navigation Satellite System	VIC	Vehicle Infrastructure Collaboration
GPS	Global Positioning System (US)	VN	United Nations
HLDI	Highway Loss Data Institute	VRU	Vulnerable Road User
HMI	Human Machine Interface	V2I	Vehicle to Infrastructure
HSF	High Speed Following	V2P	Vehicle to Pedestrian
IIHS	Insurance Institute for Highway Safety	V2X	Vehicle to Everything
ISA	Intelligent Speed Adaptation	V2V	Vehicle to Vehicle
ISAD	Infrastructure Support for Automated Driving	WHO	World Health Organization

Appendix 3 – Perspectives of "human factors" researchers (Tabone et al., 2021)

- "Maybe we'll see infrastructure like lights on the ground to support interactions between pedestrians and AVs. Smart infrastructure is expensive, so the question is: who is going to pay for it? This might mean that smart infrastructure is only introduced in certain selected shared spaces, where the investment could be made more efficiently. Smart infrastructure allows the AV to expand its horizon of perception and "see around corners" (detecting objects and/or events outside the field of view of the sensors in the vehicle). Wearables are likely to improve pedestrians' perception of smart infrastructure elements. I think this is something that is going to happen and it will probably be accepted by road users as long as privacy issues are handled properly."

- "It's hard to say what role smart infrastructure will have in the future because there will be a need for standards and many different agencies will need to work together. The European view is that this infrastructure will exist in future, while in other parts of the world and in certain industrial sectors there is a desire for independence, with vehicles communicating with each other without the need for specific communication with the infrastructure."

- "Pedestrians are very vulnerable, and high-density pedestrian areas are not a good place for AVs to be operating because a conservative algorithm would drastically slow down the vehicle's movement. Since the intelligence does not necessarily have to be in the AV itself, pedestrian environments of this kind could benefit a lot from smart infrastructure. However, this presents both political and technical challenges, including making roads work intelligently for non-AVs and the limitations of sensor capacities in different geographical locations. Another problem is the funding model. Infrastructure is for the public benefit so it would presumably need a public-private transformation in order to bring about improvements."

- "Communication between AVs and pedestrians should be based on the vehicle's implicit behaviour, while eHMIs should be used in ambiguous situations."

- "Another option is to use the infrastructure to communicate with the pedestrian so that the car does not have to be used as a communication device. Smart infrastructure will play a crucial role in electrical mobility in future. Quiet cars must not be equipped with extra noise, as this is contrary to the whole idea of quiet cars. A better solution is to use infrastructure to alert people via devices such as smartphones. Infrastructure will also play a key role in keeping traffic separate. However, separating different modes of transport such as AVs from cars that are driven manually, cyclists and pedestrians is very expensive."

- "eHMIs: like smart infrastructure, eHMIs can help to improve the safety and acceptance of AVs. Our research shows that eHMIs are especially useful at low speeds, where pedestrians have time to interpret and respond to eHMI signals. Over greater distances, recognition of eHMIs is problematic. Our experiments showed surprisingly small differences between fundamentally different types of eHMIs in terms of acceptance and effects on behaviour, and the participants learned to use eHMIs quickly. Possibly our participants simply reacted to the changing colour, text or symbol on the eHMI. This eHMI change always involved implicit communication, which remains an important factor."

- "I am not optimistic about smart road infrastructure, as it is challenging in terms of both cost and backward compatibility. A virtual traffic light may work well for vehicles that are equipped [to work with it], but it will be invisible to vehicles [that are not equipped with these intelligent features]. So it would be difficult to get people to invest in this. I think the most challenging part would be how to communicate with pedestrians. If this is virtual, it will require equipment on the pedestrian to send signals to the infrastructure and display the signals received. That may be possible in a country with a high standard of living where everyone can be equipped with smart glasses. In other countries, however, there are economic disparities, so large sections of the population do not have access to all types of smart devices. Non-smart infrastructure could be a more productive way forward. Best practices in terms of infrastructure design that are currently helping drivers and pedestrians to use the roads can also help pedestrians and AVs to interact safely."

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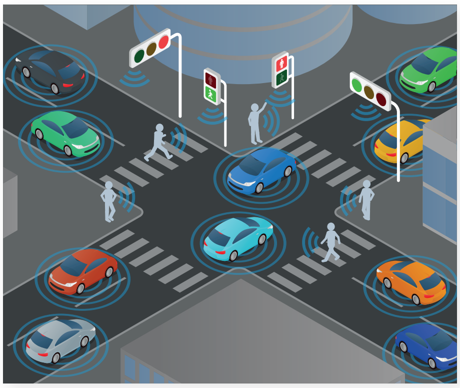

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Improving road safety is a prominent motivation for policy makers and companies to focus on autonomous mobility. The gradual emergence of autonomous mobility as a valid alternative to more traditional modes of transport is a challenge, and it also presents opportunities to build a safer traffic system.

In this report, we describe that road safety promise, and add some concerns by addressing emerging road safety risks. It provides an overview of relevant background information, elements of research and testing, road safety policies and goals. It gives more insight into the infrastructure component. This knowledge contributes to informed choices by road authorities, which choices are needed in the short and medium term.

ITRD keywords

0173 - Policy - 0698 - Journey- 1055 - Transport infrastructure - 1145 - Transport mode - 1244 - Autonomous vehicle - 1665 - Safety - 8735 - Intelligent transport system - 8743 - Electronic driving aid - 8771 - Route guidance - 9105 - Mobility (pers)