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What do we know and what do we need to know?

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Summary

Automated vehicles are gradually entering our roadway system. Before our roads will be solely used by fully automated vehicles, a long transition period is to be expected in which fully automated vehicles, partly automated vehicles and manually-driven vehicles have to share our roads. The current report looked into the position of pedestrians and cyclists in such a future traffic system. The report provides an overview of current knowledge, theoretically and empirically, about the interaction of pedestrians and cyclists with (partly) automated vehicles. Furthermore, it identifies what we need to know in order to ensure that an automated driving system, particularly during the transition period, does not compromise the safety of pedestrians and cyclists.

So far, it can be concluded that automated vehicle technology has mainly focused on the detection and recognition of pedestrians and cyclists by the vehicle and even though good progress has been made, many difficulties are yet to be overcome (e.g., reliable operation in adverse weather conditions). Technology to reliably predict intentions and behaviour of pedestrians and cyclists, so that the automated vehicle can accurately adjust its behaviour is an area that is also crucial for safe interactions between automated vehicles and pedestrians/cyclists. However, this is by no means straightforward because it appears very difficult to predict behavioural intentions of pedestrians and cyclists by current technology. In addition, it cannot be excluded that pedestrians and cyclists will respond differently to (partly) automated vehicles than to manually-driven vehicles.

However, the decision making and behaviour of pedestrians and cyclists in interaction with (partly) automated cars have received very little attention in the research community. Aspects known to determine current interactions, such as formal rules and regulations, informal rules and non-verbal communication, expectations, and behavioural adaptation are likely to play a different role in a system with automated vehicles or in a system with a combination of (partly) automated and manually-driven vehicles. If decisions and behaviour of pedestrians and cyclists towards (partly) automated vehicles are found to be different from their behaviour towards a vehicle driven by a human driver, the software developers cannot base their algorithms on what is known about current interactions and behaviour patterns.

The few studies that did examine the behaviour of pedestrians and cyclists in their interaction with automated vehicles, generally found that they were fairly cautious when interacting with an automated vehicle and not per definition confident of its 'skills'. Furthermore, pedestrians and cyclists were found to appreciate messages and/or signals from the car indicating whether the car has detected them and what it intends to do. However, which exact messages need to be brought about and the method of communicating them are not yet settled and this requires further study.

These and many other questions need to be answered in order to ensure that further developments towards automated driving will not result in a traffic system that is (even) less safe for pedestrians and cyclists than it is presently. Questions, identified in the current report relate, for example, to decision

making and behaviour of pedestrians and cyclists when interacting with automated vehicles; the effect of a system with a combination of automated and non-automated vehicles on their behaviour and the options for optimizing the interactions, for example, through training, infrastructure or regulations.

Contents

1. Introduction

1.1. Background

Automated vehicles are gradually entering our roadway system. Before our roads will be solely used by fully automated vehicles, it is likely that there will be a long transition period in which fully automated vehicles, partly automated vehicles, and manually-driven vehicles have to share our roads. In urban settings in particular, these different types of motorised vehicles have to interact with pedestrians, cyclists and other non-motorised road users. Not only does this require the vehicles to reliably detect these other road users, but it also requires the non-motorised road users to interact with vehicles with different levels of automation and potentially different response patterns (Hagenzieker, 2015; Schladover, 2016).

A large amount of research is presently being conducted in the field of automated vehicles. The vast majority of studies concentrate on the automated vehicle itself, and focus on its technology and on its potential impact on transport, mobility and society as a whole (for an overview see e.g., ERTRAC, 2015; BCG, 2016; KiM, 2015; Litman, 2016). More recently, research also increasingly focuses on human aspects, such as the drivers and their interaction with varying levels of automated vehicles (e.g., Toffetti et al., 2009; Vlakveld et al., 2015; Weyer, Fink & Adelt, 2015; Seppelt & Leeb, 2015; Cunningham & Reagan, 2015; Zeeb, Buchner & Schrauf, 2016; Preuk et al. 2016) and on user acceptance of automated vehicles (e.g., Bazilinksyy, Kyriakidis & De Winter, 2015; Kyriakidis, Happee & De Winter, 2015; Madigan et al., 2016). The growing interest in human aspects in automated driving is further reflected in an increasing number of research programmes in this field. Examples are the research programme *Automated Vehicle Research* of the US Department of Transport[1] and the *Human Factors in Automatic Driving* project of a consortium of European research institutes and car manufacturers[2]. Both programmes, however, focus on the driver and not on (the perspective of) other road users, such as pedestrians and cyclists.

Usually, researchers and road safety experts emphasize the potential road safety benefits of automated vehicles. Since automated vehicles do not make human errors and do not deliberately violate traffic regulations, they are assumed to outperform the human driver and therefore contribute to substantial reduction of road accidents (Iliaifair, 2012; Fagnant & Kockelman, 2015; OECD/ITF, 2015; Miller & Oldham, 2016). However, some studies express certain reservations about the expectations. As ETSC (2016) indicates, the actual impact of automated driving on road safety is largely unknown (ETSC, 2016), and the first analyses of accidents with automated vehicles even indicate hardly lower accident rates than those of manually-driven cars (Sivak & Schoettle, 2015).

Apart from these uncertainties, there is the uncertainty related to the interaction of (partly) automated vehicles with non-automated road users, in

[1] http://www.its.dot.gov/automated_vehicle/avr_plan.htm
[2] http://hf-auto.eu/

particular with pedestrians and cyclists, and the subsequent safety effects. So far, research on the interaction between automated vehicles and vulnerable road users has been largely limited to the technical aspects of detection and recognition of pedestrians and cyclists by the vehicles, again solely considered from the perspective of the vehicle. However, it is at least equally important to look at matters from the perspective of pedestrians and cyclists. Will cyclists and pedestrians be able to interact with automated vehicles? For example, would this affect their crossing decisions or their red light compliance? And if so, in what way? Would they accept smaller gaps or would they just take larger safety margins? Would they be inclined to run against the red light more often or not? And during the transition period, with its combination of automated vehicles, partly automated vehicles and manually-driven vehicles, will pedestrians (be able to) differentiate between these vehicles and would they adjust their behaviour accordingly?

Until now, the interaction between (partly) automated vehicles and pedestrians and cyclists from the perspective of the latter has received very limited attention and the answers to the questions above are unknown (Twisk et al., 2013). As a consequence, it is hardly possible to estimate the safety effects of (a transition towards) automated vehicles, nor to identify the actions to minimize the risk that interactions between automated vehicles and non-automated road users induce unsafe situations and accidents.

1.2. Aim, method and structure of this report

This report aims to provide an overview of current knowledge, theoretically and empirically, about the interaction of pedestrians and cyclists with (partly) automated vehicles, considering matters from the perspective of the non-automated pedestrians and cyclists. Both decision making and behavioural aspects will be discussed, in addition to potential road safety consequences. Based on this, the report aims to identify knowledge gaps, identifying what we need to know in order to ensure that an automated driving system and the transition period towards such a system do not compromise the safety of pedestrians and cyclists.

In *Chapter 2* we briefly set out some basic information about various types and stages of automated driving, as well as the main technical aspects, focusing on the implications for the interaction with cyclists and pedestrians. This chapter is based on a non-exhaustive selection from the general literature on this topic with the objective to give the reader a quick introduction into some of the issues concerning vehicle automation.

Chapter 3 presents a brief overview of the safety of pedestrians and cyclists in the current non-automated traffic system, and the main accident characteristics. It aims to illustrate the relevance from a safety point of view by explicitly looking at the interactions between automated vehicles and pedestrians and cyclists. Although this chapter has a European focus, where relevant, it will zoom in on the situation in the Netherlands as a typical ‘bicycle country’.

Illustrated by examples of targeted studies, *Chapter 4* first describes the general features and principles of the current interactions between pedestrians, cyclists and motorised vehicles and identifies the potential consequences for future interactions with automated vehicles. Subsequently, *Chapter 4* describes studies that directly focus on the interaction of pedestrians and cyclists with automated vehicles, as comprehensively as possible. For this chapter we researched several databases, including Google Scholar, Web of Science, SCOPUS and the SWOV library. We included both peer reviewed scientific papers and technical reports from research institutes and road safety organizations (the ‘grey literature’). Studies specifically focusing on pedestrian and cyclist interaction with automated vehicles are still rare. Therefore, if useful and appropriate, we also used non-scientific sources, such as webpages and news articles, contacted other experts and used our own knowledge to identify additional articles or reports.

Finally, *Chapter 5* summarizes what we currently know and identifies what we still need to know in the field of pedestrians and cyclists sharing a road system with partly or fully automated vehicles, not in the least during the transition period towards this situation.

2. Basic information about automated driving

Automated vehicles are being developed at a rapid pace and automated driving systems are becoming more and more advanced. For example, truck platooning[3] allowing trucks to drive closely together, is being extensively tested on public roads. An automated '*future bus*'[4] was driven through Amsterdam, and in Wageningen the 'WEpod'[5] is being tested to carry students between the campus and the train station. In several European cities projects using similar automated minibuses are being conducted or are being planned. Examples are the CityMobil2 project in a number of European cities[6], and the SOHJOA-6Aika project in Helsinki[7]. In the USA, for example, the Massachusetts Institute of Technology (MIT) is developing automated driving systems for golf carts and scooters[8]. At the level of passenger cars, the Google demonstrations with self-driving cars[9] are well known. The car industry is also working hard to automate an increasing number of the functions of cars. This chapter provides some basic information about automatic driving, including definitions, classifications and technical aspects with a focus on the implications for the interaction with cyclists and pedestrians.

