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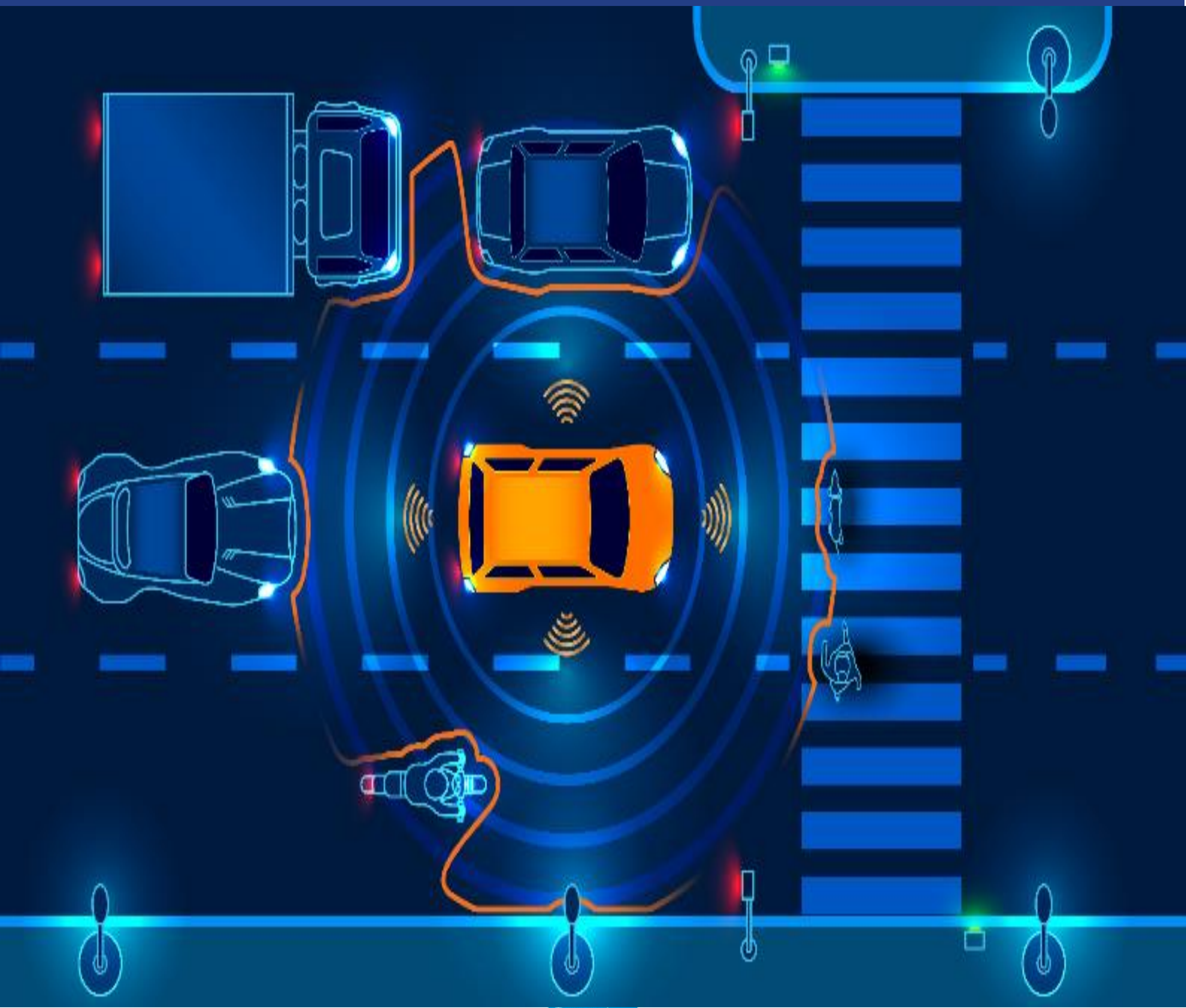


Transport

Contents

1 Overview

In recent years, autonomous vehicles (AVs), connected vehicles (CVs) and all relative technology have been in the spotlight, being intensively researched and developed. There is high anticipation on the benefits of automation and the overall reform it will bring throughout the transport sector, with some optimistic estimates considering it a reality within the few next years. However, since it is still an emerging technology, its impacts on several aspects are still unclear.

One such aspect, probably amongst the most critical from a social, economic and scientific point of view, is traffic safety. There is considerable uncertainty regarding the repercussions that will occur when AVs and CVs start operating in real traffic conditions, and several pertinent questions have reasonably arisen:

- Will there be an impressive reduction in crashes when full automation is reached?
- Could vehicles be freely repurposed when there is no need for human hands-on driving?
- What do we have to change from the current state to reach safe automation?
- Where does the fault or liability lie in the event of a crash?
- What will happen during the transition phase, when human drivers share the road with artificial intelligence algorithms?

Researchers, authorities and stakeholders have strived to provide respective answers, which, however, do not always seem to agree. This report aims to provide a synthesis of current knowledge and a discussion on current and future challenges of connected and autonomous vehicles regarding traffic safety, by analysing relative research from scientific, governmental and industrial viewpoints and commenting on general directions for future advancement and overcoming of challenges.

This report is structured in chapters following specific themes: after a brief introduction that reflects current road state and definitions of AVs, CVs and automation levels, the technological progress of AVs and CVs is examined and then the particularities of the transition phase are explored. The synthesis continues with direct and indirect safety impacts and other implications. Additional issues of safety such as the legal and financial implications are investigated as well.

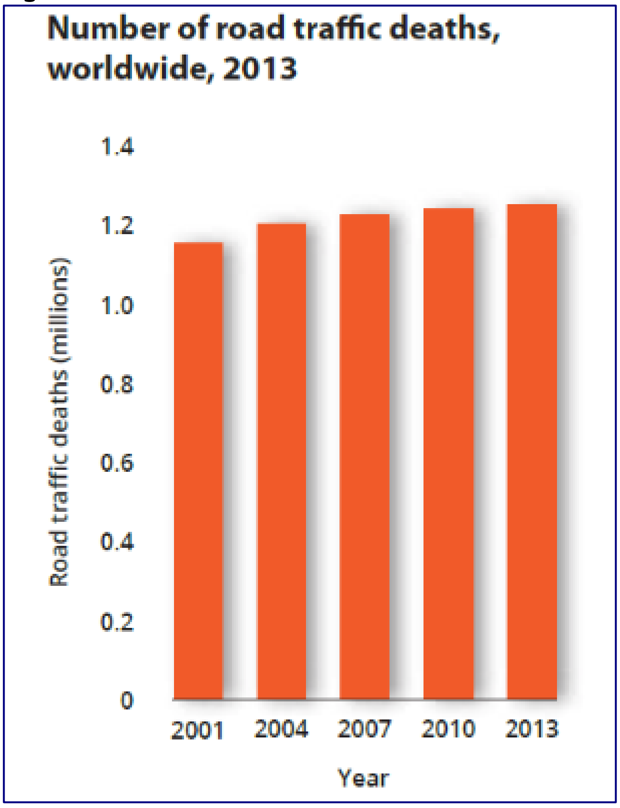
Evidently, AVs and CVs are attracting considerable attention and are developed very rapidly, cultivating great expectations for traffic safety improvements. While their potential is enormous and undeniable, benefits are not automatically guaranteed as there are parameters that currently appear unforeseen. Increased efforts and participation of all stakeholders will be required to ensure a smooth and lengthy transition period, where safety and public acceptance of AVs will be tested in earnest. AV progress will not be confined by a lack of preparation in any front; rather all interested parts should anticipate their arrival beforehand.

2 Introduction

2.1 Current traffic safety state

Conventional traffic safety has improved by leaps and bounds ever since the operation of the first motor vehicles, with considerable advancements in contemporary road operations, and even more ambitious targets. One such target is the Vision Zero initiative that originated from Sweden, which states that "it can never be ethically acceptable that people are killed or seriously injured when moving within the road system" (Tingvall & Haworth, 2000; Whitelegg & Haq, 2006). Traffic and road safety practices have been implemented to save lives by halting the increase of road traffic fatalities against an ever-rising population, as seen in Figure 1 (WHO, 2015). The still occurring fatalities, however, suggest a lot of untapped potential and margin for safety improvements, since they are mainly caused by the very high presence of human error in road crashes, which is estimated at over 90% (OECD, 2015). These improvements will reduce the lessening of the respective burdens on society in human and economic terms as well.

Figure 1: Worldwide road traffic fatalities in recent years



Source: WHO, 2015.

2.2 Motivation

In the face of rapid and successive developments in the transport sector, Autonomous Vehicles (AVs) and their respective technological advancements have been dominating all relevant interest. This is not without good reason, as there is high anticipation of the benefits that AVs will bring to the field. In the eventuality of complete automation (SAE Level 5 automation - see also Chapter 3), dramatic changes to all aspects of road transport are expected, including, among others, safety, mobility, accessibility, environment, infrastructure design, and goods and cargo transport.

The artificial intelligences that would drive AVs would not suffer from distraction, emotions, fatigue, poor or clouded judgment, or cognitive impairments, and would have enhanced perception of the road environment and of each other. Their calculating and decision-making skills would take a very small time fraction in comparison to human ones, and they could aid in not only avoiding a crash but even after it happens (for instance e-call functions). It is highly likely that increased application of AV and CV mechanisms will grant increased self-sufficiency to older drivers, and even allow non-drivers, such as underage passengers or people with mobility or visibility impairments, to travel by car on their own. A more advanced stage could be drone-like flying vehicles that deliver goods or perform other tasks (e.g. surveillance) without any need for "hands-on" human intervention.

The benefits of automation are expected to gradually materialize in the more imminent future through implementations of Connected Vehicles (CVs) that will aid human drivers with advanced sensor technology with easy to access and process information about the road environment.

It is therefore reasonable that institutions, societies and individuals expect the same high standards of safety and reliability for AVs and CVs as with conventional safety, and even higher, in order to tap into the potential benefits of automation. No system can ever be considered 100% safe, however, and that would be the case for autonomous systems. It might even be possible that ultra-conservative reservations and demands of road users for an infallible AV system can impede the advent of AVs and its respective public acceptance. Other innovative technologies were similarly at this crossroads in the past, and would not be available today if caution outweighed boldness (Winkle, 2016). Thus, the current challenge that road safety experts have to answer is the accurate forecasting of the benefits of AVs and CVs and proper path towards the gradual transition from human to artificial intelligence drivers.

2.3 Aim of the Report

Within the above context, this report is undertaken with the explicit aim to provide a synthesis of current knowledge and a discussion on current and future challenges of connected and autonomous vehicles regarding traffic safety. This aim is achieved through a critical analysis of the current scientific literature and technical and policy reports, thus providing a snapshot of the state-of-the-art and outlining the next steps that will have to be undertaken to ensure a safe transition into connected fleets and gradually increasing automation Levels. An endeavor is made to evaluate the impact of critical aspects of autonomous vehicles on traffic safety and set the trend for the future pacing of transport and traffic safety.

3 Definitions

3.1 Autonomous Vehicles

Autonomous or Automated Vehicles (AVs) are vehicles that are operated by an artificial intelligence in place of a human driver (various similar definitions are found in pertinent literature – e.g. in Zmud et al., 2016). AVs use arrays of sensors and auxiliary devices to collect information of the surroundings of the vehicle. These devices in turn provide input to the algorithms that are used to provide all driving related controls and decision making that substitutes traditional drivers. This is achieved through intercommunication of vehicles with other vehicles or infrastructure elements, namely vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication (collectively known as V2X schemes).

