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Interactions between vulnerable road users and automated vehicles:
A synthesis of literature and framework for future research

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Abstract

Partially and fully automated vehicles (AVs) are being developed and tested in different countries. These vehicles are being designed to reduce and ultimately eliminate the role of human drivers in the future. Most fatal accidents of vulnerable road users (VRUs), pedestrians, cyclists and mopeds, involve a motorized vehicle. In addition, most of the accidents involving VRUs and motorized vehicles happen at road crossings. By replacing human-driven vehicles with automated vehicles, the human role will be altered and reduced which could lead to an increase in traffic safety. However, drivers are not the only ones who will have to adapt to automated vehicles, other road users, such as pedestrians and cyclists, will have to interact with vehicles with various levels of automation, too. Pedestrians and cyclists will still be humans and might behave in an unpredictable manner which could lead to unsafe behaviors. The main goal of this paper is to propose a theoretical framework which describes the interactions between automated vehicles and road user behavior under different road design conditions. This is a prerequisite to understand how to design safe urban environments where VRUs and automated vehicles can interact safely. A synthesis of the existing literature about the interactions between automated vehicles and VRUs, and the main factors that could influence VRUs' behavior is presented. The results of the synthesis and the identified knowledge gaps are discussed. Based on this, a theoretical framework for the interactions between VRUs and automated vehicles is developed and discussed.

Keywords

Automated Vehicles; Vulnerable Road Users; Interactions; Urban Environments; Theoretical Framework.

1 Introduction

Automated vehicles (AVs), of different levels of automation, will have an impact on many aspects of the transport system, including traffic safety (Milakis, van Arem, & van Wee, 2015). The main argument used is that the occurrence of accidents is primarily attributed to human drivers' errors (National Highway Traffic Safety Administration, 2008) and by replacing human drivers with automated systems the amount of traffic accidents would decrease (Fagnant & Kockelman, 2015). However, the deployment of automated vehicles in traffic, and the developments towards higher levels of automation will be gradual, and therefore, human drivers will continue to play an important role. For example, when automated systems fail and the driver has to take over control, or when other road users, such as cyclists and pedestrians, interact with automated vehicles. How the other road users will be affected by automated vehicles is a knowledge gap that has until recently largely been neglected. Road users are, at this moment, able to communicate and express their intentions through non-verbal communication such as hand gestures, eye contact, nodding. AVs will, thus, have to use other methods to communicate with the non-automated road users.

In the literature few studies focused on the interactions between vulnerable road users (VRUs) and AVs. Cyclists and pedestrians are vulnerable, and have the most fatal casualties when involved in an accident with motorized vehicles (Vissers, van der Kint, van Schagen, & Hagenzieker, 2016). Therefore, they should be taken into account when designing and deploying AVs. VRUs could experience confusing situations when they interact with AVs due to possible discrepancies between their expectations from AVs and the actual behavior of AVs. Blau (Blau, 2015) studied whether VRUs would adapt to AVs by changing their behavior. He used a survey in which he asked the participants about their stated-preference about road crossing facilities. The results indicate that AVs increased the preference for using bicycle and pedestrian crossing facilities, which could indicate that VRUs do not feel safe around AVs. This finding seems in contrast with what Núñez Velasco et al. found (Núñez Velasco, Rodrigues, Farah,

& Hagenzieker, 2016). In this study, the researchers used a questionnaire and a focus group to study VRUs perceived safety of AVs. They found that cyclists indicated to feel safer interacting with an AV than with a traditional vehicle but only at unsignalised intersections. Pedestrians did not report differences in perceived safety. The contradicting findings of these two studies could be associated with the physical presence of an AV. While in the study of Núñez Velasco et al. (Núñez Velasco et al., 2016) AVs were actually operating in the study area, in Blau's research no AV was present in the vicinity. This could have affected the perception of the VRUs. Another study that found similar results as Blau et al. was performed by Hagenzieker et al (2016). In their study, a photo experiment, indicated that VRUs were conservative about the performance of AVs, perhaps pointing towards a conservative disposition towards AVs (Hagenzieker et al., 2016). Another study on VRUs and automated vehicles was performed, but instead of photos, the researchers used virtual reality assuming it to be a more realistic experience. The researchers presented a crossing scenario with different gaps and non-automated and automated vehicles to their participants (Farooq, Cherchi, & Sobhani, 2018). Their findings showed that cycling males preferred to interact with AVs rather than with traditional vehicles. The photo and VR studies (Farooq et al., 2018; Hagenzieker et al., 2016), no clear assessment of the realism of the study was taken, which is one of the main drawbacks of stated preference studies, thus the results should be compared with results from studies performed in a more realistic setting.