2.1. Defining vehicle automation

When considering vehicle automation, usually two approaches are distinguished (Timmer & Kool, 2014; ETSC, 2016):

1. smart infrastructure with a non-intelligent car, and
2. non-intelligent infrastructure with an intelligent car

The European Union, including the Netherlands, focuses on the cooperative driving scenario (EC, 2016[10, 11; 12;] Timmer et al., 2015). The basic idea is that information about the road system and the traffic situation is sent to the individual cars so that they can automatically respond to and anticipate on each other and the actual situation. Data exchange goes two ways, with the vehicle transferring information both to the infrastructure, as well as to other vehicles. This is also known as cooperative driving. In order to enable this, Europe and the Netherlands aim to evolve from broadcasting (one-to-many) and to develop a consistent combination of collective and individual information services. It is expected that a number of stand-alone systems will be replaced, using direct communication between in-vehicle systems and smart infrastructure instead. The smart infrastructure includes loops embedded in the road, cameras, and matrix signs. This way, developers of

[3] https://www.eutruckplatooning.com/About/default.aspx and http://www.gcdc.net/en/i-game
[4] https://www.daimler.com/innovation/autonomous-driving/future-bus.html
[5] http://wepods.nl/
[6] http://www.citymobil2.eu/en/About-CityMobil2/Overview/
[7] http://sohjoa.fi/in-english
[8] http://news.mit.edu/2016/driverless-scooters-1107
[9] https://www.google.com/selfdrivingcar/
[10] https://ec.europa.eu/transport/sites/transport/files/themes/its/doc/c-its-platform-final-report-january-2016.pdf
[11] https://english.eu2016.nl/latest/news/2016/04/14/eu-ministers-to-try-out-self-driving-cars-in-amsterdam
[12] http://europa.eu/rapid/press-release_MEMO-16-3933_en.htm

automated vehicles are looking into the possibilities of connecting the smart infrastructure with smart vehicles to create cooperative driving. Vehicles will drive in convoy and information is shared with other vehicles and traffic managers. They will communicate with systems along the road and amongst each other.

By means of this cooperative driving-approach, developments towards full automation will be implemented in stages, with an increasing number of tasks being automated until finally the fully automated vehicle becomes a reality. Within this approach, different paths and scenarios have been envisioned. ERTRAC (2015) distinguishes the urban environment path, with high automation in areas with low speed and/or dedicated infrastructure (e.g. the Dutch WEpod and the European CityMobil2 project) and the automated vehicle path building on the gradual development from stand-alone advanced driver assistance systems (ADAS) to full automation of cars and trucks. OECD (2015) also distinguishes two paths to automation. The first path is described as ‘something everywhere’ with a few tasks being automated and applicable to all situations; these are already present today, e.g. in the form of an ADAS. The second path, ‘everything somewhere’, envisages full automation but only in specific contexts. High-speed motorways seem suitable for the early application of automated cars and trucks (including platooning), urban areas are well suited for specialised passenger and delivery shuttles. Over time, the application of the automated vehicles can be expanded to other contexts. All of these different scenarios will have implications for other road users, including cyclists and pedestrians (ETSC, 2016).

Intelligent self-driving cars in a non-intelligent infrastructure, also known as robotic cars, constitute a different approach (Timmer & Kool, 2014). The Google car is an example of how a robotic car drives automatically by only using systems included in the vehicle and being independent from road infrastructure communication systems. The underlying idea is that cooperative elements can be added as an option in a later stage, if needed. Prototypes of fully automated vehicles have already covered several hundred thousand kilometres, and reportedly by their manufacturers without the intervention of a human driver. This has stimulated the faith in a market launch of completely automated cars. The robotic car scenario is more popular in the United States than in Europe.

In any case, vehicle automation will require cyclists and pedestrians to adapt to a changing road traffic system and a different type of ‘road user’. The adaptation process might be different for the two trajectories described, although we do not yet know in what way. Will a step-by-step transition of the cooperative driving approach help road users adapting to the changes at a more reasonable pace or will it be more confusing when various cars are automated to a different extent? For example, when is the driver driving and when is the car in control? With the robotic car scenario, this transition will be fast and quick, but will pedestrians and cyclists have sufficient time to grow accustomed to and gain experience with these vehicles? In either case, the consequences for pedestrians and cyclists have to be considered, because the transition is likely to bring substantial changes in the way pedestrians and cyclists interact with cars.

2.2. Levels of automation

In the cooperative approach it is assumed that cars will gradually become more automated and that the role of the human driver gradually decreases. Several attempts have been made to define and classify different levels of automation, but this has not yet resulted in a generally accepted definition of the different levels of automation (Habibovic, Englund & Wedlin, 2014).

The best-known and most recently updated classification is that of the Society of Automotive Engineers (SAE) that distinguishes six levels[13] (*Table 1*). The six levels of the latest SAE classification are descriptive rather than normative, and reflect the minimum, rather than maximum capabilities of each level. At level 0 (no automation) the whole driver task is performed by the driver, while at level 5 (full automation) it is entirely executed by the automated driving system.

Level 0	No driving automation	The driver controls the vehicle at all times. However, vehicles can be equipped with active safety systems such as collision warning or anti-lock brakes.
Level 1	Driver assistance	Some individual vehicle controls are automated (either the lateral <u>or</u> longitudinal subtask), but not at the same time. An example is adaptive cruise control to maintain correct speed based on following distance. The driver is expected to perform the remainder of the driving task. The Driving Automation System disengages immediately upon driver request.
Level 2	Partial driving automation	The vehicle is able to automatically perform the lateral <u>and</u> longitudinal driving tasks. Vehicles are able to execute, for example, adaptive cruise control and lane keeping. The driver is expected to perform the remainder of the driving task and supervises the driving automation system. The Driving Automation System disengages immediately upon driver request.
Level 3	Conditional driving automation	The car performs the dynamic driving task (DDT). When needed, the car transfers control to the driver, which means that the driver must be in the loop at all times. It is expected that the driver is able to respond appropriately to any request from the car to intervene.
Level 4	High driving automation	The car is able to perform the entire DDT and has fall-back responsibility for the driving task. The driver is not required to respond to a request to intervene. However, the system is not able to operate the car everywhere.
Level 5	Full driving automation	Sustained and unconditional (i.e. able to operate the car everywhere) automation. It is not expected from drivers that they respond to the request to intervene.

Table 1. *Summary of levels of vehicle automation as distinguished by the Society of Automotive Engineers (SAE, 2016).*

[13] Other available classifications are from BASt (German Federal Highway Research Institute) and NHTSA (National Highway Traffic Safety Administration in USA).

Level 0 is rapidly becoming irrelevant, because all new modern vehicles that come on the market have technologies that bring them up to level 1. The OECD (2015; see also ETSC, 2016) describes level 1 cars as cars performing under the *'something everywhere'* strategy, meaning that these cars can do some things under most circumstances. For level 4 cars, the *'everything somewhere'* strategy would apply, meaning that in some (but not all) circumstances, the vehicle is able to perform the entire driving task.

In order to reach full *'everything everywhere'* automation (level 5), vehicles will have to be able to manage the full range of traffic environments, from the rather simple and predictable motorways to the very complex urban areas. One thing that makes the urban area so complex is the wide variety of road users who share the road traffic system, including non-automated road users like pedestrians and cyclists with their different and often unpredictable behavioural patterns. And the unpredictability might even become more apparent if they have to deal with (partly) automated vehicles.

Situations with cars of different levels of automation lacking a clear indication of the level of control by the human driver will pose a special challenge to ensure a safe interaction of pedestrians and cyclists with cars. It can be argued that it is important for pedestrians and cyclists - in particular in this type of mixed traffic situation - to understand what type of vehicle they encounter and what they can expect from it (see also *Section 4.1.4*).

2.3. Technical aspects of automated driving

When looking at the higher levels of automation, cars have, in fact, become highly complex computers on wheels (OECD, 2015). The developments have been part of the technological revolution that has brought us personal computers and mobile phones. All these recent technologies have been blended together, resulting in machines that sense and interact with the physical environment. When it concerns the sensory part of automated driving, it implies that the automated vehicle first has to collect data and information before being able to take decisions. This information is gathered by the vehicle, but also received from neighbouring vehicles and the infrastructure, either physical, digitally, or both.

The technical aspects of highly automated driving are developing fast. Radar, LIDAR (Light Detection And Ranging), Global Positioning System GPS and cameras are combined with highly accurate maps, to allow the automated vehicles to navigate, identify (and avoid) obstacles and detect and interpret relevant road markings and traffic signs. The more recent Single Frequency Precise Point Positioning (SF-PPP) is much more accurate than normal GPS and allows for determining in which lane a car is driving (Li et al., 2014).

In a nutshell, and highly simplified, automated cars function as follows. First, the automated car creates a map of the surroundings and defines its position on it. It then uses this map to distinguish between static and dynamic (moving) objects. In case of moving objects, and based on programmed algorithms, it subsequently predicts the movement patterns of the moving objects. Based on the map and on predictions, the car plans its path in order to avoid other road users and other objects. The process of mapping, defining location, detecting objects, and path finding is repeated continuously, until the vehicle has reached its destination. In practice, this process takes place in parallel with different systems being involved (instead of one central system).

Pedestrians and cyclists are examples of moving objects that have to be detected, recognised and whose movement patterns have to be predicted. A number of research programmes and projects are investigating and developing technologies for detecting and recognizing pedestrians and cyclists more efficiently (e.g., in the context of DAVI, and projects such as PROSPECT, XCYCLE and VRUITS[14]). These projects primarily focus on the technology to improve cyclist/pedestrian detection and recognition (Keller & Gavrila, 2014; Li et al., 2016). Accurate and reliable detection and recognition of cyclists and pedestrians is the first challenge, but understanding their intentions and predicting their behaviour have proven to be even more difficult. The cues that automated driving systems need to pick up are very subtle and of a kind that even humans themselves have difficulties with to interpret accurately if they have to base their prediction solely based on indirect visual cues. Westerhuis & De Waard (2016) showed, for example, that it is very hard for human observers to predict the direction of a turning cyclist when cyclists do not use their arm to indicate their intended direction, and have to base their prediction on other, very subtle visual cues before the turning manoeuvre is actually initiated.

Another aspect that still needs further consideration and study relates to the reliability of the automated driving systems. While the systems can scan and interpret the traffic situation much faster than human drivers, they are not yet without failure. One of the problems automated vehicle technology faces concerns reliable operation in adverse weather conditions such as rain, snow, fog or bright sunlight (Levinson et al., 2011; EU project Robust Sense[15]). Other challenges include the great variation in appearance of relevant objects in traffic, and the problem of partial occlusion (Chandel & Vatta, 2015). The latter occurs, for example, when part of an object is hidden by another object or by the scene itself. Whereas human observers will ‘complete’ the picture based on their ‘knowledge of the world’, current sensors have difficulties in interpreting such incomplete objects.