3.2 Connected Vehicles

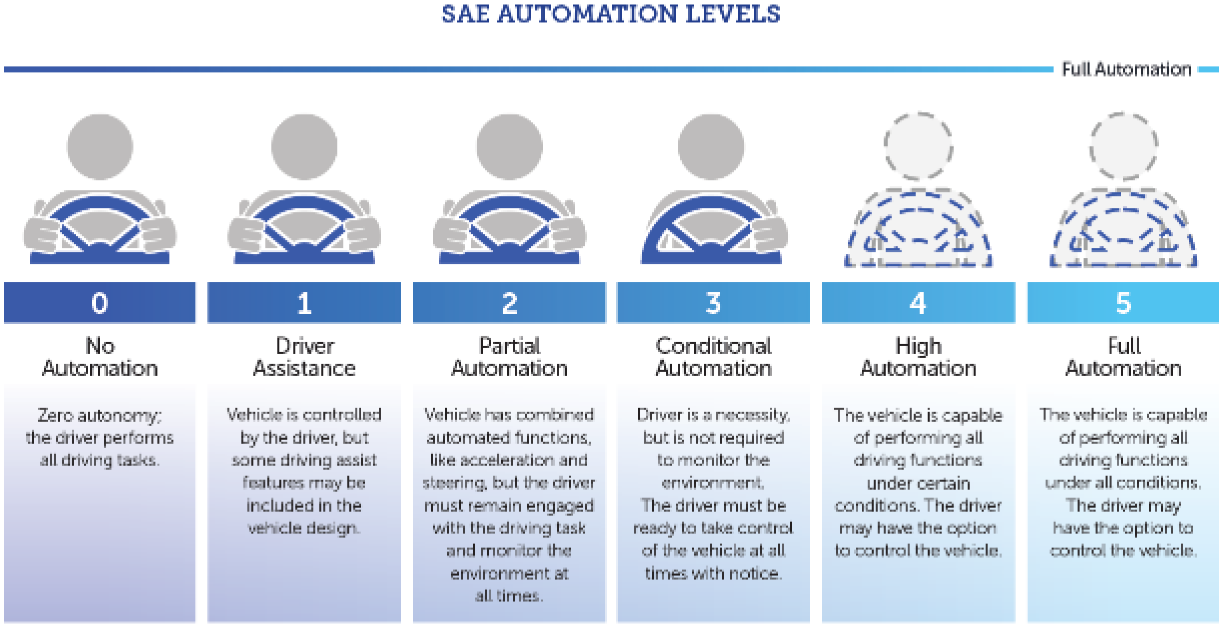
Connected Vehicles (CVs) are in essence conventional vehicles, in that they are still operated by a human driver, which are also enhanced via various technological and electronic devices and upgrades (various similar definitions are found in pertinent literature – e.g. in Guler et al., 2014). These devices allow intercommunication of vehicles through V2X schemes as well. Thus drivers receive more enriched information about the entirety of the driving environment than they normally would, with expected benefits similar (but lesser in scale) to full automation. CVs with certain technologies are currently available and are expected to be developed increasingly until the stages of partial or full automation, namely as the transition towards artificial intelligence operation occurs.

3.3 Automation Levels

Within the transport community, five (5) Levels of automation additional to baseline unautomated driving have been introduced by SAE in Standard J3016, first issued in 2014 and updated in 2016 (SAE International, 2016). These automation Levels are currently widely recognized and are depicted concisely in Figure 2 and in more detail in Figure 3. As Levels increase, vehicles become gradually more independent and less reliant on human drivers, and require increasingly more sophisticated equipment in order to operate.

SAE further notes that these Levels are descriptive rather than normative and technical rather than legal, and imply no particular order of market introduction. These features are considered minimum capabilities for each Level. A particular vehicle may have multiple driving automation features such that it could operate at different Levels depending upon the feature(s) that are engaged. Warning and momentary intervention systems are excluded, because they do not automate any part of the dynamic driving task on a sustained basis and therefore do not change the human driver's role in performing the dynamic driving task.

Figure 2: Automation Levels (concisely)



Source: NHTSA, 2017.

Figure 3: Automation Levels (extensively)

SAE level	Name	Narrative Definition	Execution of Steering and Acceleration/ Deceleration	*Monitoring* of Driving Environment	Fallback Performance of *Dynamic Driving Task*	System Capability *(Driving Modes)*
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Source: SAE International, 2016.

4 Current Technological State

4.1 Connected Vehicle Progress

Viewed as the premise of automation, Connected Vehicle (CV) technology (mostly related to Level 1 automation) typically places emphasis on enhancing the capabilities and information available for drivers, instead of aiming to replace them. There is considerable common ground between AV and CV technologies, however, as both involve collecting and exchanging information via V2X schemes. Several technologies that are expected to be part of AV fleets are currently used in CV applications, such as collision warning systems and emergency braking. Additionally, V2X technologies that use several different forms of telecommunication (such as cellular, Wi-Fi, and Bluetooth) are being currently developed (Zmud et al., 2017).

Level 1 driver assistance has been available for many years. Cruise control is commercially available since the 1960s, electronic stability control in the 1990s, and various lane-keeping and lane departure warning systems in the 2000s. ABS and electronic stability control is currently standard on all new cars sold in Europe. A non-exhaustive list of systems that can be found on CVs is listed in Table 1 – the categories are not exclusive, rather they are assigned based on the primary role of each system.

Table 1: Basic CV technologies available today

Category / Domain	System / Mechanism
Perception - Information	Surround view
	Parking assist
Collision avoidance	Collision warning/ avoidance
	Cross traffic warning
	Autonomous emergency braking
	Pedestrian detection
Navigation control	Intelligent speed adaptation
	Lane departure warning
	Adaptive cruise control
	Traffic sign recognition
Safety augmentation	Seatbelt reminders
	Electronic stability control
	Alcohol interlock systems
Post-crash aid	E-call
	In-vehicle event data recorders

Adaptive Cruise Control (ACC) systems control a set speed while the human driver controls steering, and must be able to retake full control at any time (typically occurring by pressing any of the pedals). Autonomous emergency braking (AEB) systems have also been implemented, either as part of ACC systems, or for use under dire circumstances. For instance, there is a commercially available "emergency assist" in case of a non-reacting driver, where the car takes the control of the brakes and the steering until a complete stop.

Collision warning systems have been implemented in manufactured vehicles; these systems use mechanisms of forward detection (such as radar and lidar technologies) to detect a crash and avoid or mitigate its consequences. This occurs by braking at appropriately low speeds and steering at higher speeds, as is more appropriate (Kanarachos, 2009).

Furthermore, lane keeping assist or lane departure warning systems are available in several forms to aid drivers in staying on a set driving lane (for instance nudging or vibrating the steering wheel, providing a warning tone or audio-visual warnings, or actually providing counter-force or utilizing steering torque). Several vehicle manufacturers have begun integrating variations of these systems, typically in larger and higher-end models. Finally, several parking assistance systems have been in use; they provide drivers with visual aid from a parking camera or simply a warning tone while their vehicles are in reverse gear. These systems typically "hunt" up to 200m ahead for readable road centre lines and edge markings and do not operate on tighter curves (EuroRAP & EuroNCAP, 2011).

An overview of these systems, also known as Advanced Driver Assistance Systems (ADAS), can be found in the ERSO Traffic Safety Synthesis on Advanced Driver Assistance Systems.

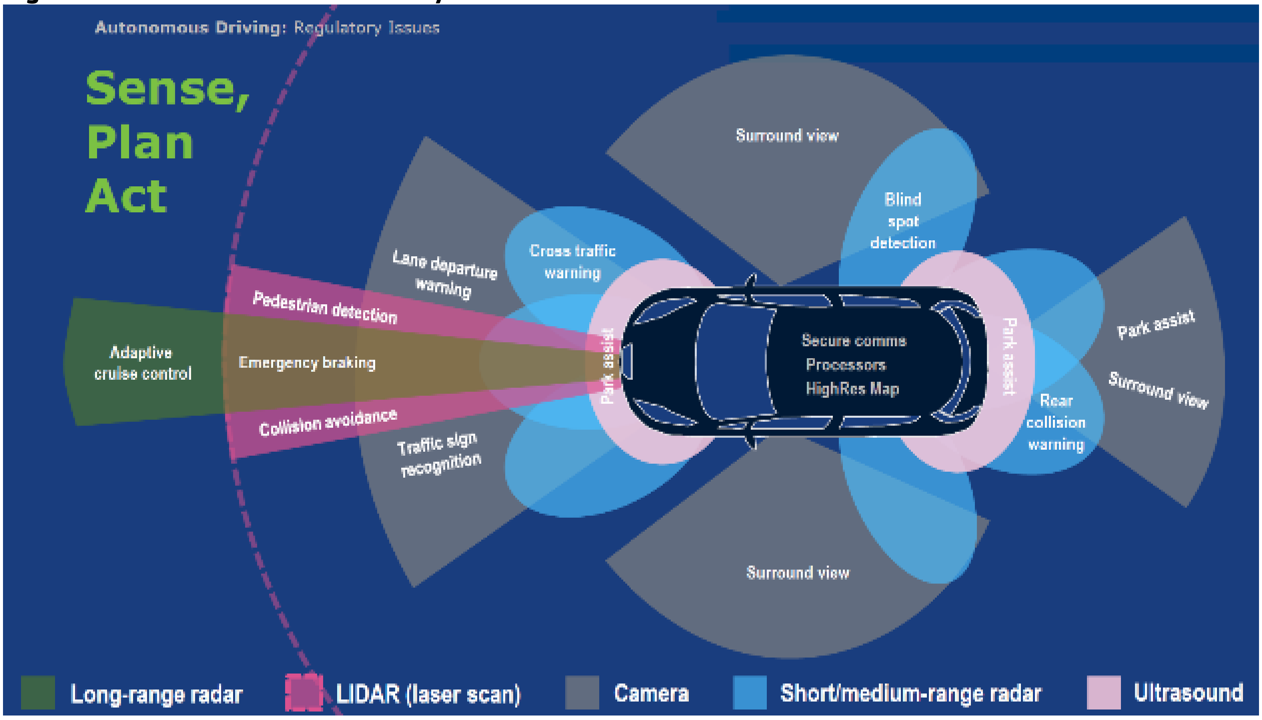
Box 1: Road testing of Connected Vehicles

New York City CVPD Project:
A CV pilot operation experiment was conducted by the US Department of Transport in New York City with the goal of addressing safety concerns regarding fatalities and severe injuries from traffic crashes in the city. The most noticeable impact will be the introduction of warnings to the vehicle driver/operators. It is unknown how frequent these warnings will be as this project will be the first to introduce over a dozen applications into a highly congested urban environment. The first phase has been completed and two others are underway. The function of Dedicated Short Range Communications (DSRC) for sample vehicles and intersections was featured, along with corresponding RoadSide Equipment (RSE) (Galgano et al., 2016).

Safety Pilot Model Deployment:
The project, aiming to evaluate V2V technology, included more than 3.000 vehicles and 30 infrastructure sites. On one hand, it was found that RoadSide Equipment (RSE) collected a much larger volume of data than was estimated due to the overlaps of coverage. On the other hand, each vehicle class and type required different installation configuration for the required data collection. It was also found that a relatively small number of total equipped vehicles can generate a large number of V2V interactions with a multi-faceted experimental design (Bezzina, 2015; Gay & Kniss, 2015).

An indicative arsenal of the sensor arrays and additional systems that can be found on board of a highly sophisticated CV or even a self-driving AV is presented in Figure 4 (OECD, 2015).