Field experiments on the interactions between VRUs and AVs have also found conflicting results. Lundgren et al. used a vehicle with the steering wheel on the passenger side to simulate interactions between a pedestrian and an AV, a so called wizard of Oz technique (Lundgren et al., 2017). A fellow researcher sitting on the driver side would behave in ways which could become possible once the vehicle is automated, such as reading a newspaper and talking on a phone. The results showed that pedestrians decided to cross the road less often when the 'driver' seemed distracted. In addition, the pedestrians experienced the interactions with an inattentive driver as more unpleasant. However, the participants had no reason to expect the vehicle to be automated as they were not told this. Thus, their behavior could have been triggered by a distracted driver and not the interaction with an automated vehicle. In a similar study by Rodríguez Palmeiro, et al. crossing situations with a traditional and an automated vehicle were simulated using the Wizard of Oz technique (Rodríguez Palmeiro et al., 2017). This study varied the speed profile of the approaching vehicle, the presence of labels indicating the vehicle to be automated, behavior of the driver (attentive of distracted), and yielding behavior of the vehicle, resulting in 20 scenarios. The participants had to indicate when they thought that it was safe to cross, as well as the last moment they would have crossed. No differences were found between the scenarios, non-AV and AV, indicating that the 'automated' vehicle did not change the crossing intentions of the participants. However, these results could be biased by the fact that pedestrians were not allowed to execute their crossing decision out of ethical reasons. Rothenbücher et al. also used the Wizard of Oz technique to let other road users believe the vehicle was not being driven by anyone. They drove in two areas where they expected VRUs to have to interact with the vehicle. They found that their driverless 'AV' did not have an effect on pedestrians' crossing behavior except when it misbehaved (e.g. drove in to the zebra crossing when the pedestrians were about to cross; Rothenbücher, Li, Sirkin, Mok, & Ju, 2016). Furthermore, the expectations and trust in the vehicle were studied. The participants seemed to use two concepts of expectations and trust, and thus reported to have low expectations and trust in contemporary AVs, but high expectations and trust in future versions. To summarize, findings point towards a conservative crossing pattern of VRUs even when it was explicitly stated that they were interacting with AVs. It could be that communication devices mounted on AVs indicating what the VRU should do, would affect VRUs' behavior.

Merat et al. (Merat, Madigan, Louw, Dziennus, & Schieben, 2013) used a questionnaire to study the preference of how VRUs would like AVs to communicate with them, which were operating in the area. The participants were asked to indicate what information they would like to receive from AVs. Furthermore, the participants' perceived safety was measured. The results indicate that the participants prefer to be informed whether they have been detected by the AV, but they are not interested in knowing the speed of travel of the vehicle. The results also indicated that perceived safety of AVs depends on the presence of road markings indicating where the vehicle will drive. Clamann et al. conducted a field test to study the effectiveness of communication methods of vehicles by using a display mounted on the front of a vehicle (Clamann, Aubert, & Cummings, 2017). The researchers experimented with different sign designs, such as a 'cross advisory' and a 'don't cross advisory' indicating when the pedestrian can cross. Their participants had to report whether they would cross. The response time and safety of the pedestrians' crossing behavior were analyzed. Their findings pointed out that contrary to the participants' own beliefs, their decisions appeared to rely on past crossing behavior experience and that they did not make use of information provided by the AV. In another study, a real vehicle with a LED-strip mounted on the front window of a vehicle was used to communicate with the participants who were instructed to cross the street (Habibovic, Andersson, Nilsson, Lundgren, & Nilsson, 2016). The results of this experiment showed that the participants experienced interactions with an AV with the LED-strip as more positive as compared to one without it. Finally, a study performed in virtual reality, assessed how simulating eye contact could affect VRUs' crossing behavior. The researchers placed eyes on the headlights of their AVs (Chang, Toda, Sakamoto, & Igarashi, 2017). The eyes of the vehicles made eye contact with the participant. The researchers found that their participants were able to make a crossing decision faster, with less errors, and that the participants felt safer when they were making eye contact with the vehicle. In conclusion, the presented studies show that people may like AVs that have a communication device, but that they nevertheless whether they use it to make a crossing decision remains inconclusive.