A few recent fatal accidents in various countries show that the technology is not yet fail-proof and that intervention by the human driver is not always realised in time (see *Section 2.4*).

2.4. Transition of control

At level 2 and in particular at level 3 of the SAE classification (*Table 1*) a specific issue arises that is crucial from a safety point of view: transition of control. At these levels the automated driving system can ask the human driver to intervene and resume the driving task, e.g. when the vehicle enters a situation that is not (yet) mastered by the automatic system or in case of system failures. Resuming the driving task after a period of automated driving makes specific demands on the human driver and this may result in making errors. Automated driving allows the human driver to do something else when the system is in charge, like reading a newspaper, making a phone call or even sleeping. However, while performing these secondary

[14] http://davi.connekt.nl/; http://www.prospect-project.eu/; http://www.xcycle-h2020.eu/; http://www.vruits.eu/
[15] https://robustsense.eu

tasks, drivers do not or hardly pay attention to the driving task and the traffic situation. In other words, they lose their awareness of the situation and become what is called ‘out-of-the-loop’ (see e.g., Vlakveld et al., 2015). In general, human beings are very badly equipped for this type of supervisory or monitoring task, and in the case of automated driving this might be the case even more so if they have great and occasionally unjustified faith in automated systems (see e.g., Parasuraram, 1997; De Winter et al., 2014; Hagenzieker, 2015). The more the driver is out-of-the-loop, the more hazardous and difficult the transition from automated driving to manual driving will be (Vlakveld et al., 2015). Behavioural research in driving simulators showed that this type of transition of control can lead to accidents and near-accidents (De Winter et al., 2014).

This issue of transition of control and being out-of-the-loop potentially becomes a serious problem in the interaction with cyclists and pedestrians. If it takes too much time for the driver to take over adequately when needed, he might not be able to avoid a crossing pedestrian or cyclist in time. This is very relevant, because the occasionally rather unpredictable behaviour of pedestrians and cyclists could very well be the reason that the automated car system malfunctions and the human driver has to take over.

Car manufacturers are familiar with the out-of-the-loop problem and some have already started thinking about possible solutions. Developers have been looking into the possibilities of skipping SAE level 3 altogether, moving directly to level 4. It is not clear how realistic this option is. Other solutions that have been suggested aim to keep the driver 'in the loop' so as to remain attentive, e.g., by software that demands drivers to keep their hands on the steering wheel or by a system that uses eye-tracking software to warn drivers if their eyes move away from the traffic situation[16]. While these attempts are commendable, the question then arises if ‘automated’ driving would be attractive for drivers if they still have to act as if they drive. Moreover, we should keep in mind the potential effects of this type of solution on cyclists and pedestrians. Seeing a driver holding the steering wheel or looking into your direction could suggest that he is actively in control, whereas this may not necessarily be the case. Though it is not yet known whether pedestrians and cyclists respond differently to automated vehicles and manually-driven vehicles, it is imaginable that they get confused or incorrectly interpret the (assumed) non-verbal cues of the driver.

2.5. Summary and conclusions

Automated vehicles are being developed at a rapid pace and automated driving systems are becoming more and more advanced. The exact routes to full automation are uncertain and depend on many factors, including policy perspective, technological developments, legal aspects, and user acceptance. The levels of automation as distinguished by the Society of Automotive Engineers assume a stepwise approach from just a few automated tasks to full automation, rather than a one-step switch from non-automation to full automation.

A special challenge to be faced when moving toward automated driving is the interaction of (partly) automated vehicles with cyclists and pedestrians.

[16] See, for example, http://articles.sae.org/15018/

So far, technology has mainly focused on the detection and recognition of these road user groups and even though good progress has been made, many difficulties are yet to be overcome (e.g., Li et al., 2016). An area that so far has received less attention, although being crucial for safe interactions, concern techniques that can reliably predict the intentions and behaviour of pedestrians and cyclists, so that the vehicle can choose the right path. This is extremely difficult, not in the least because it cannot be excluded that pedestrians and cyclist respond differently to automated or partly automated vehicles than to manually-driven vehicles. Whether this is the case and in what way is largely unknown. Until now, this area has been left largely unexplored.

Another challenge relates to the role of the human driver. Taking the SAE levels of automation as a starting point, it is expected that the human driver will play a role until the very last level of full automation. However, this role will change from being actively in command to that of monitoring the situation as a supervisor. People are known to be unfit for this supervising role, because people are hardly able to remain attentive for a longer period of time when they are merely supposed to monitor the environment. Hence, remaining in the loop and taking over control adequately and in time when required to do so has been found to be a major problem. This could lead to accidents in every situation, but especially in situations with many pedestrians and cyclists. Their behaviour is less predictable than that of motorised traffic and, as a consequence, might require intervention of the human driver more often.

3. Some background about pedestrian and cyclist safety

This chapter provides some background about the safety of pedestrians and cyclists in the current non-automated road traffic system and the role of motorised vehicles. Ours is an international, mainly European perspective, but if useful and feasible, we zoom in on the Netherlands that differs from other countries, being a typical bicycle country,. This safety information helps us identify the potential benefits of vehicle automation as well as its potential risks for the safe interaction of automated vehicles with pedestrians and cyclists.

3.1. Pedestrian and cyclist fatalities and serious injuries

Cyclists and pedestrians are classified as vulnerable or unprotected road users. Contrary to car occupants, pedestrians and cyclists do not have a protective 'shell' that reduces the impact in case of a collision or a fall. As a consequence, they have a high risk of getting seriously injured, in particular when colliding with much heavier vehicles, even at relatively low speeds (Pucher & Dijkstra, 2003; Rosén, Stigson & Sander, 2011; Jang et al., 2013).

The WHO (2016) reports that of all road fatalities worldwide pedestrians make up circa 22% and cyclists circa 5%, implying that, as a group, they contribute to over one quarter of all road fatalities worldwide. *Figure 1* shows that there are substantial differences between different regions in the world. In the European region, for example, the share of pedestrian and cyclist road fatalities is somewhat higher. According to the WHO figures, these averages are circa 27% for pedestrians and circa 4% for cyclists.

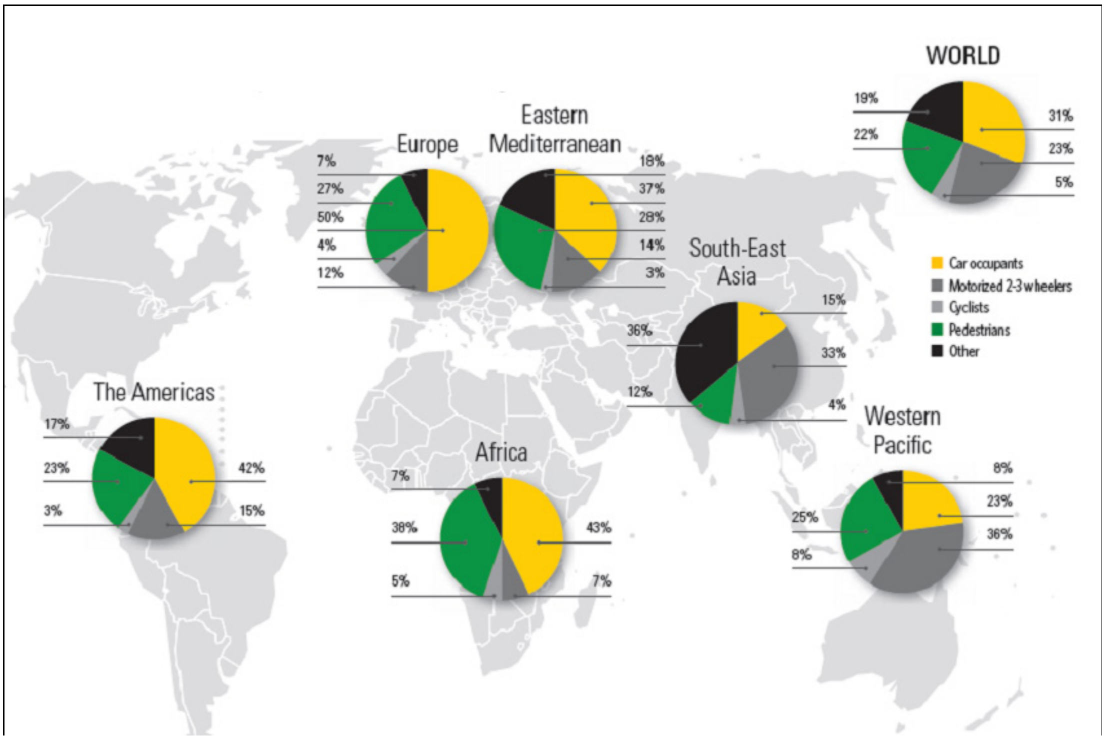

Figure 1. *Share of road fatalities per transport mode in different world regions (WHO, 2016).*

Zooming in on the European Union, the figures published by ETSC (Adminaite, Allsop & Jost, 2015), show that pedestrians and cyclists account for 29% of all road fatalities (21% pedestrians and 8% cyclists).

However, Europe also shows notable differences between regions and countries. When we zoom in on the Netherlands (Korving et al., 2016), we see that 39% of all road fatalities in 2015 involved pedestrians or cyclists. Whereas in most countries the share of pedestrian fatalities is much larger than that of cyclists (OECD/ITF, 2013), in the Netherlands this is the other way around: in 2015, 9% of the Dutch fatalities (equalling 57 fatalities) were pedestrians, and 30% cyclists (equalling 185 fatalities). This is not surprising, considering the high number of cyclists and the high mileage in the Netherlands compared to most other European countries (De Groot-Mesken, Vissers & Duivenvoorden, 2015).

Next to to road fatalities, road injuries occur far more frequently. Worldwide, as well as on a European level, statistics of traffic injuries are lacking or are very unreliable. In the Netherlands, based on hospital data, we do have a fairly reliable estimate of the number of serious injuries[17]. This data shows that in 2015 there were approximately 21,300 serious injuries. An estimated 2% of these serious injuries were pedestrians and an estimated 63% of these serious injuries were cyclists (Korving et al., 2016). The vast majority of the cyclist injuries occurred in accidents without a motorised vehicle (52%), many of which are single vehicle accidents. The remaining 11% occurred as a result of a collision with a motor vehicle.