Figure 4: Indicative arsenal of AV systems



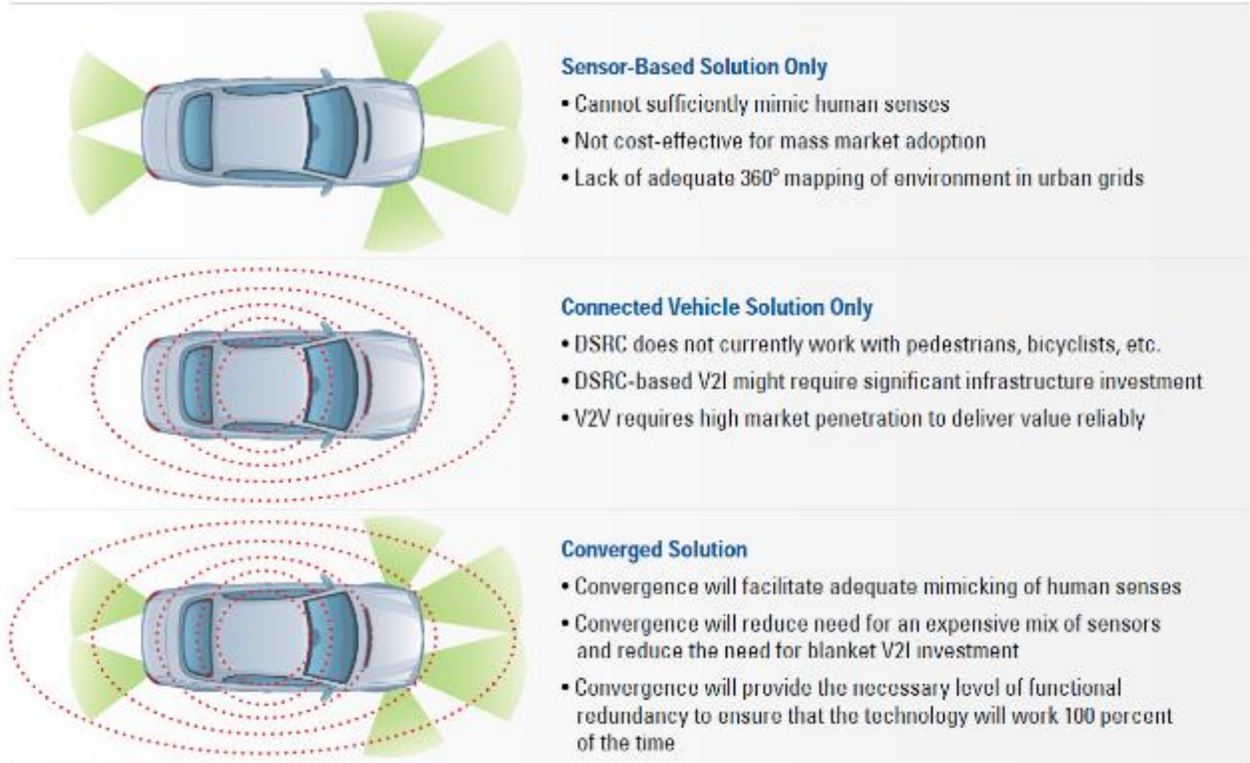
Source: OECD, 2015.

4.2 Autonomous Vehicle Progress

As the circumstances become more favorable for automation, there has been some debate on how to attain it. There have been two main fronts of technological groups: 'sensor-based' and 'connectivity-based' technology (Van Nes & Duivenvoorden, 2017). The first technological group focuses on developing devices to observe the road environment in order to take over the driving task from the driver and navigate independently. The second technological group uses wireless networks to communicate in real-time with other vehicles and with infrastructure elements.

This distinction is important for CVs, and even more so for AVs, which are expected to operate without human supervision eventually. Nevertheless, both groups are important in order to create truly safe and independent AVs. In fact, there will be a systemic fusion or convergence phase that will adequately replace human senses with considerable operational equipment redundancies. This will also balance the required sensor and infrastructure adaptation costs, as seen in Figure 5 (Silberg & Wallace, 2012).

Figure 5: Benefits of systemic fusion for AVs



DSRC: Dedicated Short-Range Communication; V2V: 'vehicle to vehicle'; V2I: 'vehicle to infrastructure'.

Source: Silberg & Wallace, 2012.

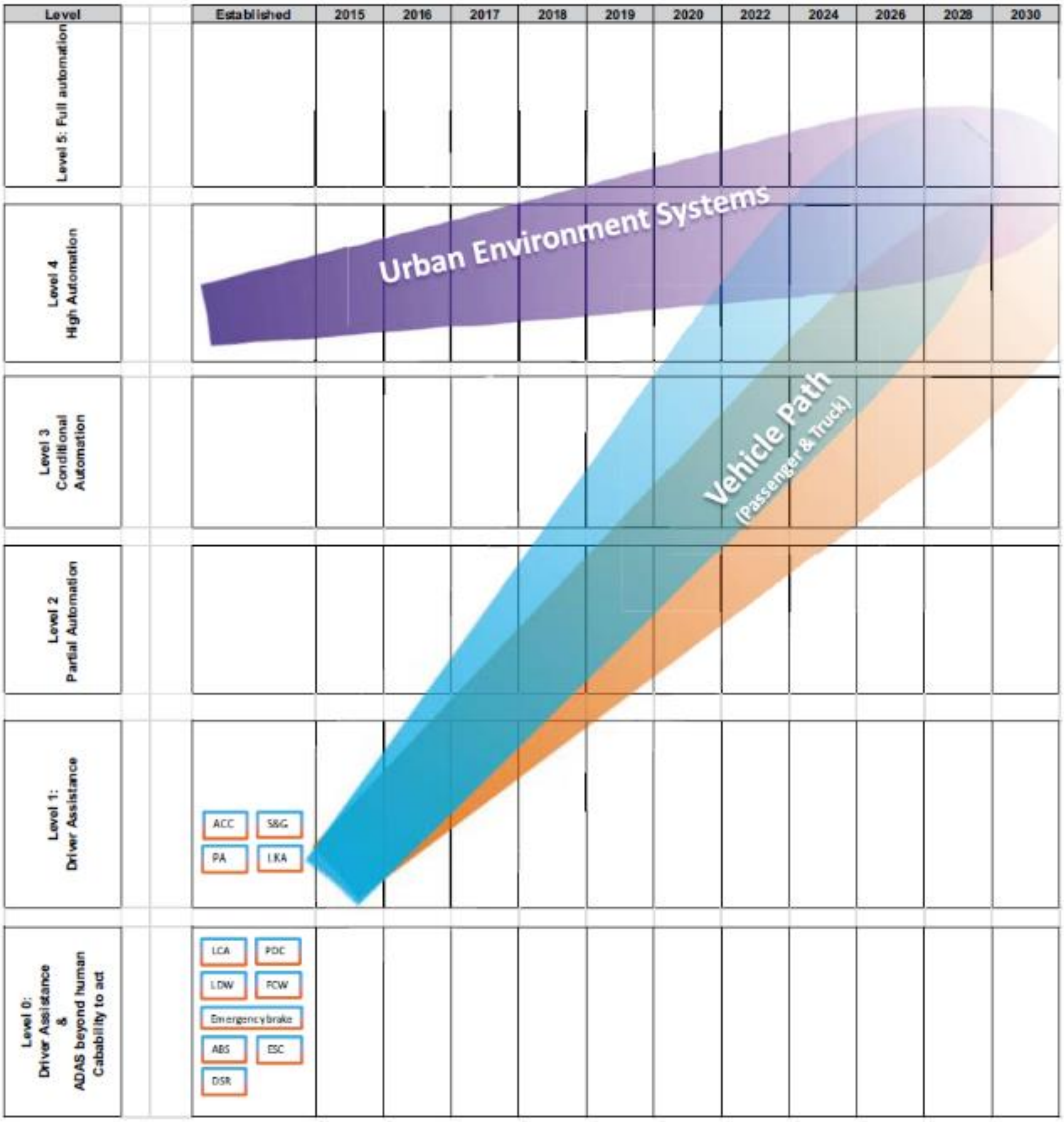
Similarly to CVs, adaptive cruise control, autonomous emergency braking, collision warning systems and lane keeping assist or lane departure warning systems are currently being adapted or redesigned for integration in AVs, with the expectation that they would provide feedback or otherwise cooperate with the driving algorithms instead of the human driver. As an extension to ACC systems, Tesla has implemented its autopilot technology in its Model S via a software over-the-air update. There is a discussion on whether this system fulfils the criteria of a Level 2 or even Level 3 system, as it partly monitors the driving environment; at any rate it is placed at that ballpark (Hedlund, 2017). Similarly, some Google prototypes have been qualified as Level 3 since the driver is still required to be able to retake control when the need arises (Zmud et al., 2017).

Waymo (formerly part of Google) has released advanced AV versions that claim Level 4 automation (Lee, 2017), or completely eliminate the driver by featuring no steering wheel or floor pedals (Hedlund, 2017). Several other manufacturers have reached Level 4 vehicles as well (for instance Volvo in 2017, Tesla in 2018), or expect to have completed them in the near future (BMW, Ford, Nissan, and Toyota in 2020-2021) (Ong, 2017). The more optimistic members of the industry already speak of automation benefits manifesting in the late 2020's or early 2030's (ERTRAC, 2015), while full automation becoming common and affordable (thus replacing conventional driving) between 2040 and 2060 (Litman, 2017).

What is more, a number of original equipment manufacturers (OEMs) have also begun to mobilize with interest in higher Level automation, independently developing systems essential to the assembly of a functional AV. One such example is the aforementioned lidar sensors; they are an integral part of SAE Level 4 and 5 autonomous systems, and are currently being developed with pulse infrared lasers for advanced imaging technology (Borst, 2018).

On a road authority level, several documents known as roadmaps have been published to anticipate future developments. The European Road Transport Research Advisory Council (ERTRAC) along with several stakeholders (iMobility Forum, EUCAR, CLEPA, ERTICO, EPoSS), have provided relevant timelines for the various stages of automation, which differ for passenger and commercial vehicles, as shown in Figure 6.

Figure 6: Timelines for AV developments



Source: ETRTAC, 2015

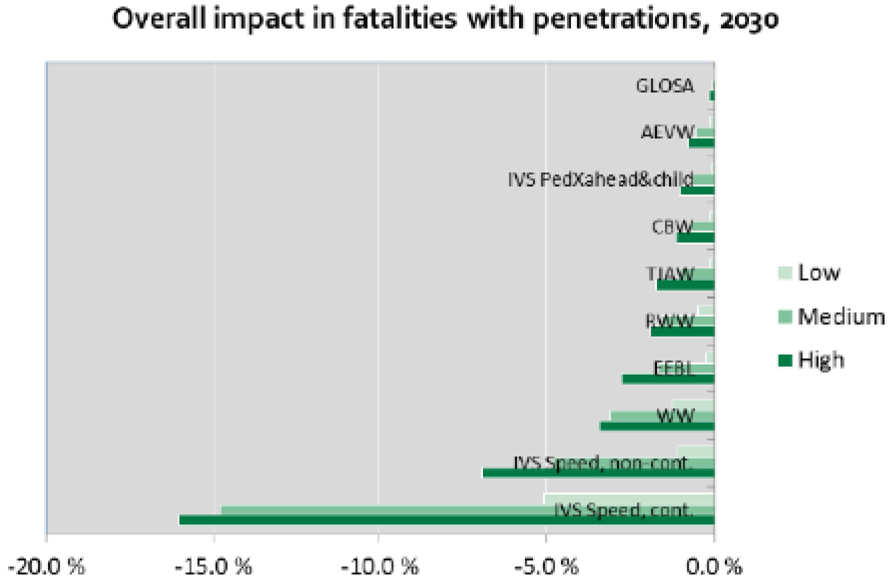
4.3 Safety lessons drawn from current practices

A number of systems that are expected to be prominently featured in AV and CV functions have already been in operation in conventional driving for some years. Thus informative results can be drawn from current practices up to this point.

A study of past crash records from previous years (2004-2008) indicated that crash avoidance technologies have considerable potential for preventing crashes of all severities, applying to more than a million crashes in the US annually. Lane departure warning/prevention systems and side view assist/adaptive headlights could display similar but lesser effects, while lane departure warning/prevention was found to be relevant for most fatal crashes. The author notes that simultaneous application of all four technologies could prevent or mitigate up to 1,866,000 crashes each year (Jermakian, 2011).