To summarize, limited studies have investigated the interactions between VRUs and AVs, and a (theoretical) explanation of how VRUs' would adapt and change their behavior is missing. This study will fill this gap by proposing a theoretical framework explaining how VRUs' behavior could be influenced when they interact with AVs. The proposed framework, based on the Theory of Planned Behavior, aims to describe and explain how an AV will affect other road users' behavior when they both interact. Trust, feedback and expectations are included as well in the framework as these factors have been proven to affect road users' behavior. This framework is aimed to create more insight in how road users' behavior could change due to AVs' characteristics.

In the following sections a synthesis of research literature and useful models and concepts will be presented, followed by identified knowledge gaps, and the proposed theoretical framework. Finally, the paper concludes with a discussion and conclusion.

2 Synthesis

This section discusses the theories and constructs behind the theoretical framework proposed in this study, and the argumentation for their choice. We will also review behavioral models of relevance in the context of cyclists' and pedestrians' behavior when interacting with AVs. These interactions could be in the form of crossing in front of the vehicles, in areas where they rarely or often will be present, will ride in the (lateral, frontal, etc.) proximity of AVs and, overtaking slow driving vehicles.

Our framework requires a model that facilitates the understanding and in a later stage predicts VRUs' behavior. It should, in addition, contain the constructs that have been proven to affect road users' behavior and constructs that could be relevant for the interactions between VRUs and AVs. This could provide the possibility to improve road users' behavior in a later stage. Their behavior could be improved through, for example, self-explaining road design addressing critical points in interactions between VRUs and AVs, educational programs addressing the proposed constructs (e.g. trust and expectations), or AVs communication design to interact with other road users.

A variety of models have been designed to predict behavior based on motivational constructs. These models propose sociodemographic mediator variables, such as age and gender, to explain the effects on behavior, and have been used in various health behavior studies (Panter, Griffin, Jones, Mackett, & Ogilvie, 2011; Parker, Manstead, Stradling, & Reason, 1992). Health Belief Model (Janz & Becker, 1984) is a motivational model that includes six determinants of behavior, such as Perceived Severity and Perceived Benefits. This model has been criticized because of its poor definition of constructs, low discriminant validity, and therefore poor predictive validity (Armitage & Conner, 2000). Similarly, the Protection Motivation Theory (Rogers, 1983), which contains two appraisal strategies - Threat appraisal and Coping appraisal also lacks predictive power (Armitage & Conner, 2000). Social Cognitive Theory (Bandura, 1986) accounts for one's confidence in successfully carrying out certain behaviors - self-efficacy - and the perception of effects out of one's control depending on the situation - outcome expectancies -. Self-efficacy, in particular, has been found to be a principal behavior predictor. However, only small to medium predicting effects have been found despite the central role of this predictor in the Social Cognitive Theory (Armitage & Conner, 2000). The Theory of Planned Behavior is also one of the motivational models. This theory is based on the Theory of Reasoned Action (TRA) (Ajzen, 1991). TRA was designed to understand and predict the behavior of individuals based on their intentions, which were affected by their attitudes and subjective norms. However, this model has been criticized for only being able to predict behavior that is volitional (Fishbein, 1993). Therefore, Perceived Behavioral Control was added to the model to create the Theory of Planned Behavior. From all of these four models, the Theory of Planned Behavior has been proven to be better at predicting road users' intentions and their behavior (Armitage & Conner, 2000). It has also often been used in traffic research (e.g. Evans & Norman, 1998), and for those reasons it has been chosen as a basis for the proposed framework.