3.2. Some accident characteristics

This section briefly describes some of the main characteristics of pedestrian and cyclist accidents, both in the European Union and in the Netherlands. It should be noted that information presented in this section is based on the characteristics of fatal accidents. As already indicated, only very few countries have reliable information on non-fatal accidents. The Dutch information on non-fatal accidents comes from hospitals and contains only very limited information about the accident accident and its circumstances.

3.2.1. *Many pedestrian and cyclist fatalities on urban intersections*

In Europe, most of the pedestrian and cyclist fatalities take place on urban roads. ETSC reports that for the European Union as a whole, over the period 2011 to 2013, this was the case for 69% of all pedestrian fatalities and for just over half of all cyclist fatalities (Adminaite, Allsop & Jost, 2015). There are, however, substantial differences between countries. According to these European statistics, the share of both pedestrian and cyclist fatalities in urban areas in the Netherlands is just over 60%[18].

Dutch statistics show that the majority of fatal cyclist accidents in urban areas occur at intersections. In the period 2013-2015 this was the case for around 60% of the fatal cyclist accidents. Around 40% of the fatal pedestrian

[17] In the Netherlands a serious injury is defined as a victim who has been admitted to hospital and whose injuries have a score of 2 or higher according to the Maximum Abbreviated Injury Score (MAIS). MAIS is an international standard to indicate the severity of an injury.
[18] This international source is used here to allow for direct comparison of Dutch shares to those in other countries.

accidents occurred at intersections[19]. When zooming in on pedestrians, and based on somewhat older data, SWOV (2010) reported that in the Netherlands circa one third of all pedestrian accidents occur at pedestrian crossings and 41% happen while pedestrians cross the road without using a crossing facility.

3.2.2. *Most pedestrian and cyclist fatalities in collisions with cars*

The majority of pedestrian and cyclist fatalities are the result of a collision with a motorised vehicle, in particular passenger cars, but also light and heavy goods vehicles and buses. In the European Union, in the period 2011-2013, 68% of pedestrian fatalities was the result of an impact with a passenger car, and 22% was due to impact with goods vehicles or buses; for cyclist fatalities 52% was the result of a collision with a passenger car and 24% of a collision with a goods vehicle or bus (Adminaite, Allsop & Jost, 2015). Compared to the average in the European Union, this data shows that in the Netherlands relatively fewer pedestrians get killed in a collision with a passenger car (approximately 57%), and relatively more in a collision with a goods vehicle or bus (approximately 28%). For cyclists, the Netherlands do not differ much from the European Union average: circa 50% was killed in a collision with a passenger car, and just over one quarter in a collision with a goods vehicle or bus.

3.2.3. *Most pedestrian and cyclist fatalities are male*

With respect to gender it is consistently found that males are overrepresented in the accident statistics. This is also the case when we look at pedestrian and cyclist fatalities. According to ETSC (Adminaite, Allsop & Jost, 2015) on average, in the period 2011-2013, 36% of the pedestrian fatalities in the European Union was female and 64% male. For cyclists, the corresponding figures were 22% and 78% respectively. According to these European statistics, in the Netherlands relatively more females get killed in traffic as a pedestrian or cyclist than in other European countries: 40% of the pedestrians fatalities and 36% of the cyclists fatalities in the Netherlands were female.

3.2.4. *Highest fatality risk for older pedestrians and cyclists*

Older pedestrians and cyclists run a higher risk of getting killed in traffic than children and younger adults. This is due to a combination of age-related functional limitations that can affect road user behaviour, an increased accident risk, and a higher physical vulnerability that increases the risk of a fatality in case of a crash (Davidse, 2007).

ETSC (Adminaite, Allsop & Jost, 2015) reports that in the European Union the risk of being killed in traffic as a pedestrian or cyclist widely differs between age groups and also between countries (see *Figure 2* and *Figure 3*). The risk of being killed as a pedestrian is the lowest for children, with 3.4 deaths per million child population. For adults under 50 the risk is circa 7.5 deaths per million adult population. The risks of being killed as a pedestrian for people aged 50-64 and especially for those over 65 are substantially higher with 13 and 28 deaths per million population. We see the same picture when looking at the risk of being killed as a cyclist. The risk of children under

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[19] Based on the police registered Dutch accident statistics BRON

15 is circa 1.1 deaths per million child population; the risk of adults under 50 is circa 2.6 deaths per million adult population; the risk for the 50-64 year old cyclists is circa 5.3 deaths per population and the risk for cyclists over 65 circa 10 deaths per population. Comparing the individual EU Member States, people over 65 years in the Netherlands have the greatest risk of being killed as cyclists (30 deaths per million inhabitants in that age group), but the lowest risk of being killed as a pedestrian (10 deaths per million inhabitants).

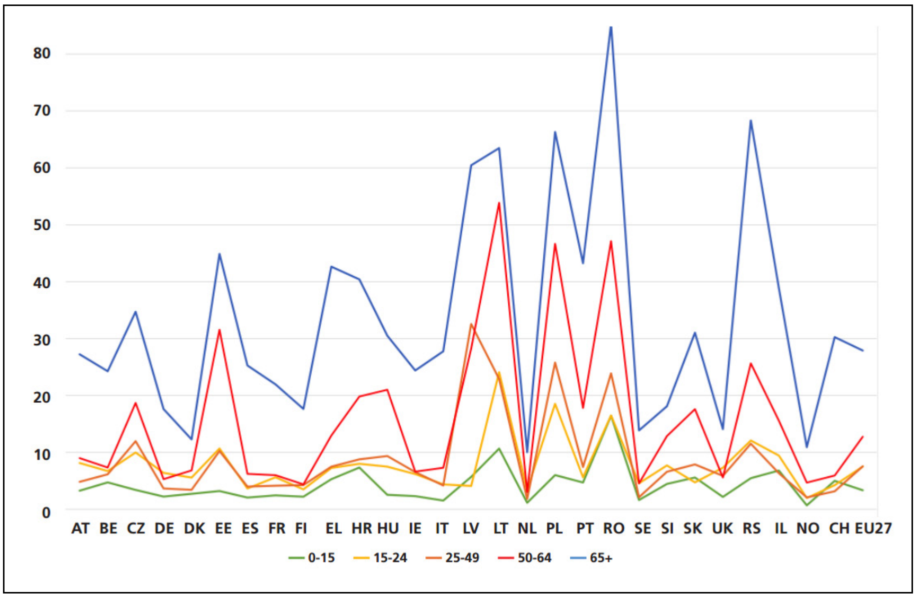

Figure 2. *Average annual pedestrian fatalities in 2011-2013 per million inhabitants in 2013 for different age groups in EU countries and EU-27 (Source: ETSC, 2015).*

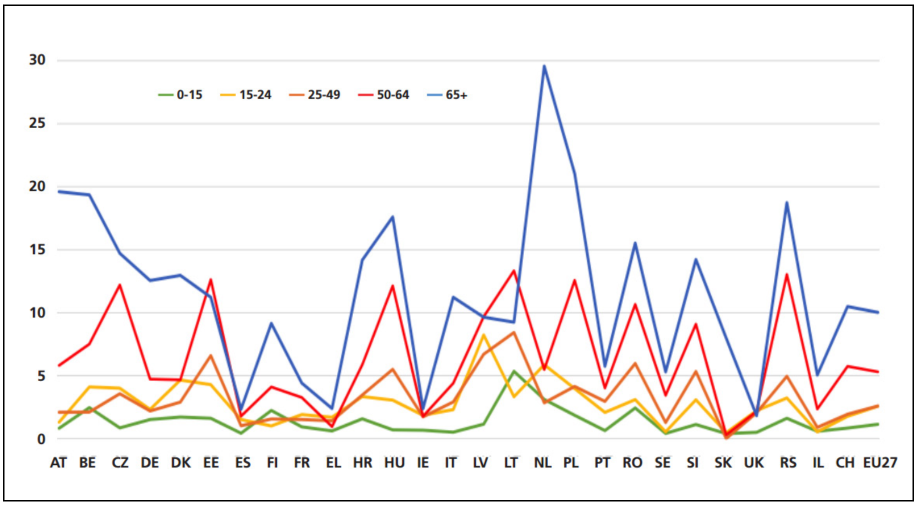

Figure 3. *Average annual cyclist fatalities in 2011-2013 per million inhabitants in 2013 for different age groups in EU countries and EU-27 (Source: ETSC, 2015).*

3.3. Summary and conclusions

Pedestrians and cyclists are unprotected road users and as such vulnerable to sustain serious injuries in road accidents, in particular when colliding with a much heavier car or truck. Worldwide, pedestrians and cyclists account for just over 25% of all road fatalities, in the European Union for almost 30% and in the Netherlands for almost 40%. Whereas both worldwide and in Europe, the share of pedestrian fatalities is substantially higher than the share of cyclist fatalities, in the Netherlands this is the other way around, with 30% of all Dutch road fatalities being cyclists (185 in 2015) and 9% pedestrians (57 in 2015). Reliable statistics about serious injuries amongst pedestrians and cyclists are hardly available at world or European level. In the Netherlands, based on data from hospitals, circa 2% of the more than 20,000 serious injuries were pedestrians and circa 63% were cyclists. Of the latter group, the vast majority was the result of an accident that did not involve a motorised vehicle; only in 11% of the crashes a motorised vehicle was involved.

Most of the fatal pedestrian and cyclist accidents occur in urban settings, at an intersection and in collisions with motorised traffic. Passenger cars are the most common collision partner, but vans, trucks and buses also account for a substantial share. Most pedestrian and cyclist fatalities are men, with older pedestrians and cyclists (especially the 65+) having a much greater risk to get killed in traffic as a pedestrian or cyclist than younger adults and children. In the Netherlands, the risk for older pedestrians is substantially lower, and the risk for older cyclists substantially higher than the European average.