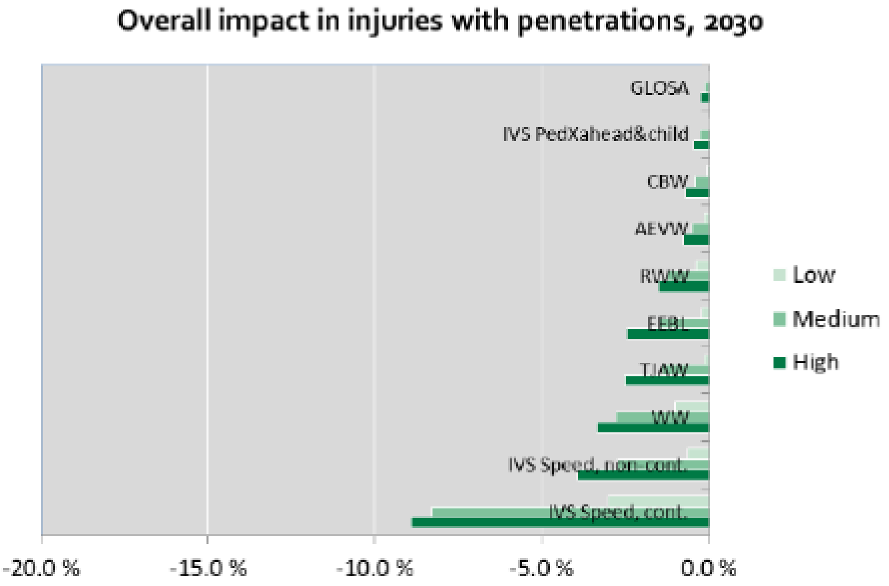
The safety effects of Cooperative Intelligent Transport Systems, such as those providing warnings about road hazards (road works, weather, etc.) or information to optimize arriving at and passing a traffic light, have been investigated in Europe within the framework of the DRIVE C2X Project. The assessment used data resulting from Field Operational Tests (FOTs) carried out on several test sites located in different EU countries. An analysis for several penetration rates was conducted, calculating fatality and injury reductions for a period up to 2030 (Malone et al., 2014). Expected results are presented in Figures 7 and 8.

Figure 7: C-ITS fatality reductions with various penetrations



Source: Malone et al., 2014

Figure 8: C-ITS injury reductions with various penetrations



Source: Malone et al., 2014

The safety effects of C-ITS and Automated Driving have also been examined for Australia and New Zealand by AUSTROADS. An analysis of real past serious injury crashes was undertaken, with quite promising results. For C-ITS, it was found that V2I C-ITS application would result in reductions of 20-30% for run-off-road or head-on crashes in major roads. V2V C-ITS applications were predicted to result in reductions of 20-30% for same direction crashes, in reductions of 35-50% for adjacent direction crashes and in reductions of 35-50% for right turn crashes (Logan et al., 2017).

Regarding autonomous emergency braking systems, a meta-analysis based on accident data from six countries identified that vehicles equipped with City-AEB systems were effective in preventing 38% of front to rear collisions (Fildes et al., 2015). More recently it was observed that AEB in conjunction with forward collision warning systems (FCW) reduced rear end collisions with injury by 44% (Ciccino, 2016), however the reduction from FCW systems alone was not significant.

The effects of Intelligent Speed Adaptation have been examined in the EU-funded project PROSPER (PROSPER, 2006). Potential crash reductions for six countries were calculated and reductions in fatalities between 19-28%, depending on the country, were predicted in a market-driven scenario for voluntary systems. Even higher reductions were predicted for a regulated scenario – between 26-50%.

Benefits are generally larger on urban roads and are also larger if more intervening forms of ISA are applied (Carsten & Tate, 2005; Carsten et al., 2006). Trials with ISA have been carried out in many European countries: Austria, Belgium, Denmark, Finland, France, Hungary, The Netherlands, Spain, Sweden (ETSC, 2006) and the United Kingdom (Carsten et al., 2008) as well as in the USA, Canada and Japan. An earlier study in the Netherlands showed that ISA could reduce the number of hospital admissions by 15% and the number of deaths by 21% (Loon, van & Duynstee, 2001). Research has shown that ISA and physical infrastructure measures to reduce road speed are complementary rather than competing methods (PROSPER, 2006).

There have also been other endeavors for analysis of the safety impacts of CV technology. A recent study has assessed fifteen major CV and AV technologies (CAV collectively) and conducted respective sensitivity analyses (Yue et al., 2018). Results indicated a 70% related crash avoidance rate as the highest effectiveness for several singular technology applications; past crash data analysis revealed reduction margins by at least 28,56% per year for light vehicles and by at least 37,06% for heavy trucks. The impacts of backing-crash countermeasures have been investigated by Perez et al. (2011), and reductions of 9% to 71% were found, according to several different scenarios.

Regarding lane departure warning (LDW) and lane keeping assistance systems (LKA), Gordon et al. (2010) investigated lane exit related crashes in the US and reported that lane departure warning systems can reduce 47% of all lane-departure crashes. Sternlund (2017) reported a reduction of 30% in head-on or single vehicle crashes comparing 146 LDW equipped cars, 11 LKA equipped cars and 1.696 cars without LDW or LKA. Nodine (2011) conducted a field trial with 16 vehicles equipped with Lane Departure Warning Systems and found a 33% reduction in near-crash events related to lane change and a 19% in those related to road departure. Birrel et al. (2014) conducted a similar trial with 33 participants in England and observed a 12% reduction in lane deviations however this was not statistically significant.

However, most of the aforementioned research results on the safety effects of various intelligent systems on traffic safety and their impact of crashes should be considered indicative; in most cases isolation of the effect of the examined system from that of other vehicle safety equipment is a challenge and the results are often unclear or without proper statistical verification (Theofilatos et al., 2017). Therefore, there appears to be a lack of knowledge in the application and performance of certain subsystems regarding safety; this is especially true for safety-critical events such as road crashes and not only behavioral variables. This area needs to be further explored by road safety experts worldwide, as well as any mechanisms that are not yet investigated.

An overview of the safety effects of ADAS systems can also be found in the ERSO Traffic Safety Synthesis on Advanced Driver Assistance Systems.

4.4 Safety lessons from incidents to date

As AVs have begun circulating in test areas, there have been some crash incidents that while unfortunate, merit consideration. They can be a learning experience, not only for manufacturers and programmers that have an opportunity to reassess and improve their product, but also for the public, in order to avoid any misconceptions of an ideal and infallible system. Interestingly enough, the public perception on the issue of safety of AVs has shown a mostly positive outlook on yielding control to an AV algorithm – 89,2% answered 'definitely yes' or 'probably yes' – in order to avoid a crash (Hyde et al., 2017).

The majority of crashes involving AVs have been attributed to either their operation by a human at the time of the crash or another vehicle being at fault (for instance, this applies to 13 of 14 incidents for Waymo/Google cars. In February 2016, the first incident attributed to an AV occurred in the US. In this incident, a Waymo/Google car was in automated mode as it encountered a lane obstacle and attempted to circumvent it, by entering an opposite traffic lane.

The software falsely reached a decision that an approaching bus would yield to it, allowing the AV the margin required, which did not happen (Google, 2016). The resulting crash was fortunately minor, and, interestingly enough, was an imitation of a common misunderstanding among conventional drivers.

In May 2016, a second incident in which the AV was at fault occurred, again in the US. A Tesla Model S vehicle was in automated mode while driving on a highway, as a tractor trailer was making a left turn in front of it. Its sensors did not properly recognize the white side of the tractor trailer as an obstacle and consequently the AV did not break. Unfortunately, the crash was fatal for the driver (Yadron & Tynan, 2016). Tesla recognized the algorithm as 'not perfect' and still requiring driver intervention at the time (Tesla, 2016). For Tesla, there had been another fatal crash in China on January 2016, but the mode which the car was in at the time of the crash was not confirmed (Boudette, 2016).

Noy et al. (2018) argue that neither human nor artificial intelligence will be in a position to gauge the reactions of other road users in the foreseeable future. They do recognize, however, that it would be impractical to devise algorithms that do not require the cooperation of other road users (as an AV would run out of gas while waiting to find a completely legal margin of right of way by the Arc de Triomphe in Paris, for instance). In an advanced road network state, where all vehicles are automated, such misunderstandings would not occur in theory (or at least they would occur with an acceptable very low rate, and very lower than human misunderstandings occur today). However, the aforementioned incident is an indication of the dangers of a poorly prepared and hurried transition state.

5 Transition Phase

5.1 Non-linear progression through automation Levels

Ever since the efforts for automation have begun in earnest, there was a perceivable gap between Levels 3 and 4 of automation: this is the tipping point where the human driver does not have to be on standby to reassume driving. It is very probable, however, that the industry will not pass through all automation Levels linearly.

Results from a driving simulator study (Merat et al., 2014) on drivers taking over from a virtual automated system indicated a 35s to -40s lag in behavioral and control variables, such as lateral control of the vehicle and steering corrections, when transition to manual control was unpredictable, which dropped to about 10s when the transition was predictable. These results suggest that drivers might not be sufficiently ready to resume manual driving control in Level 3 automation systems. Additionally, systems must be also able to satisfactorily evaluate the state of the driver, as it is unlikely that drivers themselves will remain vigilant (Vlakveld, 2016). Hedlund (2017) further questions the point of partially self-driving cars, highlighting contemporary habits (such as smartphones and social media) that attract attention whenever the user feels idle.

Moreover, it has been reported that Level 3 technologies can be too difficult to engineer in a way that would meaningfully mitigate risks similar to the above, and that a leap from Level 2 straight to Level 4 could be preferable instead. Several vehicle-sharing schemes would like to eliminate expenses of human drivers (Visnic, 2016), and relative exposure-related crashes, by removing human drivers altogether. Therefore, it is probable that Level 3 applications; although currently actively explored, might never come into widespread fruition (Ong, 2017).

5.2 Pending barriers

To ensure a successful transition, there are several steps that remain to be taken. Thomas (2014) suggests three main pillars to improve effectiveness of safety systems. These include choosing the optimal safety technologies from evidence-based assessments, introduce a lengthy and smooth transitional page and solve the conundrum of crash liability. A very noteworthy point is also highlighted by Smith and Svensson (2015) who emphasize that conventional traffic safety research must not be side-tracked amidst AV-induced fervor; actions to reduce intoxicated driving, distracted driving, speeding, poor vehicle maintenance and other common behaviors that substantially increase crash and injury risk can also increase the attraction of automated driving.

In addition to the previous, there are several barriers that must be overcome before AVs can become a commonplace reality. Most probably field tests will become more varied and more frequent, and will be able to encompass a wide variety of circumstances (e.g. different road or vehicle types, adverse weather, varieties of vehicle configuration etc.). Additional tools, such as simulation testing might become widespread to facilitate the transition (Zhao et al., 2017). This process will mark the transition phase between conventional vehicles to CVs and ultimately to AVs, and will demand new practices in all stages of safety.

Winkle (2016) mentions that before complex AVs can go into mass production and circulation, inter-disciplinary concerted development and sign-off processes are required. The updating of Advanced Driver Assistance Systems (ADAS), with experience based internationally valid guidelines is also suggested. There have been initial recommendations of analysis for safe developments of ADAS and Human-Machine-Interactions (HMIs). The framework has been laid for several concepts to be compared (through stages such as ‘definition phase’, ‘best concept selection’ and ‘proof of concept’) and then the most beneficial and feasible one is proposed to be selected (Knapp et al., 2009). This iterative procedure should be expanded for AV/CV ADAS whenever a new, untested line of concepts is proposed for integration.