The literature also contains other constructs that affect road users' behavior, which are not explicitly part of the Theory of Planned Behavior, and, thus, should be included. Research has demonstrated, for example, that expectations about the situation play a major role in road user behavior (Houtenbos, Jagtman, Hagenzieker, Wieringa, & Hale, 2005). Trust is a very important construct in human-machine interactions, which is the case when humans interact with AVs, (Madhavan & Wiegmann, 2007) . Behavioral adaptation (C.M. Rudin-Brown & Noy, 2002) could develop over time and take place when VRUs gain positive and negative experience with AVs. For behavioral adaptation to take place, a clear feedback loop is needed. Humans would need to learn to adapt. Lastly, demographic factors have also been related to road user behavior (Vissers et al., 2016).These constructs and theories, and the motivation for their choice, will be further explained in the following sections.

2.1 Theory of Planned Behavior

The Theory of Planned Behavior (TPB) is relevant for studying road user's behavior in their interactions with AVs as it can be used to understand and predict this behavior. Therefore, it can be used to guide interventions designed to increase road safety (Elliott, Thomson, Robertson, Stephenson, & Wicks, 2013). TPB has been widely used to predict behavior in different areas (for a review, see (Godin & Kok, 1996)). Several meta-analyses on TPB have confirmed the strong relationships between attitudes, social norms, and perceived behavioral control with behavioral intention (Armitage & Conner, 2001; McEachan, Conner, Taylor, & Lawton, 2011; Notani, 1998). The results of the meta analyses showed that the variance explained in intention by the three TPB variables was between 42% and 45% according to McEachan et al. (McEachan et al., 2011), and between 27% and 39% according to Armitage & Conner (Armitage & Conner, 2001). In addition, a review of the literature resulted in a mean correlation ranging between 0.59 and 0.66 between the TPB variables (attitudes, perceived social norms, and perceived behavioral control) and intentions (Ajzen, 2011).

TPB and TRA (Ajzen, 1991), both have behavioral intention as a central factor. The stronger the intention to perform a certain behavior, the more likely it is that the individual will perform it. In TRA the intention is predicted by attitudes and subjective norms (Ajzen, 1985). In TPB perceived behavioral control is added to the model, as can be seen in Figure 1 (Ajzen, 1991). Attitudes are defined as the positive or negative judgements of a certain behavior by the individual. Subjective norms are the perceived judgements of the behavior. Perceived behavioral control is the perceived ability to perform a behavior, and is a direct predictor of behavior. This is how TPB is able to predict non-volitional behavior in addition to voluntary behavior.