This data shows that from a road safety point of view pedestrians and cyclists are of special concern. On the one side it is expected that automated cars will help to improve the safety of pedestrians and cyclists. Automated vehicles will stick to the traffic rules and regulations, not exceeding the speed limit, not running against the red light, et cetera. Moreover, automated vehicles will not make errors as a result of being distracted, fatigued, under the influence of alcohol or other psychoactive substances. On the other hand, however, it must be kept in mind that these automated vehicles have to interact with pedestrians and cyclists, i.e., road users who are not automated and, consequently, do make errors and violations, and, in addition, look and/or behave differently than the automated vehicle can detect or recognize. The next chapter will describe why the interactions between automated vehicles and pedestrians/cyclists will not automatically lead to fewer accidents and less serious injuries.

4. Vehicle automation and effects on pedestrians and cyclists

Within societal and scientific discussions about car automation, many questions arise about the way they can safely enter our current road system, and the knowledge and information we need to realize this. One of the questions concerns the safe interaction of automated cars with pedestrians and cyclists, and in particular how pedestrians and cyclists react to automated vehicles and whether this would affect their expectations and, subsequently, their behaviour. The importance of this question is underlined by the fact that potentially unsafe behaviour of pedestrians and cyclists in interaction with automated vehicles is one of the main criteria for assessing the safety of trials with automated cars on public roads in the Netherlands (De Craen et al., 2015). Also in the UK, in the context of the so-called Venturer[20] project, the interactions between automated vehicles and pedestrians and cyclists are explicitly addressed (Parkin et al., 2016).

This chapter looks for some answers to this type of question and aims to identify critical elements in vehicle-pedestrian/cyclist interactions in a future (partly) automated era. Firstly, we describe the more general factors that affect road user behaviour when interacting with others and extrapolate those to identify possible effects in a situation when cars are partly or fully automated. Secondly, we focus on the studies that were specifically designed to describe the interactions between automated vehicles and pedestrians and cyclists.

4.1. General principles of vehicle-pedestrian/cyclist interactions

4.1.1. *Formal rules and regulations*

In theory, the interactions between road users are governed by a comprehensive set of formal rules and regulations. All interactions can be described in the IF-THEN type of algorithms (Wickens et al., 2004). Applying these algorithms will, in theory, prevent all undesirable outcomes of an interaction. For example, when a cyclist approaches an intersection:

IF a car approaches from the right, and
I cannot pass in front without obstructing its free passage
THEN I have to yield and give priority

Or, when a car approaches a pedestrian crossing:

IF a pedestrian is about to cross,
THEN I have to yield

However, there are many reasons for this type of algorithms not to be so straightforward in practice. These reasons have to do with the fact that road users are no machines, no robots; they are humans and as such limited in what they can and affected by what they know, want, believe and expect.

[20] http://www.venturer-cars.com

For example, Bjørnskau (2015) studied the interaction between cars and cyclists that cross the road at a pedestrian crossing while cycling. Formally, according to the Norwegian traffic rules, car drivers do not have to yield for people who cross the street at a pedestrian crossing while cycling. However, the study showed that this type of interaction between cyclists and cars generally did not follow this formal traffic rule, but relied on informal rules: the majority of car drivers yielded to the cyclists crossing the road.

In other words, traffic interactions take place in a wide variety of contexts and fulfil different needs for different types of road users. In order for these interactions to be safe, their interpretation of the situation needs to be compatible (Salmon et al., 2012; Walker et al., 2011). If this is not the case and, for example, a car driver and a pedestrian differ in their interpretation or awareness of the situation, conflicts are likely to occur (Endsley, 1995). In addition, individual road users differ in their skills, capabilities, knowledge, motivation, personality, and state-of-mind, all of which will affect road behaviour, one way or another.

In a situation with fully automated vehicles, interactions between these vehicles would not be affected by human peculiarities. The vehicles could in theory be programmed to follow these formal rules and regulations, although in practice there will always be specific situations in which these rules will be difficult to apply. However, this is not the case in interactions with pedestrians and cyclists; the interaction with them requires more than applying such algorithms as the next sections of this chapter will show. So, for the time being, the human factor will continue to play a role in the transport system, and this presents several challenges for the development of further vehicle automation. One could even wonder whether the current priority rules and other regulations that steer the interactions between road users will all be applicable in a future (partly) automated traffic system.

4.1.2. *Individual differences*

The fact that road users are not at all a homogenous group constitutes a challenge. While road user behaviour is often studied by means of general models and theories about traffic behaviour, there is in fact no such thing as "the average road user" (Godthelp et al., 2012). There are large differences between road users in the way in which they behave in traffic with respect to skills, capabilities, knowledge, motivation, personality, and state-of-mind. In addition, there are differences with respect to age and gender.

In the field of vehicle-pedestrian/cyclist interactions a large amount of research has focused on the effects of age. For example, Bernhoft & Carstensen (2007) found that older pedestrians and cyclists appreciate crossing facilities (zebra crossings, signalized intersections, cycle paths) significantly more than younger people and that they feel less safe when these facilities are absent. Demiroz, Onelcin & Alver (2015) found that crossing gaps accepted by older pedestrians were larger than those accepted by younger pedestrians. Furthermore, older pedestrians appeared to be more cautious when crossing (Dommes et al., 2015). Furthermore, Dommes et al. (2015) as well as Zito et al. (2015) pointed out effects of age on pedestrian’s looking behaviour when crossing. For example, they found that older pedestrians tend to look towards the ground when crossing and not at their surroundings. Studying children, it was found, for example, that children that are frightened are more likely to behave hesitantly before crossing roads, leading to a higher accident risk (Shen, McClure & Schwebel, 2015).

When it comes to gender, it was found that male pedestrians are more inclined to copy behaviour of other pedestrians when crossing the street than female pedestrians (Faria et al. 2010). Moreover, a survey study indicated that men commit more violations, make more errors, and are more prone to aggressive behaviour than women when crossing streets (Antic et al., 2016).

Vehicles can also show different ‘behaviour’, e.g. related to driving speed. The effect of speed on pedestrian behaviour has been studied relatively often. For example, Demiroz, Onelcin & Alver (2015) showed that when the vehicle speed is low, pedestrians cross more slowly and feel safer than when the vehicle speed is high. Schneeman & Gohl (2016) found that speed of the vehicle influences decision making processes of the pedestrian: slow approach and early braking positively influences the decision making of the pedestrian. According to Kadali & Vedagiri (2013) the accepted gap of pedestrians is larger if the approaching speed of the vehicle is higher.

The fact that the average pedestrian and cyclist do not exist has important consequences for the development of automated vehicles. It is impossible to ‘programme’ a standard interaction situation with pedestrians and cyclists. First of all because of large differences between decisions and behaviour of individual pedestrians and cyclists. Secondly, also one and the same road user will behave differently in different situations and at different moments. Moreover, it is very likely that the mere fact that pedestrians or other road users meet a (partly) automated vehicle will affect their behaviour. Therefore, knowledge about current behavioural patterns will be insufficient for defining the vehicle algorithms.

4.1.3. *Expectations*

Another aspect that is known to have a large effect on road user decision making and behaviour are expectations about the presence and behaviour of other road users (Theeuwes & Hagenzieker, 1993; Räsänen & Summala, 2000). These expectations have been found to be a major factor in current interactions between road users (Houtenbos, 2008). Road users base their expectations of what others are going to do on a variety of aspects. According to Björklund & Åberg (2005) they base their expectations on a combination of the traffic rules that are in force, the design characteristics of the road, and the behaviour of the other road user(s). In addition, they base their expectations on past experiences in similar traffic situations (Herslund & Jørgensen, 2003). Expectations lead to predictions about the likeliness that other road users are present, and how they will behave. This, in turn, affects the decision of what to do.

In most cases this process will lead to correct decisions and safe interactions. However, problems may arise if a situation unfolds that does not match expectations. For example, at bi-directional cycle paths car drivers might not expect a cyclist approaching an intersection from the ‘wrong’ side of the road, and they may easily fail to see the cyclist, even if they look in the right direction (Räsänen & Summala, 2000). Other studies also showed that drivers looked but failed to see other road users, and that expectations are an important explanatory factor (Herslund & Jørgensen, 2003; Akhtar et al. 2010; Klassen, El-Basyouny & Islam, 2012).

Drivers have found to fail detecting cyclists because they prioritize their attention towards approaching cars since they do not expect cyclists at all. Especially experienced drivers make this type of error (Herslund & Jørgensen, 2003). Similarly, in case of signalised intersections, car drivers generally expect pedestrians to wait for red and not to cross when they themselves face a green light. Car drivers have been found to fail to detect a red light runner in time because they were less alert (Klassen, El-Basyouny & Islam, 2012). This type of expectation is likely to be at least partly based on traffic culture and traffic composition (see e.g., Haworth et al., 2015).

In a situation with automated vehicles and, in particular, in a transition situation with a mixture of automated vehicles, partly automated vehicles and manually-driven vehicles, the expectations of pedestrians and cyclists may not be very reliable. A first specific point of concern is how to ensure that pedestrians and cyclists distinguish these different types of vehicles. A second specific point of concern is how to ensure that they know what sort of behaviour to expect from each of these vehicles. A subsequent question is whether this would need to be reflected in the priority regulations and in the design of, for example, intersections, roundabouts, and pedestrian crossings (see also Parkin et al., 2016). This is one of the issues that is currently studied in the framework of the Dutch NWO-STAD project[21].

4.1.4. *Behavioural adaptation*

Behavioural adaptation also affects the interaction between road users. Behavioural adaption has been defined as the collection of behaviours that may occur following the introduction of changes to the road-vehicle-user system and that were not intended by the initiators of the change (OECD, 1990). Behavioural adaptation could arise, for example, if a road measure is introduced and road users believe that the road or the vehicle has become so much safer that they could safely drive somewhat faster or safely make a telephone call. This process is generally not very conscious, and it is difficult to prove the effect of behavioural adaptation in a scientifically sound way. However, behavioural adaptation has been reported to having reduced the effect of anti-lock braking systems (Aschenbrenner & Biehl, 1994) and road lighting, for example (Assum et al., 1999).

In case of automated vehicle-pedestrian/cyclist interactions, one form of behavioural adaptation that could arise is acceptance of smaller gaps when crossing the road, or running red lights, because pedestrians and cyclists expect that the automated vehicle will notice them and will be able to stop in time.