A major front that needs to be advanced for AVs and CVs to become a reality is sensor capabilities. Recently, a study on sensors reached several interesting conclusions (Schoettle, 2017): Artificial intelligence can be considered suitable for the driving task, especially when calculating speed, distance and power output and control, and at slow speeds might actually surpass ideal human driver performance. Many sensors can provide capabilities not available for humans (such as lidar); with those capabilities current risk factors might be circumvented (such as safely navigating through adverse weather with radars). On the other hand, the aspect of humans which is the most difficult to replicate appears to be rationality and perception. The author concludes that an AV that is fully connected with each environment will offer the safest and most efficient operation on high automation Levels (Levels 4 and 5) and reaffirms that CV technology will aid both human and AV drivers. Findings from the study for each sensor type per performance aspect are presented in Table 2 (CAV refers to vehicles that are both connected and automated).

There are certain revolutionary ideas that have been proposed for sensor development. For instance Schoettle and Sivak (2017) analyse the potential capabilities of intelligent (or smart) tires for AVs. Intelligent tires, according to the authors, would not only monitor the state of the tires themselves (e.g. pressure, tire loads, age and health etc.), but that of the roadway as well (e.g. wetness, friction, material type etc.), providing feedback to the AV artificial intelligence. This would increase safety performance through real-time measurement of the roadway.

Table 2: Current sensor performance

Performance aspect	Human	AV			CV	CAV
		Radar	*Lidar*	*Camera*	*DSRC*	*CV+AV*
Object detection	Good	Good	Good	Fair	n/a	Good
Object classification	Good	Poor	Fair	Good	n/a	Good
Distance estimation	Fair	Good	Good	Fair	Good	Good
Edge detection	Good	Poor	Good	Good	n/a	Good
Lane tracking	Good	Poor	Poor	Good	n/a	Good
Visibility range	Good	Good	Fair	Fair	Good	Good
Poor weather performance	Fair	Good	Fair	Poor	Good	Good
Dark or low illumination performance	Poor	Good	Good	Fair	n/a	Good
Ability to communicate with other traffic and infrastructure	Poor	n/a	n/a	n/a	Good	Good

Source: Schoettle, 2017.

5.3 Traffic safety in the transition phase

Nearly all AV applications are expected to have safety impacts potentially (Innamaa et al., 2017). That being said, there will certainly be unforeseeable developments, and there has been some questioning of the benefits of automation. Sivak and Schoettle (2015), for instance, claim that zero fatalities cannot be expected, and that the superior performance of an AV over an experienced, middle aged driver regarding safety is not undoubtable. A critical point that the authors support is that during the transition phase, where AVs will share the road network with human drivers, safety levels might decline, at least for human drivers.

In the transition phase towards fully autonomous vehicles, traffic system will have to cope with 'mixed traffic', i.e. with vehicles of different Levels of automation (or no automation) operating simultaneously. This can potentially be confusing and impose an increased risk to road users, who will not be able to know to what extent another vehicle is automated, what behavior is therefore to be expected, and how they must anticipate and interact (Van Nes & Duivenvoorden, 2017).

For some AV systems, penetration rate, i.e. percentage of vehicles or roads equipped with that system, is relevant and sometimes critical in order to achieve the desired safety effect. Especially for cooperative ('connectivity-based') systems, the performance of the system depends on the number of vehicles and/or roads that are equipped with this technology. A 'critical mass' needs to be attained, which will certainly require some time to achieve, as the vehicle fleet is gradually replaced and gradually will include a greater number of (more) intelligent vehicles (Van Nes & Duivenvoorden, 2017; Sivak & Schoettle, 2015). This makes the introduction of new autonomous systems difficult, because the user cannot take advantage of the functionality until sufficient other road users also have it.

Apart from technological transition, which will determine which devices and products (vehicles) are roadworthy, the actual driving transition is a sensitive and currently unclear period for traffic safety. Wide-scale field tests for AVs in real conditions have not been performed yet, and the safety effects while interacting with human drivers have only been studied in simulations, with all the limitations that characterize simulator research. The pace for the transition process is a parameter on itself, which will simultaneously determine and be determined by AV safety performance through constant feedback. Consequently, this stage will be crucial for public acceptance for AVs.

An often overlooked aspect of traffic safety is the role of pedestrians and cyclists in the future road environments (Van Nes & Duivenvoorden, 2017). In future traffic systems, a large degree of urbanization can be foreseen, which inevitably leads to many different types of road users mixing together. It is therefore critical that autonomous vehicle systems take properly into account the interaction with vulnerable road users, such as pedestrians, cyclists and powered two wheelers. Vulnerable road users should be recognized under all reasonable circumstances, and without any adaptations on their part (such as reflective clothing), their intentions predicted and their behavior anticipated (Vissers et al., 2016). Also, it is at least as important that the behavior of automated vehicles - or partially automated vehicles in the transition phase - is understandable and predictable for vulnerable road users.

5.4 Authorities activities and enforcement in the transition phase

Moving in tandem with road authorities, enforcement agencies will have to increase their readiness for the advent of AVs, in order to ensure a safe transition. This includes the training of personnel to be able to handle cases with AVs, and to determine whether any fault or liability for traffic safety misconduct lies with human road users or artificial intelligence AV algorithms.

Such pre-emptive measures have been examined by Hedlund (2017), who claims that, in the event of a crash, police officers should have a way of determining the autonomous capabilities of a vehicle (such as AV Level), whether they are operating in automated mode, and if so, whether they are operating automated while inside or outside their Operational Design Domain (ODD). Another report provides similar directions, and adds that authorities must be aware of how the driving mode was selected, i.e. from a human driver or from a default setting. A visual identification (e.g. light activation) to signal the operation of automated mode for AVs is therefore proposed (Cunningham et al., 2017).

An issue of particular importance in the transition phase is required authorities' activities and enforcement related to real world AV testing in the coming years of automation development. Preliminary policy recommendations on how to safely conduct such testing on public highways have been provided by NHTSA (2013), focusing mainly on the following issues:

- ensuring that the driver understands how to operate a self-driving vehicle safely;
- ensuring that on-road testing of self-driving vehicles minimizes risks to other road users;
- limiting testing operations to roadway, traffic and environmental conditions suitable for the capabilities of the tested self-driving vehicles;

- establishing reporting requirements to monitor the performance of self-driving technology during testing;
- ensure that the process for transitioning from self-driving mode to driver control is safe, simple, and timely;
- ensuring that self-driving test vehicles have the capability of detecting, recording, and informing the driver that the system of automated technologies has malfunctioned;
- ensuring that installation and operation of any self-driving vehicle technologies does not disable any federally required safety features or systems;
- ensuring that self-driving test vehicles record information about the status of the automated control technologies in the event of a crash or loss of vehicle control.

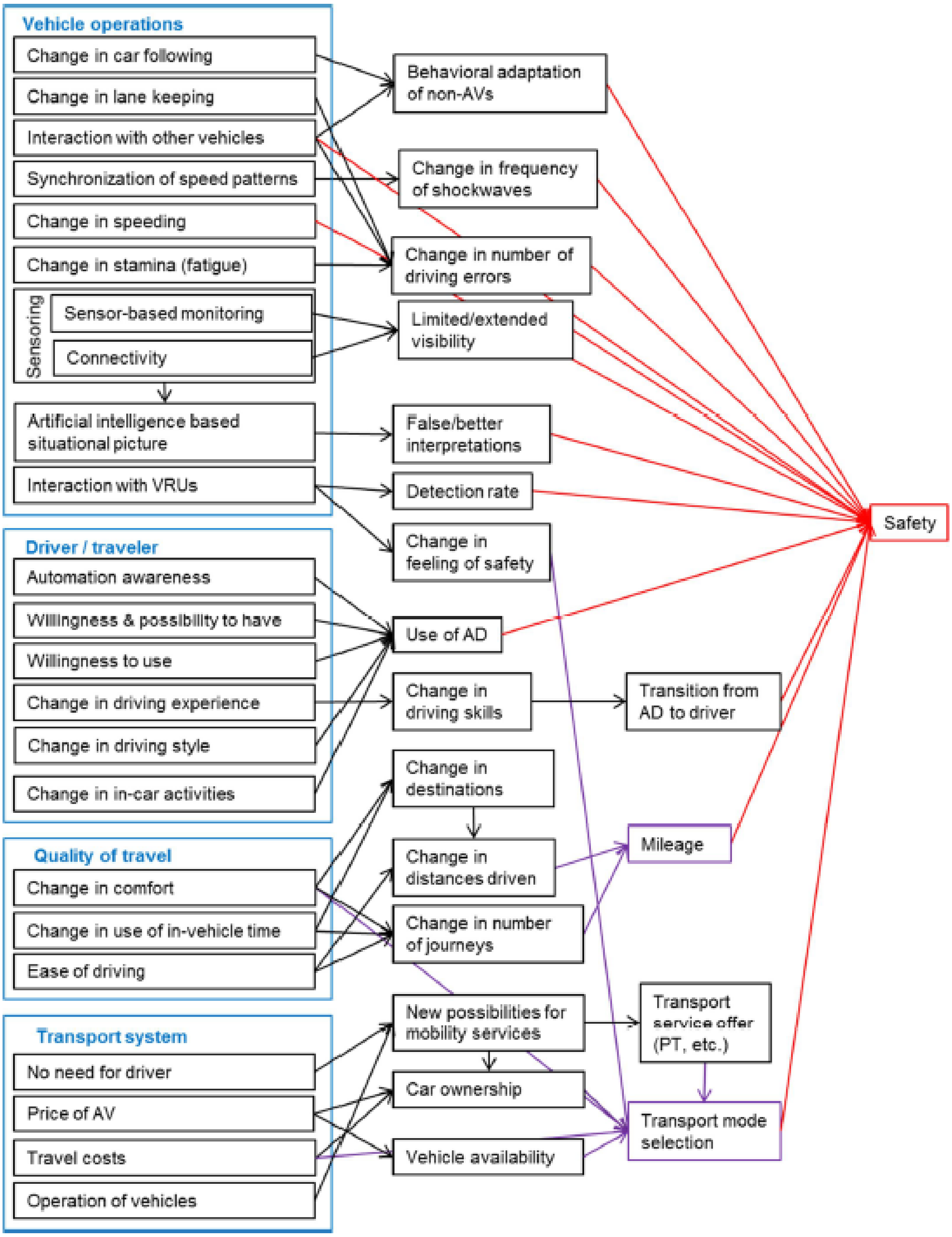
UK government has also supported data recording of similar information in relevant documentation (UK Department for Transport, 2015). An analogous direction, comparable to the 'black boxes' found in airplanes, was announced by the German government in a press release, possibly urged by the fatal Tesla S incident (Wacket, 2016). Law enforcement should also be constantly improving in order to anticipate cybersecurity concerns (discussed in Chapter 7).

6 Direct Autonomous Vehicle Impacts

6.1 AV impacts on safety

As previously stated, AVs are expected to create impressive impacts in all aspects of transport, including traffic safety. In Figure 9, safety-related implications stemming from the widespread applications of AVs are summarized.

Figure 9: Impacts of automation on safety.



Source: Innamaa et al., 2017.

The exact safety benefits of the implementation of AVs are quite difficult to estimate, even as an order of magnitude, due to the extreme number of unknown parameters, as illustrated in Figure 9. As a numerical indication, the estimates of Fagnant and Kockelman (2015) for the US are provided: for AV penetration rates of 10%, 50% and 90%, the authors project a corresponding 1.100, 9.600 and 21.700 lives saved (in the US) per year. However, these estimates include several assumptions involving AV assimilation into the road network and how it might actually work, such as changes in market-penetration shares, vehicle miles traveled, AV technology costs, and appropriate discount rates for net present value calculations.

Despite the inevitable uncertainty, conclusions can be drawn from the interrelations depicted in Figure 9. Some behavioral adaptations are predicted from AV implementations and adjustments of human drivers, such as headways (car following) and lane keeping. Speeding patterns are also anticipated to be altered, with more robotic or mechanized driving, and forward (in)compatibility (as explained in the following section). These points raise valid concerns for the safety of conventional road users (especially drivers), especially given the high percentages of crashes currently attributed to human error. In other words, there must be preparation to prepare drivers from being surprised by AV behavior, or to avoid crashes that can be otherwise caused from it. For instance, a driver might become too impatient to wait for a cautious AV to move; they could try to circumvent it with a dangerous maneuver and as a result crash with another vehicle or infrastructure element.