Road users’ faith in the adequate response of vehicles might increase with an increasing number of in-vehicle warning systems and driver assistance systems, and also with increasing automation of the driver tasks. For example, in a traffic system with automated vehicles, pedestrians and cyclists will consistently experience that a vehicle stops and yields to them, even if they do not have right of way, simply because this vehicle is programmed to do

[21] http://stad.tudelft.nl

so. Eventually, this consistent behaviour of the vehicle might lead pedestrians and cyclists to have such great confidence in this technology that they get less attentive to the presence of other traffic. It is even possible that they start testing the automated vehicles to see how it responds when they suddenly enter the road just in front of the car. This might result in dangerous situations: even though the automated vehicle will react faster than human drivers, the car might not be able to stop in time because of the physical braking limitations of the car itself (Sivak. & Schoettle, 2015). Also Millard-Ball (2016) points at this issue and uses game theory to argue that it would be profitable for pedestrians and cyclists not to choose risk aversive behaviour when interacting with automated cars. However, according to his analysis this would not affect pedestrian or cycling safety. It would primarily cause automated vehicles to be seriously slowed down in urban areas. In a transition period, however, when pedestrians and cyclist also interact with partly automated or manually-driven vehicles, the overreliance on the response of automated vehicles could affect safety. Pedestrians and cyclists may be insufficiently aware of the fact that these partly or non-automated vehicles do not automatically stop. As a consequence, the net profit of the introduction of automated vehicles could be smaller than theoretically expected or could even be absent.

4.1.5. *Informal rules and non-verbal communication*

In theory, road users' decision making in interactions is based on formal priority rules and regulations (see *Section 4.1.1*). Sometimes, however, the formal traffic rules are replaced by informal ones. This happens, for example, if the formal rule is ambiguous or if the traffic situation demands it. In those cases, road users often apply some sort of non-verbal communication in order to exchange their intentions (Schramm, Rakotonirainy & Haworth, 2008; Keferbock & Riener, 2015; Kitazaki & Myrhe, 2015; Malmsten Lundgren et al., 2017). Non-verbal communication includes the use of blinker and light signals, position and speed changes of the vehicle, as well as behavioural cues, such as eye contact, nodding and hand gestures (Walker, 2005; Kitazaki & Myrhe, 2015; Malmsten Lundgren et al., 2017). The behavioural cues are particularly relevant in vehicle-pedestrian/cyclist interactions, because they well predict attention for and awareness of each other (Rakonitorainy, Feller & Haworth, 2008; Sucha, 2014).

A few studies looked into the effects of different communication cues on the interaction between pedestrians, cyclists and motorised vehicles. Guéguen, Meineri & Eyssartier (2015) studied the effect of eye contact between a pedestrian who wants to cross and an approaching car driver. They found that if a pedestrian looked at or just above a driver, this driver was more inclined to give way to the crossing pedestrian. In another study, these same authors found that a smile given by the pedestrian also had a positive effect on the stopping behaviour of the driver (Guéguen, Eyssartier & Meineri, 2015). Ren, Jiang & Wang (2016) studied the effect of eye contact of pedestrians on the 'comfort zone' (studied as time to collision (TTC)) of the driver. They found that eye contact increased the TTC, implying that car drivers had more time to react and decelerated more smoothly, which decreased drastic braking and contributed to pedestrians' safety.

Non-verbal communication also plays a role in car-cyclist interactions. For example, for cyclists the formal way to communicate an intended change of direction is by pointing their arm in the intended travel direction. However, cyclists, do not use this formal communication cue very systematically. And then it becomes very difficult to predict an intended change of direction. Westerhuis & De Waard (2016) carried out a video survey in which participants had to predict the turning direction of a cyclist based on other visual cues (than using an arm), such as head movements and speed before the manoeuvre. The results showed that it is very hard to predict the intended turning direction of a cyclist solely based on indirect visual cues.

Thus, in current interactions, informal rules and non-verbal communication are important aspects of vehicle-pedestrian/cyclist interactions. However, with an increasing level of automation, this type of communication will more or less lose its function, both from the perspective of the car and from the perspective of the pedestrian and the cyclist. It will be very difficult for the automated car to predict the behaviour of pedestrians and cyclists if they do not use the formal non-verbal communication channels such as using an arm to indicate a change of direction. Informal communication cues are generally subtle and not unambiguous, and hence difficult to 'read'.

For pedestrians and cyclists, interaction with automated vehicles implies that they cannot rely on informal communication cues anymore. The effect of making eye contact with or smiling to a 'car driver' is not the same if this driver is not the person who is actually controlling the car, and may even be involved in completely other tasks, such as reading the newspaper or typing a text message.

4.2. **Pedestrian and cyclist interactions with automated vehicles**

The previous sections showed that many of the current mechanisms that steer the interactions between vehicles and pedestrians/cyclists will change or lose their function. This indirectly indicates a number of potential challenges for ensuring that the automated car will respond adequately to pedestrians and cyclists, as well as for ensuring that pedestrians and cyclists will deal safely with automated cars and with a combination of automated cars, partly automated cars and manually-driven cars. Relatively few studies have been carried out that focus directly on the interactions between automated vehicles and pedestrians/cyclists from the perspective of the latter. This section presents these studies. *Table 2* provides an overview of the studies cited and their main characteristics.

4.2.1. *Pedestrian and cyclist reactions to automated vehicles*

Hagenzieker et al. (2016) carried out a photo-experiment in which participating cyclists had to assess different bicycle-car interactions with both manually-driven cars and automated cars. Participants were asked questions about how certain they were of being noticed by the cars, whether or not the car would stop for them, and what they would do in such a situation (e.g. stopping, decelerating, accelerating). The results of this study generally showed that cyclists do not expect to be noted better by an automated car than by a manually-driven car, nor were they more sure the automated car would stop for them as compared to the manually-driving one. These findings appear to point at a conservative, rather cautious disposition of the participants towards automated cars.

This cautious attitude of cyclists (and pedestrians) towards automated vehicles was also found by Blau (2015). In a stated-preference survey, pedestrians and cyclists indicated to prefer the number of separated facilities (cycling paths, pavements, etc.) to increase if the volume of traditional traffic and their speeds increased. The (future) presence of automated vehicles made these preferences even stronger (significant difference). Malmsten Lundgren et al. (2017; see also Lagström & Malmsten Lundgren et al. 2015; Habibovic et al., 2016) carried out a field experiment as well as a questionnaire survey, which showed that pedestrians are less willing to cross the street when the driver of an approaching car is inattentive or behaves in a way that is not common practice nowadays, but can be expected when drivers are ‘driving’ automated vehicles (i.e. using laptop and smartphone, reading a newspaper, looking at a computer screen, having a rest or even sleeping).

However, not all studies pointed at more cautiousness and less confidence in interactions with automated vehicles. Rodriguez et al. (2016) conducted an interview and questionnaire study on how pedestrians and cyclists perceived their safety when interacting with the first self-driving pod on Dutch roads, the WEpod. The questionnaire study with nearly 200 respondents showed mixed findings regarding confidence in and perceived safety of the self-driving pod. In general, and in comparison to manually-driven vehicles, pedestrians and cyclists reported to feel somewhat safer when sharing the road with the self-driving pod. However, at unsignalised intersections cyclists reported to feel less safe when interacting with the WEpod compared to manually-driven vehicles. Similarly, pedestrians more often indicated to prefer to cross at a pedestrian crossing in the presence of the WEpods than in the presence of manually-driven vehicles. The question arises what the effect will be on the requirements for pedestrian and bicycle facilities, and on the concept and design of Shared Space areas (see also Parkin et al., 2016).

Authors	Research Question	Method	Description	Results
Pedestrian and cyclist interaction with automated vehicles				
Blau (2015)	How will automated vehicles affect the environment for pedestrians and bicyclists and how might it change their perceptions, preferences, and behaviour	Questionnaire	750-1,312 respondents (not all participants responded to all questions) answered an online survey in which they indicated which bicycle/pedestrian facilities they prefer as a cyclist and pedestrian in both a contemporary and driverless environment.	A driverless environment increased the preference for separated facilities (cycling paths, pavements etc.), indicating a careful and less confident attitude.
Hagenzieker et al. (2016)	Do cyclists' expectations and (self-reported) behaviour in interaction with an automated vehicle differ from those with a manually-driven car?	Photo experiment	35 participants answered questions about traffic situations involving either a manually-driven car or an "automated car", indicated by either a sticker on the side of the car or a text on the roof top.	The results of this study showed that on average cyclists do not expect to be noted 'better' by an automated driven car than by a manually-driven car. Cyclists indicated not to be more sure the automated car would stop for them as compared to the manually-driving car.
Lagström & Malmsten Lundgren (2015); Malmsten Lundgren et al. (2017); and Habibovic et al. (2016)[22]	Will there be new communication needs to warrant safe interactions with automated vehicles?	Field experiments, questionnaire	13 Participants had to indicate whether they were comfortable crossing the street in case of manually-driven and (Wizard-of-Oz simulated) automated vehicles. Additionally, 50 participants participated in a survey that showed pictures of a vehicle that was being driven manually or using a Wizard-of-Oz setup. Their (un)willingness to cross the street and their emotional experience were explored.	Pedestrians were less willing to cross the street when the driver of the approaching car was inattentive or showing uncommon driver behaviour.
Rodriquez et al. (2016)	How do pedestrians and cyclists perceive road safety when they interact with a WEpod?	Interviews, focus group, questionnaire	22 face-to-face interviews, 1 focus group (8 participants), and 194 respondents to an online survey.	Overall, pedestrians and cyclists felt somewhat safer with a WEpod. However, for cyclists this was not the case at unsignalised intersections, and pedestrians preferred to cross at a pedestrian crossing in the presence of the WEpod.
Rothenbücher et al. (2016)	How will pedestrians and bicyclists interact with automated vehicles when there is no human driver?	Field experiment	67 participants encountered a vehicle that appeared to have no driver.	A driverless car did not interfere with a smooth interaction. Only when the vehicle misbehaved, some pedestrians became more hesitant.

Table 2a. *Overview of studies on interactions of pedestrians/cyclists with automated vehicles (in alphabetical order of first author).*

[22] The various parts of this study have been reported in different publications. Lagström & Malmsten Lundgren (2015) report on field experiment, questionnaire and the AVIP-field experiment. Malmsten Lundgren et al. (2017) report on field experiment and the questionnaire and Habibovic et al. (2016) report on this field experiment as well.

Authors	**Research Question**	**Method**	**Description**	**Results**
		Communication needs in interaction with automated vehicles		
Clamann et al. (2016)	What is the effectiveness of new methods of vehicle-to-pedestrian communication	Field experiment	50 participants made crossing decisions in interaction with automated vehicles with different messages displayed on a forward facing display. Response times were measured.	Pedestrians tend to rely on existing crossing strategies rather than responding to displays on the car.
Lagström & Malmsten Lundgren (2015)	ICan pedestrians recognize an Automated Vehicle Interaction Prototype (AVIP) and can the vehicle provide any aid for pedestrians in the interaction with an automated vehicle.	Field Experiment	9 participants interacted with an automated vehicle that informed the pedestrian about its mode and intentions using a LED-strip in the windshield displaying different communicating patterns.	The AVIP helped pedestrians understand the intentions of the automated vehicles. Participants were more willing to cross the road before the vehicle stopped and they were calmer when doing so.
Merat et al. (2016)	What do vulnerable road users think about Automated Road Transport Systems (ARTS) and how do they want to interact and communicate with ARTS?	Questionnaire	664 participants answered 20 questions about demographics, Unified theory of Acceptance and Use of Technology (UTAUT), and questions related to interaction/information signals.	Pedestrians want to be notified by auditory signals and lights when they are seen by an automated vehicle.

Table 2b. *Overview of studies on communication needs in interaction with automated vehicles (in alphabetical order of first author).*

Authors	Research Question	Method	Description	Results
		Opinions about automated vehicles[23]		
Bazilinsky et al. (2015)	What is the public opinion on fully automated driving?	Questionnaire	8,862 respondents from 112 countries answered three surveys on (1) driving behaviour, (2) opinion on automated driving systems and (3) user acceptance of auditory interfaces in modern cars.	Public opinion is split with many respondents being positive towards fully automated driving and many being negative.
IEEE (2015)	What are challenges for the future of driverless vehicles?	Questionnaire	An unspecified number of IEEE experts and IEEE social media followers answered different questions concerning driverless vehicles.	Safety, faith in technology and technology development were seen as the main challenges. Respondents indicated that environmental sensing by automated vehicles were imperative to the development and advancement of intelligent technology.
Kyriakidis et al. (2015)	What are road users' acceptance, concerns and willingness to drive partially, highly and fully automated vehicles?	Questionnaire	5,000 respondents from 109 countries (40 of which having over 25 respondents) completed a 63-question internet survey.	33% of the respondents indicated that they would highly enjoy fully automated driving. Respondents were concerned about software hacking, legal issues and safety.
Madigan et al. (2016)	Which factors might influence acceptance of Automated Road Transport Systems (ARTS) vehicles?	Questionnaire	349 participants answered a 42-item survey about expectancies concerning the ARTS vehicles, and intentions to use them.	Expectancies about the performance of the ARTS is the strongest predictor for using it. The influence of other people and perceptions of how difficult it is to use the system also influences the use of ARTS.
Schoettle & Sivak (2014a/b)	What are the public opinions about self-driving vehicles in China, India, Japan, USA, United Kingdom, and Australia?	Questionnaire	1,553 participants answered a questionnaire that explored familiarity, expected benefits, concerns and overall interest about self-driving vehicles.	Many respondents were concerned that automated vehicles could get confused in unexpected traffic situations. 30-40% of the respondents were very concerned about the position of pedestrians and cyclists.

Table 2c. *Overview of studies on opinions about automated vehicles (in alphabetical order of first author)*.

[23] Only the Schoettle and Sivak (2014a,b) surveys have explicitly included the position of pedestrians and cyclists. Note that the other studies mentioned in this part of the table serve as examples, and do not intend to present a complete listing of all available surveys on this topic.

Rothenbücher et al. (2016) reported that, in a field study, pedestrians showed smooth interactions with a car that had no visible driver and that they generally adhered to current interaction patterns with cars. Only when the car behaved unexpectedly, e.g., moving onto the zebra crossing when the pedestrian was about to cross, some pedestrians became more hesitant about the intentions of the vehicle. However, most decided to cross nevertheless. Only a few participants looked for a driver to communicate with and indicated that they would have shown negative behaviour towards the driver if there had been one.

4.2.2. *Communication in interaction with automated vehicles*

The lack of confidence in automated cars is also reflected in the results of a study by Merat et al. (2016). In their evaluation of the self-driving pods during the CityMobil2 trials, they found that pedestrians, as well as cyclists, want to be notified by auditory signals and visual lights when they are 'seen' by the automated vehicle. This is in line with the study from Malmsten Lundgren et al. (2017) that suggested that pedestrians expect to get confirmation from the 'driver' of the car, even if he is not the one who is actually driving the car.

A few studies have focused on the effects of different means and strategies of automated vehicles to communicate with pedestrians and cyclists. Lagström & Lundgren (2015) did so by assessing the effects of different external automated vehicle interfaces on the emotional experiences and behaviour of pedestrians. They used the Wizard of Oz approach with simulated self-driving vehicles (in principle because of the limited access to automated vehicles) [24]. This study tested an Automated Vehicle Interaction Prototype (AVIP) that informed the pedestrian about the automated vehicle's mode and intention, by means of a LED strip in the windshield. LED strips display different communication patterns that are able to convey different messages. An example is a light signal that starts from the top of the windscreen towards the centre, indicating that the vehicle is about to stop[25]. Results showed that pedestrians are calmer and more willing to cross the street if they are informed about the intentions of the automated vehicle to stop. On the other hand, Clamann, Aubert & Cummings (2016) concluded that pedestrians are more likely to rely on existing crossing strategies than on the novel displays mounted on the front of the automated vehicle. At the same time, they found that a majority of the participants believed that an external vehicle display is necessary for automated vehicle-pedestrian communication.

Car manufacturers and engineers are also developing means of communication of automated vehicles with pedestrians (and cyclists). They have designed several possible techniques for the communication of automated vehicles with other road users, with a special focus on interactions in urban settings. One of the techniques suggested includes the use of laser projection: if the automated car has detected a crossing pedestrian and is going to give way, it will project a zebra crossing in front of the vehicle on the street. Other techniques build on current informal communications, for instance, a smile that lights up on a display in front of the car (Semcon, 2016[26]). The aim is to enable automated cars not only to detect a crossing

[24] https://en.wikipedia.org/wiki/Wizard_of_Oz_experiment
[25] For an illustration of the AVIP, see https://www.youtube.com/watch?v=qG9fH2EDa1g
[26] For an illustration of the concept see https://www.youtube.com/watch?v=INqWGr4dfnU

pedestrian or cyclist, but also to perceive the latter's head movements and gaze directions towards the car. As a consequence, the automated car will ‘understand’ that this road user is seeking eye contact in order to get confirmation to cross the street safely. This type of communication technology would allow pedestrians and cyclists to communicate with automated cars in the same way as they are used to in the current roadway system. It is not clear to what extent these techniques have been tested in practice.

4.2.3. *Acceptance of automated vehicles*

In addition to the more experimental studies on the interaction between pedestrians/cyclists and automated vehicles and the ways to communicate, survey studies have been carried out to investigate the public opinion about automated vehicles, in particular the user acceptance of fully-automated vehicles. For example, Bazilinsky, Kyriakidis & De Winter (2015) found that the public opinion appears to be split, with many respondents being positive and many respondents being negative towards fully automated driving. It is likely that early adopters of new technology belong to the group that responds positively to fully automated driving, although this was not explicitly addressed in this study. In another study, Kyriakidis, Happee & De Winter (2015) found that one third (of the 5,000 respondents from 109 countries, 40 of which had at least 25 respondents) indicated that they considered automated driving highly enjoyable. On average, however, respondents considered manual driving the most enjoyable mode of driving. Respondents were most concerned about software hacking, legal issues and safety.

The 2015 international survey by the Institute of Electrical and Electronics Engineers (IEEE)[27] also indicated that people are concerned about the safety of automated vehicles, with safety and faith in technology being the main barriers to consumer adoption. Participants were especially uncomfortable with automated vehicles transporting their children.

These findings are more or less in line with the findings of Schoettle & Sivak (2014a), who conducted a survey in the United States, the United Kingdom and Australia. Their study showed that 90% of the respondents had concerns that automated vehicles would, in general, not drive as well as human drivers. They were particularly concerned about the possibility that automated vehicles could get confused in unexpected traffic situations. This concern about safety issues and automated vehicles not performing as well as manually-driven vehicles was also found in another study of Schoettle & Sivak (2014b), which included respondents from China, India and Japan. In their survey studies, Schoettle & Sivak also explicitly asked whether respondents were concerned about the interaction between pedestrians and cyclists with automated vehicles. In the English-speaking countries, many respondents indicated to be ‘very concerned’: 42.1% in the United States, 35.6% in Australia, and 33.4% in the United Kingdom. In the Asian countries, the Chinese appeared to be the most concerned (42.6% ‘very concerned’), followed by the Indian people (40.4%) and the Japanese (22.2%).

Madigan et al. (2016) focused on automatic road transport systems (ARTS) for public transport. In a survey they asked about expectancies about ARTS

[27] https://www.ieee.org/about/news/2015/15october_2015.html. [Accessed 12 05 2016

and the intentions to use them. The results indicate that people will base their decision to use an ARTS mainly on how well they believe it will perform in comparison to other public transport systems. In addition, but to a lesser extent, the influence of other people and the perception of how difficult it is to use the system will influence the decision to use an ARTS. About 23% of the respondents considered themselves among the first when it comes to trying a new technology product.

The results from these surveys show that not all people consider the development towards fully automated driving desirable and that many have their concerns about the safety consequences. It is imaginable that these concerns, and more generally, a lack of confidence in automated vehicles will influence the behaviour of pedestrians and cyclists when meeting an automated or partially automated vehicle.