Personal characteristics, such as individual driving styles, might be suppressed in large amounts from AV use. This provokes the question of whether different manufacturers will introduce different driving styles that will be similar throughout the manufacturers' vehicle fleet. In that case, road authorities should ensure basic sharing and communication within the market, in order to have agreements in AV functions. If there is consistent disarray from different driving styles on the roads, resulting from extremely "polite" and "aggressive" algorithms, to the degree that traffic safety is compromised, relevant standards will have to be issued and enforced instead. Another perspective is to train AVs and CVs, which leaves some questions about the timeframe that this training will require, and whether safety will be compromised therein.

A noteworthy point is that the exact levels of traffic safety from AV operations highly depend on their market penetration, as it will change the composition of vehicle fleets. Market penetration is greatly influenced by public acceptance (or willingness to have or to use), which in turn depends on public information and advertising and awareness and personal perception of safety (including incidents such as those described in Chapter 4). Demonstrations of safe autonomous operations in similar fields, such as public transport, will aid in creating a more positive picture for AVs as well. Market penetration is also relevant to AV costs (both investment and generalized) and infrastructure readiness and availability, among other factors.

The best case scenario is a virtuous circle of increased safety (and other AV benefits) which will lead to increased public acceptance and market penetration, which will in turn lead to even more AVs with increased overall benefits and so on. At any rate, after the first AVs start their operation there will be a prolonged period of considerable adaptation in AV safety performance rates, which may or may not coincide with the transition period. The traffic system will eventually balance and safety indices are expected to evolve in more foreseeable rates afterwards.

6.2 Human factors issues

The human factor is an ever-present issue in traffic safety and human factor implications of automation need to be explored.

6.2.1 Connected and partly automated vehicles

In the more short term future, CVs are going to be commercially available, to a more increased extend compared to today. A set of impacts are expected for driver behavior from CV implementations, as their primary role is to aid and inform drivers.

An issue that should not be overlooked is behavioural adaptation, i.e. the driver adjusting his behaviour to the new (driver assistance) technology. This can result in the intended safety effect being reduced, annihilated, or even reversed, for example when a driver over-relies on a system and does not pay sufficient attention anymore (known as rebound effect). An example is drivers adjusting their driving habits when they have a Lane Departure Warning system (LDW) installed. The driver may become overconfident that he will get a warning if necessary and perform secondary tasks, thus increasing the risk (Van Nes & Duivenvoorden, 2017). Another form of behavioural adaptation seems to occur after platoon-driving. Simulator studies have shown that drivers who have driven in a platoon - with short headway distances - e.g. relying on adaptive cruise control systems, tend to persist in short headway distances after having left the platoon (Skottke et al, 2014).

On the other hand, there are positive impacts as well. After field and long-term testing, research in Japan has shown speed reductions and stop signs compliance rates before intersections from C-ITS V2X applications, with systems exhibiting good user acceptance as well (Fukushima, 2011). US results showed that providing a warning to drivers resulted in fewer crashes than doing nothing (baseline condition), and that the mode of the warning (visual, auditory, or tactile) had no significant impacts (Lerner et al., 2014).

Especially during the transition phase, it has been suggested (Van Nes & Duivenvoorden, 2017) that the process occurs gradually, step by step, and information has to be prioritized. Since human drivers would still be present, distractions by less important signals must be suppressed. Warnings must be given in a proper manner (either visual, audile, tactile or a combination) and the overall workload has to be minimized. It has been found that experienced drivers achieve quicken situation awareness when transferring control and that a transition margin of at least 6s is desirable to attain that awareness (Wright et al., 2016).

6.2.2 Autonomous Vehicles

Nowadays, road user behaviour has been established for conventional road users. A pedestrian, for instance, knows when to attempt a crossing that is safe from oncoming traffic. With AVs, however, the issue of forward (in)compatibility might emerge (Van Loon & Martens, 2015); this is essentially the absence of important human cues and mannerisms that have become integrated in contemporary road user behaviour (such as a driver gesturing politely to yield priority to a pedestrian that might not normally have it). Additionally, Van Loon and Martens (2015) note that passengers of AVs expect human oriented traits in the decision-making of their vehicle under safety-critical situations, and public acceptance of AVs might decrease if that behaviour is not displayed. This unpredictable behavior that is the product of intelligent functions has been acknowledged, and one possible answer is the introduction of a safety supervisor to detect malfunctions of the intelligent functions and trigger a minimum risk maneuver such as an emergency stop (Adler et al., 2016).

It is also important to remember that not all road users are drivers, or even of adult age or otherwise experienced. Vulnerable road users, such as children, elderly, people with impairments and disabilities also have a right to share the roads, and a safe environment must be provided for them as well. Often they carry additional equipment with them on the road pavement, such as suitcases or strollers, and some even move more unconventionally with skateboards/rollerblades. Therefore AVs must be able to anticipate all these possibly unconventional conflicts, especially in tightly-knit urban environments, and have capacities to react appropriately. This is an especially critical area, since it appears very difficult to predict behavioral intentions of pedestrians and cyclists by current technology. If these road users display different behaviors against AVs compared to conventional vehicles, then current knowledge might be ineffective for the development of algorithms that would enhance safety (Vissers et al., 2016). As a possible part of an application process, there could be GPS mapping of calmer traffic zones (school zones, residential areas etc.) in which AVs and CVs would limit their operating speed and have increased defensive reaction prioritization (such as emergency stopping), but this would not be sufficient to eliminate unpredictability.

Despite all promises of automation, the human factor is not expected to vanish from either short or long-term transport systems. Not only is traffic going to be at least mixed for a long time, but the interactions of the aforementioned vulnerable road users will not be easily automated. Even the software designers and scientists designing the algorithms for automation, be they on AVs or infrastructure, will induce their own amount of human factors. Furthermore, in order to compare the road user behavior with the behavior of the AVs, and adjust the latter, extensive big data analyses are required. The ever-present question of "What an AV would hit in an unavoidable collision, a pedestrian or another obstacle?" is indicative of real time operational safety choices that AV scientists will be called to answer. Authorities will be invited to play key coordinating roles for smooth design of the new autonomous road systems when they arrive. At any rate, existing knowledge from human factor research must be exploited to improve traffic safety, while keeping the outcome as much optimized as possible between traffic and safety on both a network and AV level.

6.3 Application issues

Amidst eager anticipation of CVs and even more for AVs, there are certain safety issues that might appear unforeseen or underestimated currently, but will need to be addressed.

Temporal and spatial headways (minimum time and distance gaps between vehicles, respectively) and lane widths could both presumably be reduced with the advent of artificial intelligence drivers and the precision they will bring in controlling the AVs. Increases in speed limits are also quite likely to also be considered (Cohen & Cavoli, 2017). In principle, the realization of any of these interventions means increased capacity of the road network. In a microscopic level, however, it also means that there will be proportionately less time for any following vehicles to react to an unforeseen event, be that a mechanical fault or an unexpected obstruction in the vehicle path. While the margins can appear ample in computational terms, there need to be adequate headways for the physical aspect to the vehicle to mechanically react as required.

In the event that AVs become as widespread as conventional vehicles currently are, in combination with the higher amount of people having access to road transport via autonomous driving and increased network capacity, a higher number of vehicle-kilometers will be travelled (VKT) annually – to the point at which many of the lauded benefits of automation such as lower energy demands and ecological impacts could be reduced or even annulled (Wadud et al., 2016). This increase could climb as high as 35% (Bierstedt et al., 2014). If the AV systems are not 100% infallible – as the February 2016 incident of a Waymo/Google car striking a passenger bus suggests (Google, 2016; McFarland, 2016) – then increases of VKT translate to increases of the respective crash probability (assuming stable crash rates) for each AV. There is also the issue of computational power, meaning that the system of each AV and any central RSE must be able to handle an exceptionally large amount of simultaneous vehicle interactions, which might be underestimated with the present road network state.

If very high automation Levels (4 and 5) are realized, there is an ambitious and eager undertaking to restructure vehicles having removed human-related driving mechanisms that would have by then become redundant. The space of the cabin might include a central table, for instance, for leisure or telecommunication activities, or even sleeping space. These developments, however, will annul a lot of the current traffic safety progress and respective technological designs which assumes a conventional cabin setup, which includes forward facing and seated passengers, as discussed in relevant research (Sivak & Schoettle, 2016). One of the potentially highly dangerous configurations would be passengers facing each other, with the cabin resembling train seating. A high degree of unpredictability concerning the direction of impact forces will have been introduced if safety-oriented design is disregarded in favor of form and innovation. Furthermore, more available cabin space might mean that passengers would have larger and more numerous unrestrained objects in the event of a crash which will behave in manners that are currently unpredictable and might endanger passenger safety.

Euro NCAP (2015) and the European Transport Safety Council (ETSC, 2016) have recognized the existence of different industry priorities as well, but also regards the preparation for automation as an opportunity to promote technologies that are most beneficial to safety. All these issues merit consideration when designing the AVs of the future.

6.4 Infrastructure adaptation

In order to make AVs feasible, it is imperative that the driving environment, i.e. road infrastructure, is compatible with their requirements. These requirements may differ significantly, depending on the autonomous technology approach: 'sensor-based' or 'connectivity-based' (see also Chapter 4). As the technologies are yet emerging, each separate approach can be examined in order to outline the process of infrastructure adaptation.

If the 'sensor-based' approach is adopted, the responsibility of navigation and obstacle detection falls on AV systems. Relevant studies, however, suggest that this approach seems unable to provide adequate 360° mapping of urban environments (Silberg & Wallace, 2012). While it is fair to say that neither human drivers have 360° mapping capabilities as well, abandoning the opportunity to improve detection would be a large waste of potential. Therefore infrastructure elements must be designed or repurposed with that limitation in mind. Apart from being impractical in many cases, relevant investment costs in time and capital would be a major deterrent for the introduction of AVs.

Assuming a 'connectivity-based' perspective, there ought to be Road Side Equipment (RSE) deployed in several points along the road network under normal driving conditions. Those devices would definitely need to be present in areas where the AVs cannot detect infrastructure elements for themselves and with appropriate coverage and sufficient overlap in case of RSE malfunction. Even if the AVs can detect infrastructure elements, RSE deployments can be used as a failsafe, to alter the course of an AV (such as collision avoidance in aviation systems). In the worst case scenarios, drivers can be alerted to assume control, which would bar complete automation implementation.

Therefore, as previously stated, fusing the two technologies would lead to the required failsafes and redundancies that would realize a truly safe AV-dominated road network. At any rate, care must be taken to ensure that the necessary infrastructure, which can include infrastructure elements for other modes (for instance trams or automated buses), is sufficiently adapted, mapped and visible for AV algorithms.

This adaptation might include additional features apart from electronic devices, such as custom reflective road markings and signage that can be read from AVs. The markings would need to counter problems of poor visibility due to road condition (wet or icy surface, road gradient and curvature, lane widths) or marking condition (faded markings, low contrast etc.). These problems are likely to be exacerbated in the future as systems seek to sample shorter road lengths ahead in order to read curves or the presence of something like a turning lane (EuroRAP & EuroNCAP, 2011). Taking into account capabilities of lane departure and lane keeping systems and based on a collection of data of intervention and maintenance standards from a number of European countries, a good road marking has been identified as one whose minimum performance level under dry conditions is 150 mcd/lux/m^2 and which has a minimum width of 150 mm for all roads; for wet conditions, the minimum performance level should be 35mcd/lux/m^2 (EuroRAP & EuroNCAP, 2013).