4.3. Summary and conclusion

In our current traffic system, the interactions between road users, including those between motorised vehicles and pedestrians or cyclists, are essentially based on formal rules and regulations. However, many factors influence the correct application of these rules, either consciously or unconsciously. These factors relate to personal characteristics, such as skills and experience, knowledge, motivation, state-of-mind, as well as age and gender. In addition, expectations, the presence and behaviour of other pedestrians or cyclists, as well as feelings of safety or insecurity affect the way the interactions develop. Communication between road users, generally non-verbal communication such as nodding or a hand gesture, helps to clarify their intentions, either in support of the formal rules or, when appropriate, to suggest an informal interaction.

These traditional, well-proved mechanisms for pedestrians and cyclists may only be partly useful when interacting with automated vehicles. Expectations of pedestrians and cyclists of the behaviour of an automated vehicle might be incorrectly based on the experiences with manually-driven vehicles or on unproven, possibly unrealistic hypotheses about the behaviour of automated vehicles. This might result in undesirable and unpredictable behaviour of pedestrians and cyclists, either because they are overconfident or because they have doubts about the behaviour and responses of the automated vehicles. Moreover, in comparison with the perspective from the automated vehicle, behaviour of pedestrians and cyclists towards this vehicle might be very different from their behaviour towards a vehicle driven by a human driver, requiring other response patterns from the automated vehicle.
In particular the role of non-verbal communication and informal rules will be very different.

Few studies have looked at the interactions between automated vehicles and pedestrians/cyclists from the perspective of the latter. The results are not unequivocal, but in general road users appear to be fairly cautious when interacting with automated vehicles and not per definition confident of their 'skills'. An increasing number of studies specifically look at the important field of vehicle-to-pedestrian/cyclist *communication*. Pedestrians and cyclists indicate that they appreciate to see whether the vehicle has detected them and shows its intentions. But which exact intentions and how they will be communicated has not yet been determined and requires further study.

5. Conclusions

5.1. What do we know: summary of findings

The interaction of automated vehicles with pedestrians and cyclists is not yet a commonly studied topic. This does not mean that this aspect of automated driving is completely overlooked. Many car manufacturers, supported by scientific research, are developing safety and communication systems that aim to avoid collisions with non-motorised vehicles, such as pedestrians and cyclists. For example, some full auto brake systems are reported to already detect cyclists (and other road users) on collision course and perform an emergency brake when needed. Nevertheless, many difficulties are yet to be overcome (e.g., reliable operation in adverse weather conditions), and it is even more challenging to develop technology that can reliably predict intentions and behaviour of pedestrians and cyclists.

However, so far, systems have been mainly developed from the perspective of the vehicle. It is not clear to what extent these systems can deal with the often unsystematic and unpredictable behaviour of pedestrians and cyclists. Moreover, it cannot be excluded that the behaviour of pedestrians and cyclists changes if they have to interact with automated vehicles or, in the likely transition period, with a combination of fully automated vehicles, partly automated vehicles and manually-driven vehicles. Such interactions are very relevant from a road safety point of view. Pedestrians and cyclists are vulnerable because they are largely unprotected, missing the protective shell that most vehicles offer to their occupants. This lack of protection becomes particularly critical in collisions with vehicles that generally are much heavier and much faster. This is reflected in the accident statistics: most of the fatal pedestrian and cyclist accidents occur in collisions with motorised vehicles, and particularly in urban areas.

From this road safety point of view, the current report has described several factors that currently affect interactions between vehicles and pedestrians/ cyclists, as well as the changes that can be expected with the introduction of (partly) automated vehicles. This report also described the studies that focused directly on the interaction of pedestrians and/or cyclists with automated vehicles[28].

Based on the literature, it can be concluded that current interaction patterns and strategies cannot be automatically transferred to a situation with automated vehicles or to a situation with vehicles with different levels of automation. Pedestrians and cyclists might base their behaviour on incorrect or unjustified expectations about the behaviour of these vehicles. Similarly, the vehicles might not be able to interpret the behaviour of pedestrians and cyclists correctly, because their behaviour in interaction with an automated vehicle could differ from the behaviour towards a manually-driven vehicle. In particular, the role of non-verbal communication and informal rules will be very different. This requires far more in-depth insight into how pedestrians

[28] We have aimed to include all empirical studies that focused directly on the interaction of pedestrians and/or cyclists with automated vehicles, published up until 1 December 2016.

and cyclists respond to automated vehicles and how they deal with vehicles during a transition period.

The findings of studies that looked more directly into the interactions between automated vehicles and pedestrians/cyclists generally point at a conservative, rather cautious disposition of the participants towards automated cars. Pedestrians and cyclists do not seem to fully trust the behaviour of automated vehicles when it comes to sharing the road or interacting. And, whereas they indicate appreciating automated vehicles to use (auditory or visual) signals that show that they are seen and/or show the intentions of the vehicles, they still tend to stick to the current, traditional crossing strategies. Studies that looked into a situation where pedestrians and cyclists have to interact with vehicles in a transition period, i.e. with cars with different levels of automation, are lacking altogether.

5.2. What do we need to know: knowledge gaps and research needs

The position of pedestrians and cyclists and their interaction with automated vehicles increasingly receives attention from researchers and car manufacturers. A number of these studies take the perspective of the pedestrian and cyclist, realising that current technical solutions might not sufficiently take account of the flexibility and unpredictability of the behaviour of the non-automated pedestrians and cyclist, and realising that current behaviour of pedestrians and cyclists might not be a good predictor of their behaviour in a (partly) automated traffic system.

Nevertheless, many questions remain; questions that need to be answered in order to ensure that further developments towards automated driving will not result in a traffic system that is even less safe for pedestrians and cyclists.

Many relevant questions relate to decision criteria to describe the behaviour of pedestrians and cyclists when interacting with automated vehicles and the underlying psychological processes, e.g.,

- What is the effect of expectations of pedestrians/cyclists and how can expectations be changed?
- Are expectations and behaviour mainly dependent on type of automated vehicle (passenger car, van, truck, (mini) bus, etc.), the specific behaviour of the particular type of automated vehicle (since there is no standard behaviour yet), on the traffic situation (complexity, traffic volumes, traffic composition, etc.), or a combination of these factors?
- To what extent do personal characteristics (age, gender, experience, motivation, trust in automation, etc.) affect the behaviour and decisions of pedestrians and cyclists?
- How and how fast will pedestrians and cyclists learn how different types of automated vehicles behave in interacting with them?
- Will behavioural adaptation take place amongst pedestrians/cyclists, and in what way and to what extent?
- What cues will become important for pedestrians/cyclists when interacting with automated vehicles? Is eye contact as important as is assumed? What is, for example, the role of approach speed?
- Are add-on messages and signs on the vehicle important to communicate to pedestrians and what signs/messages are most effective?

With respect to a likely transition period, when all types of vehicles from completely manually-driven vehicles to fully automated vehicles share the road, relevant questions include:

- Do pedestrians and cyclists need to adapt their behaviour to different levels of automations and if so, how can vehicles be made distinguishable?
- Do pedestrians and cyclists adjust their behaviour to the (estimated) level of automation, and, if so, in what way?
- Would a mixture of vehicles affect pedestrians' and cyclists' assessments of risks and hazards in different situations?

Considering measures to help pedestrians and cyclists to interact safely with automated vehicles, the following questions arise:

- To what extent can automated vehicles be programmed so that they fulfil the expectations of the pedestrians and cyclists?
- To what extent need pedestrians and cyclists be trained to deal with automated vehicles, and what can be trained and how?
- Are additional infrastructural measures needed to physically separate automated vehicles from non-automated road users (e.g. extra cycle tracks, extra grade-separated crossing facilities), or is it better to apply a shared-space approach and, in that case, what are the behavioural requirements for vehicles and pedestrians/cyclists (e.g. related to speed, position on the road, signals)?
- Are the current priority rules still appropriate or do they need to be changed and if so, how? And what are the legal consequences in case of priority violations? Is the current Dutch liability rule for car-pedestrian/cyclist accidents (the car driver is liable for such an accident even if it is not proven that he has been at fault) still reasonable if it concerns an automated vehicle?

These are just a few of the gaps in our current knowledge, and relevant research topics for bridging those gaps.

It should be noted that research in this area is not easy. The main reason is that the target situation (a traffic system with automated vehicles) does not yet exist. Hence, research in this area has to rely on surveys, stated preference studies, simulations and experimental manipulations, either in real traffic, in bicycle/pedestrian simulators or in computer-based or virtual reality studies. Making the simulations and manipulations sufficiently realistic, and consequently generate valid results, is a challenge in itself (e.g. see Keferbock & Riener, 2015). Available studies to date have used a variety of methods in a variety of (small-scale) settings, and it is as yet not clear to what extent the results of these studies can be generalized.

- In order to be able to provide answers to the research questions, it is urgently needed to develop and validate research methodologies fitted to study the interactions between pedestrians and cyclists with (fully or partly) automated vehicles.

Another challenge is to ensure that the knowledge and insights derived from individual studies gets actively connected to, for example, road authorities that anticipate on how their road infrastructure needs to be adjusted for future use by a mix of road users (particularly in urban environments, with many interactions between vulnerable road users and automated vehicles). In addition, the knowledge and insights derived from individual studies need to get actively combined with the work of the automated car software developers. A formal and active exchange platform, preferably via an existing network (e.g. HUMANIST Network of Excellence or the ERTICO ITS Network) could possibly play a role here.

- An exchange platform might help to efficiently share the answers to the research questions with the intended users of the knowledge, such as road authorities and car manufacturers.

5.3. In conclusion

In short, it can be concluded that the position of pedestrians and cyclists in a traffic system with fully and/or partly automated vehicles is a very important issue from a road safety point of view. Several developments are on its way in this area, especially from the perspective of the vehicle, but increasingly also from the perspective of the pedestrian and the cyclist. The latter is crucial because it is to be expected that the current behaviour of pedestrians and cyclists will turn out to be different in a more automated traffic system and, hence, is an inappropriate basis for programming the future vehicles. Many questions remain that need to be answered, and results need to be shared with those who need it most: the road authorities, the car manufacturers, and their software developers.

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