Another critical point is to anticipate temporary infrastructure interventions and ward them accordingly. One such notion, focusing on workzones (roadworks) was proposed by Huggins et al. (2017), who highlighted the importance of good planning and real-time information provision for AVs. The information should include physical layout changes, which could in practice become more complex for an AV. Therefore, in the future, road authorities might need to provide temporary layout "patches" for AV algorithms in addition to careful planning throughout all stages and temporary signage for human drivers when planning for a workzone. All stakeholders should bear in mind that the safety of AV passengers will now depend on devices outside their vehicles, and apply relevant measures to protect those devices from all hazards such as weather effects, vandalism attempts etc.

As a final note on infrastructure, impacts from practices born from automation must be anticipated as well. One such issue is the durability of structures (e.g. bridges) in the scenario of automated heavy vehicles 'platooning', i.e. travelling in tight clusters with very small headways to reduce aerodynamic drag and increase fuel efficiency. It is therefore possible that some infrastructure elements will need to be reinforced before AV traffic is allowed to access them. Even the increased traffic demand by small vehicles mentioned previously will lead to increased infrastructure wear (repetitive loads and material fatigue). This will cause higher maintenance needs in normal roads, and structural problems in weaker areas (such as older steel bridges). Another challenge might be signal enhancement in tunnels, particularly in longer ones (such as the Mont Blanc Tunnel), in order to maintain remote control of AV fleets transporting goods without a passenger aboard.

As with conventional traffic, frequent conflicts can be foreseen between traffic and safety demands. The agenda of each stakeholder and the aim of each intervention must be clearly determined and evaluated beforehand, and road network administrators should aim for an optimized and informed solution.

7 Indirect Safety Implications

7.1 Mechanical safety

In conjunction with the previous topics of physical capabilities of vehicles, it is imperative not to ignore the remaining crashes that are not due to human error in order to maximize safety gains. At present, the residual percentage (less than 10%) can be roughly attributed equally to vehicle and infrastructure faults or deficiencies. It is possible that this percentage will appear much more considerable after the human error is eliminated by a large amount by widespread AV use.

If an increase in vehicle-kilometers travelled (VKT) also occurs, (as previously described in Chapter 7), then mechanical faults and issues of vehicles will become even more prominent due to increased exposure (for instance material fatigue). Overall, there are two important areas to take into account. Firstly, as vehicle technology becomes more sophisticated, there are more layers and thus more possible chances for equipment failure (degrees of freedom). An advanced pulsing motion-sensor infrared laser is in principle more susceptible to equipment fault than a mechanical handbrake, for instance.

Secondly, there is the issue of black box AVs, in the capacity that passengers would be out of touch with the technology of the vehicle that is transporting them. Nowadays, drivers can more or less detect a mechanical fault or at least have a rough idea on when to go for service, largely due to the fact that they are the ones actively handling the vehicle. In the future, individuals that might not possess a driving license or are not fit to drive altogether (minors, seniors, people with impairments) might not be in a position to judge the roadworthiness of their AV, which could, under unfavorable circumstances, lead to a crash.

This issue can be mitigated by providing interfaces that are thoroughly explanatory and comprehensive to passengers (and any third party maintenance contractors). It could also become irrelevant if there are no widespread privately owned AVs, and rather they are available as a constantly moving fleet from which customers summon their vehicle and rent it until their destination (e.g. sharing or subscription services). In this case, maintenance would have to be undertaken collectively by the fleet providing company.

Ironically, even the theoretical impressive traffic safety attainments of AVs can be a caveat for traffic safety itself. If there is better crash avoidance, manufacturers and road authorities would seize the opportunity of lighter vehicles, with relevant studies having predicted such directions (Somers & Weeratunga, 2015) or proposed such designs (James & Craddock, 2011) combined with increased operating speeds. Downsizing brakes and other systems has also been discussed as part of a series of positive transport reforms (Schwarz et al., 2013). A similar synergy could be achieved by what is known as platooning, namely the practice of vehicles travelling in tight clusters with very small headways to reduce aerodynamic drag and increase fuel efficiency up to 20% with hybrid vehicle operation (Manzie et al., 2007) – this practice might not require full automation, but rather CV technology, in order to be applied.

All the above trends and practices would definitely be welcome to increase road capacity (as mentioned before) and possibly reduce emissions (Innamaa et al., 2017), but should not be implemented rashly. If sensor failure occurs under such a scenario, it is important that opportunities for mass or material reductions do not jeopardize passenger safety, and that sensors and the vehicles have the necessary margins to physically react as units. Safeguards for all critical mechanisms like those described in relevant studies (Adler et al., 2016) will have to be in place as well, on top of resilient and redundancy-including design practices such as those described in Silberg & Wallace (2012).

It is obvious that, for these more advanced issues to be encountered, mechanical sensors should fulfill all set standards and that AVs have to be roadworthy under all circumstances. Therefore, incidents of subpar sensor detection that would result in crashes (such as those mentioned in Chapter 6) would be considered to have been mostly eliminated within reasonable safety margins at this stage. Additionally, similar mechanical fault issues must be considered for any required RSE deployed along the roadside.

7.2 Cybersecurity

When entrusting driving and navigation to the artificial intelligence algorithms of an AV, it is quite possible that security issues that were not present with conventional drivers might arise, including cybersecurity. One of the major hurdles in public acceptance of AVs and CVs is the feeling of loss of human control and entrusting it to an unseen, black box type algorithm. This might hinder wide propagation of AVs in particular, especially given the increase of cybercrime and similar malicious internet activities in recent years (Hui et al, 2017).

The routine activity theory (RAT) of criminology suggests that crime is formed by the presence of likely offenders, suitable targets and absence of relatively capable guardians (Cohen & Felson, 1979). When considering widespread AV and CV implementation, it is thus meaningful to think about traffic and travel security, in addition to traffic safety. This becomes highly pertinent if 'self-learning' vehicles are implemented, which will use heuristic algorithms to improve performance. These systems will actively seek more input from their environment, thus leading to greater threats of user privacy (Acharya, 2014).

There is a need of agencies fulfilling the role of 'capable guardian' and not only actively police and monitor highly automated transport environments, but also evolve and anticipate cyber-

assaults (such as hacking) in advance. RSE, where implemented, will be susceptible to similar assaults and will require similar protection.
In the UK, the government has released a set of policies concerning security and design principles. They state that organizational security functions at a board level, emphasize the need for organizational education, cooperation, interoperation and information exchange, in addition to that of product aftercare and incident response. Systems should be designed to be resilient, with multilevel security, as opposed to depending on a single critical point, and managed throughout their operational lifetimes. In conclusion, safe transfer and storage of data is considered achievable for AVs, CVs and intelligent transport systems (ITS) in general (UK Department for Transport, 2017). The need for collective decision making and knowledge sharing has also been underlined in relevant studies (Noy et al., 2018).

A relevant study (Sivak & Schoettle, 2017) underlined, among other findings, the importance of Cybersecurity in the viewpoint of the public perception of AVs. After interviewing US adults online, it was found that, when combining all respondents, their greatest concern for fully automated vehicles was hacking to cause crashes or other malicious intent, with 33,4% of replies indicating they were extremely concerned on the matter. Hacking of vehicles was of concern even for conventional vehicles, albeit less so than AVs. Nevertheless, this might indicate similar acceptance issues for CVs as well.

7.3 Road safety evaluation procedures

Interestingly, the way traffic safety is evaluated could also change by the advent of vehicle automation. Innamaa et al. (2017) suggest that new indicators will need to be measured for AVs, including selected traffic violations, instances of human intervention (assuming direct control), exposure or response to near-crash incidents, time-to-collision (TTC) under a specific threshold and others.

TTC, which is the remaining time before the collision of the vehicle occurs, has been extensively suggested in pathway and motion planning for AVs in several studies and has been used for predicting the collision likelihood between two vehicles communicating over a V2V link (Katrakazas et al., 2015, Ward et al. 2014, Ward et al., 2015). A similar indicator is time-to-react (TTR), which corresponds to the time available for the driver to act before the collision is inevitable (Lefèvre et al., 2014). Another possible method is the analysis of traffic gap acceptance (probabilistic gap acceptance models) as suggested by another study (Lefèvre, 2012 as cited in Katrakazas et al., 2015).

Traffic safety experts and stakeholders have to anticipate the introduction of AVs and adjust the way crash data is examined (post-crash analyses). A relevant study is that of Rau and Yanagisawa (2015) which outlined a method to determine target crash population that could be addressed by vehicles with higher automation Levels AVs (e.g. Levels 3 to 5) using layers of crash data. The five layers of crash data consisted of crash location, pre-crash scenario, driving condition, travel speed, and driver condition. Their methodology essentially distributes possible conditions they could operate under (e.g. travel speed is distinguished between low, high and all speeds) and matches them to automation Levels. The study provides a tool for splitting crashes in the US into separate populations, thus preparing for the implementation of different automation Levels beforehand.

8 Legislation Issues of Autonomous Safety

8.1 Legislation issues

As stated previously, the advent of automation will obviously impact all aspects of road transport, and all transport in general. There are issues that legislation will need to be capable to address, and for that to happen reforms need to be applied to the respective current legislation in every country, and provide clarity to the legal framework (Lewis et al., 2017). One of the most predominant issue that has challenged researchers is the topic of liability in the event of a crash (indicatively in: Garza, 2011; Gurney, 2013 and others). In Australia, for instance, these issues have been explicitly discussed on a governmental level (NTC, 2017b):

- Human drivers are assumed to operate vehicles by all driving laws, regulations and respective offences.
- AV systems are not considered persons and as such do not currently have legal liability and responsibility for actions or decisions taken. Furthermore, no legal entities are provided that have responsibility of the actions of AV systems instead. Apart from the previous, some of the legal duties of drivers cannot be transferred to an AV system, and they would have to be passed to someone else in the case of a self-operating vehicle.
- "Control" and "proper control" of a vehicle are not defined if an AV system is driving. There are no legal obligations that a human non-driver being ready to take over the driving task and is ready and alert to do so.
- Compliance and enforcement measures at the time were deemed as lacking the suitability to ensure safe operation of an AV.

Research conducted for the European Parliament (Gleave et al., 2016) outlines that vehicle users could be held responsible for crashes caused by their errors (e.g. negligence in maintaining the vehicle), while manufacturers would be held responsible for crashes due to technological problems. In case of litigation between the two, it will always be a court that establishes the different responsibilities.

Another example is the US: it is mentioned that safety regulations are split between driver safety (regulated by the state through licensure and driving behavior laws) and vehicle safety (generally regulated on the federal level by the US Federal Motor Vehicle Safety Standards - FMVSSs). The NHTSA specifies vehicle standards before those vehicles can be sold and can operate in the US, including standards for a wide range of safety components and standards requiring that vehicles must meet specific crash test-survivability requirements. The case of AVs, however, introduces a multitude of innovative designs that would not comply to established standards, up to a considerable, critical level that has to be tapped to unlock the expected benefits of AVs (Anderson et al., 2016, Fraade-Blanar & Nidhi, 2017).

8.2 Future legal developments

In light of those restrictions, AV developers like Waymo/Google have begun to actively pursue standard improvements (NHTSA, 2016b) so that their products find a prepared robust framework to function in. For AVs a considerable number of vehicle utilities and their respective standards could potentially require revisions, for instance those pertaining to mirrors, braking (foot and handbrake), throttle, pedals, steering wheels, pointers and other current human operated driving systems. The updating process is projected to take years, as the technology is still new, however care should be taken to ensure that the standards updating happens in stride with vehicle development. This will enable rapid integration of any changes of AV/CV design (for instance, deciding whether the pointer mechanism is "obsolete" or not). An alternative was proposed which included a centralized government system to allow operation of vehicles that have met several security-related and performance standards (Fraade-Blanar & Nidhi, 2017). These schemes can potentially present a sway for the ease of AV or CV integration and regulation.

The divide of this transitional step is furthered into legislation issues, as there is some uncertainty on where the legal lines will be drawn between SAE automation Levels 3 and 4. Another approach currently under consideration by the NHTSA is to permit AV manufacturers to develop their own methodology and the metrics for the assessment of safety outcomes (NHTSA, 2016a). Another report (OECD, 2017) suggests setting a specific rule to manufacturers, which would be risk-based and which the AVs would need to demonstrate before they are certified for autonomous operation. Yet another alternative, proposed by Australian authorities, could be to certify some roads as AV compliant (Huggins et al., 2017), a practice which would, however, pose considerable bureaucratic obstacles to AV dissemination and interoperability, requiring several permissions and processes to cross any agency border.

Similarly, there ought to be official answers for the current legal gaps in AV developments, because they are pertinent at present, as they have arisen before AVs become widespread. The UK government for instance, has issued official guidelines on how to conduct AV trials (UK Department for Transport, 2015). It is stated, amongst other legal information, that responsibility for ensuring that testing of these technologies on public roads or in other public places is conducted safely always rests with those organizing the testing. A series of requirements for the test driver, operator and assistant are provided as well.

The government of Australia has had a similar reaction as well (NTC, 2017a). It is stated that, apart from safety and risk management, organizations managing trials must be able to handle liability and properly investigate crashes – other countries will need to inform prospective AV manufacturers as well. This will not only enable them to properly conduct field trials, but also to gather significant scientific knowledge which will accelerate AV developments overall.
In the US, it was proposed that agencies could, if they possess the authority, restructure the civil and criminal framework so that involved party behavior is altered. There were several states that have established specific insurance requirements for the testing of AV systems. (Zmud et al., 2017, Douma & Fatehi, 2016 as cited in the first publication).

Given that AVs and CVs have significant computational and algorithmic elements, it is very possible that certain standards can be tested in a simulated environment, like the performance evaluation of algorithms for unsafe lane-changing scenarios (proposed by Zhao et al., 2017) for instance. Such trials could not completely substitute real, physical field testing, but they could certainly become certified consulting tools. At any rate, governments should continuously oversee the testing process, to enforce that testing occurs within a safe environment on one hand, and to be ready to provide respective legal framework on the other. This will aid in building the high degrees of trust that are essential for widespread public acceptance that will make AVs a reality (Noy et al., 2018).

9 Key Economic Impacts

9.1 Crash cost mitigation

When considering crash costs, it is important to integrate all major components that have been well documented in the literature. While delving into detailed crash cost analysis as an impact of AV operation is beyond the scope of the report, some key elements are worth mentioning.

Obviously, under the assumption that AVs and CVs will improve safety, any crash avoided is a respective cost avoided as well, which is beneficial to people that would be involved in a crash first and society second. Apart from overall crash avoidance, widespread connected services like e-call will reduce delays for first responders when crashes do occur, possibly lessening hospitalization requirements for involved road users. Furthermore, the implementation of AVs is also expected to mitigate costs per singular crash, mainly by reducing work time lost from traffic crashes (Innamaa et al., 2017).

The study of Fagnant and Kockelman (2015) estimated that, for AV penetration rates of 10%, 50% and 90%, there are corresponding savings of $1.390, $2.480 and $3.100 per year per AV in the US when comprehensive crash costs are accounted for. These estimates are quite auspicious and might provide additional incentive to intensify the preparations for AV implementation. There are several underlying assumptions in the estimates nonetheless, which include vehicle ownership and utilization, in addition to certain financial parameters (such as discount rate), which may cause actual results to differ considerably.

These positive findings may not hold for all automation applications, however. For instance, for a Park and Ride public transport AV scheme (six automated minibuses) it has been found that safety benefits would not be solely enough to render the entire scheme beneficial from an economic perspective (Portouli et al., 2016). This was highly sensitive on baseline crash numbers, however, which are overall low for public transport.

9.2 Transport externalities

As economic sciences have long established, an externality is an effect that can be translated to a monetary cost or benefit that affects a party without their respective choice. This effect is produced by a third party (consumers or producers) and is not taken into account in the market price. Policymakers often undertake efforts to internalize externalities, therefore transferring their costs to parties that select to accrue them. An example in the transport industry could be vehicle manufacturers: if they were forced to pay all costs associated with faulty vehicles, they could choose to either produce less of the product or increase self-imposed safety standards. Externalities result in suboptimal or inefficient societal outcomes because the true costs and benefits of actors' choices are not reflected in market prices (Laffont, 2008).

A common fact in crash occurrence is that a driver does not only increase self-induced risk (which appears solely by the act of driving), but also the respective risk for the rest of the road users that they meet alongside the road, such as nearby pedestrians, cyclists and other drivers. In the event of a crash they do not, however, pay for all involved costs, such as possible police intervention, hospitalization and other society related costs, despite incurring them. It can therefore be said that the current state of transport is an inefficient market with the presence of externalities.

Additional safety benefits that AV and CV commercialization will manifest are in reducing crash related externalities via V2X schemes. It is expected that by addressing the majority of vehicle crash types, V2V safety applications will reduce crash related externalities if the respective Human-Machine Interfaces (HMIs) perform well. In the eventuality of similar performance, V2I safety applications can reduce vehicle and infrastructure crashes, and therefore related costs (Zmud et al., 2017). Policymakers should not realistically anticipate externality reductions that are completely analogous to the elimination of human related errors, as AVs might possibly introduce new types of errors that are currently unforeseeable.

There is also the eventuality of a market failure, as presented by Le Vine and Polak (2014), which state that the shift of responsibility to manufacturers might lead them to be reluctant of a legal reform that threatens large losses through legal action. However, the authors suggest the remedial action for such an event by satisfying the need for government support of those technologies that provide net safety benefits and are designed to uphold safety standards. Market failure at present seems somewhat unlikely, since manufacturers have been investing so much time and effort in AV and CV development.

10 Conclusions

Evidently, AVs and CVs have attracted considerable attention and are being developed rapidly, cultivating expectations on the field of traffic safety, among others. While their potential is enormous and undeniable, benefits are not guaranteed as there are parameters that currently appear unforeseeable. Specifically, traffic safety of AVs and CVs has a multitude of aspects that can be explored, as the introduction of these technologies is expected to revolutionize large parts of the transport sector.

Current technological progress

There are several technological components integral to AVs and CVs that are commercially available currently, involving adaptive cruise control (ACC), collision warning and lane departure warning systems, among others. Field tests for more (or completely) independent vehicles are currently underway by the industry. Two crashes for which the AV software was confirmed to be at fault were determined (one was fatal).

Transition phase

Automation might be developed non-linearly, with drivers becoming obsolete rather than assuming a stand-by role, as there is evidence that this might be infeasible. More progress is required on sensor technology before automation is safely applied, as rational thinking and humane decision-making appears to still be out of reach. Infrastructure and law enforcement processes should be upgraded correspondingly.

Direct safety impacts

The exact impacts of AVs are quite unclear at this stage, since there are a considerable number of variables that will have unknown impacts and interrelations. AVs are expected to be very beneficial overall, eliminating a large amount of the human element that leads to so many crashes nowadays. However, human factors must also be taken into account and will still remain present within several aspects of automated traffic. Finally, there is no scientific evidence in expecting absolutely crash-free roads.

Indirect safety implications

Mechanical and physical safety is paramount if AVs start operating widely. AVs could likely generate additional traffic demand and vehicle-kilometers travelled, with more sophisticated and obscure functions. Thus all mechanical systems would have to have resilience and considerable redundancies, in order to not compromise passenger safety, which would be mostly dependent on the automated systems. Cybersecurity concerns should be addressed by manufacturers and governments to avoid any malicious interventions.

Legislation issues

The advent of AVs has concerned stakeholders, demanding legislative adjustments from authorities and the industry overall. The main obstacles consist of vehicles being taken from human control, and given to artificial intelligence; in the event of a crash, it can be unclear to discern whether the liability lies with the driver or the manufacturer. The consensus seems to be to charge manufacturers for actions of AVs, and drivers for altering their operational mode. Additionally, the standards with which an AV will be judged as roadworthy are under consideration via several proposals: manufacturers might have to demonstrate their products' abilities or pass certain certifications.

Economic impacts

Finally, AVs could not leave the financial side of transport unaffected. Crash costs are expected to decrease, both collectively due to fewer crashes occurring but also individually, due to improved pro-and-after crash functions (e.g. e-call). Additional reforms might be introduced in the industry since manufacturers will have to internalize several externality costs, especially when they are being assigned crash liability.

Overall, the US appears to be the most invested country in AV and CV research, with the rest of the modernized world following behind. Europe and the other westernized countries ought to place their focus on the advent of automation, and developing areas even more so, as they are very likely to be affected as well. AV progress will not be confined by a lack of preparation in any front; rather all interested parts should anticipate their arrival beforehand.

Future challenges

The greatest challenge while facing the onset of AVs and CVs is to not lose sight of safety amidst enthusiasm. New opportunities for capacity increases and vehicle repurposing will captivate the interests of manufacturers and network administrators, amongst other factors. Traffic safety could be very easily disregarded at first, in order to increase market shares of the new technologies. Thus the aims and objectives of stakeholders and their policies for AVs and CVs must be clear from their inception, especially given the potential interconnectivity of all system elements. The coming years will be a time when conflicts between transport aspects will be more measurable, and thus visible, to everyone, from a central authority level to a singular road user one.

Ultimately, the most critical parameter for the realization of AVs and CVs appears to be public acceptance. To attain it, a constant, slow trust-building exercise will be required, and for that to succeed, crashes and overall traffic safety performance must be at the very least better than that of conventional driving. Public acceptance will increase market share, and thus capital investment for AVs and CVs, for vehicle improvements, infrastructure adaptation and road user education. This in turn will increase public acceptance further, and so on. Undeniably, traffic safety seems to be the first step for creating this virtuous cycle, which should be the aim of AV supporters.

It is undoubtable that both the expertise to exploit existing traffic safety knowledge drawn from current practices and the intuition to navigate a more unpredictable, digitally intelligent transport system will be demanded from traffic safety scientists and practitioners. Specialized training may be required as part of this very challenging issue and responsibility. As a positive development, there will be interconnection with conventional road safety at least during the first years of automation, with mutual benefits.

On the road towards automation, significant initiatives have been taken up to now, particularly from the private sector. However, there is still a lot of ground to cover for proper and smooth integration and transition. There should be a consensus on how to determine whether an automated system is roadworthy, whether from adhesion to standards or self-policing demonstrations. And roadworthiness does not stop there.

Contrary to conventional vehicles, AVs and CVs will never leave the factory, in a sense. The capability to wirelessly install upgrades or patches that completely alter vehicle behavior is another novelty of automation, and one that has safety implications that should not be underestimated. Given experience with software updates, several malfunctions even in the most secure systems should be anticipated. However, instead of computer crashes, these malfunctions could cause actual road crashes. Thus a probable next step is the creation of dedicated platform environments that would safely handle and test AV calibrations (such as virtual machine environments found in computers) before they are released, under administrator supervision. Time will be of the essence to prevent crashes after an error or incompatibility is detected in the software, especially in later stages of automation, where the role of human drivers will start to lessen.

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Notes

1. Country abbreviations

Belgium	BE	Italy	IT	Romania	RO
Bulgaria	BG	Cyprus	CY	Slovenia	SI
Czech Republic	CZ	Latvia	LV	Slovakia	SK
Denmark	DK	Lithuania	LT	Finland	FI
Germany	DE	Luxembourg	LU	Sweden	SE
Estonia	EE	Hungary	HU	United Kingdom	UK
Ireland	IE	Malta	MT		
Greece	EL	Netherlands	NL	Iceland	IS
Spain	ES	Austria	AT	Liechtenstein	LI
France	FR	Poland	PL	Norway	NO
Croatia	HR	Portugal	PT	Switzerland	CH

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