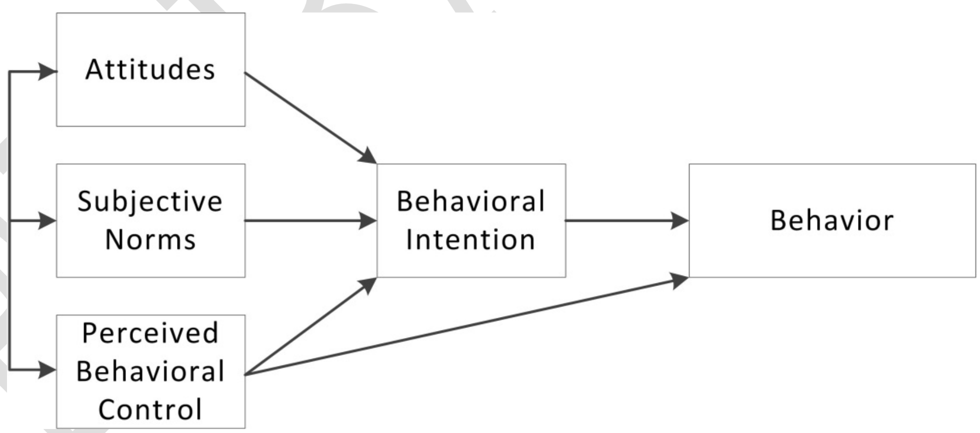

Figure 1. The Theory of Planned Behavior (Ajzen, 1991)**.**

Evans and Norman (Evans & Norman, 1998) applied TPB to the prediction of crossing intentions of adult pedestrians. They expected that perceived behavioral control would be the main predictor. To test this they deployed a TPB questionnaire and four different scenarios. The participants had to read each scenario and then complete the TPB questionnaire, which contained questions about the attitudes, subjective norm, behavioral control, self-identity (*do you see yourself as a 'safe pedestrian*), and behavioral intention. They found that the TPB is able to explain between 37% and 49% of the variance in road crossing intentions. Perceived behavioral control was the strongest predictor, in line with previous studies on road safety behavior [18, 19]. This means that the chances of participants performing a certain behavior is higher if they think they can do it successfully. The limitation of these studies is that only stated intentions are measured. In addition, the limited number of items per scale are a limitation, although, the scales predict the behavioral intentions significantly.

A study on pedestrians' violations (Moyano Díaz, 2002) used TPB to predict the relation between intentions and reported violations. The researchers of this study found a significant fit for TPB constructs as predictor of behavioral intentions. In addition, they found significant high correlations between pedestrian behavioral intentions and reported violations which proves the ability of TPB to predict behavior. Research among college students (Jalilian, Mostafavi, Mahaki, Delpisheh, & Rad, 2015) also demonstrated the utility of TPB in predicting their crossing behavior. Jalilian et al. studied the safe road-crossings by creating and distributing a custom made TPB questionnaire. The researchers found significant correlations between the TPB factors, confirming that TPB can be used for research about crossing behavior. In addition, there have been studies about distracted pedestrians (Barton, Kologi, & Siron, 2016), adolescent pedestrians' intentions to follow the crowd in a risky road-crossing situation (Zhou & Horrey, 2010), child pedestrians railway-crossing violations (Darvell, Freeman, & Rakotonirainy, 2015), and pedestrian's intention to jaywalk (Xu, Li, & Zhang, 2013). When it comes to cyclists, there have been studies using TPB for predicting the intentions of wearing bicycle helmets (Lajunen & Räsänen, 2004; O'Callaghan & Nausbaum, 2006) and predicting the willingness to commute by bicycle (Lois, Moriano, & Rondinella, 2015). TPB research on VRUs' behavior when interacting with an AV has, for obvious reasons, not been performed.

TPB is criticized for depicting decision making as a rational process. Ajzen (Ajzen, 2011) explains that rational and/or flawless beliefs are not an assumption of the TPB. TPB focusses mainly on behavior aimed to achieve a goal, which is why it is misinterpreted as a rational process. In addition, TPB has been criticized for not being good enough to predict intentions and behaviors of human beings completely (Conner & Armitage, 1998) and it is unclear whether attitudes affect behavior or vice versa (Kroesen, Handy, & Chorus, 2017). Another critique often raised is the fact that TPB supposedly does not take affect and emotions into account. These critiques should be taken into account when working with TPB. As evaluations of TPB suggest that there is room for expansion of the model [9, 38], we see the need of adding the behavioral models and concepts, behavioral adaptation, trust, and expectations, to our framework in addition to TPB.

2.2 Behavioral Adaptation

Behavioral adaptation refers to "the collection of behaviors which may occur following the introduction of changes to the road–vehicle–user system and which were not intended by the initiators of the change" (OECD Scientific Expert Group, 1990). Thus, the road users must perceive the change in the system before they can start to alternate and learning their behavior. Risk homeostasis (Wilde, 1982) is an precursor of the behavioral adaptation concept .The main concept of risk homeostasis is that individuals target a certain level of risk. If their actual level of risk is lower than their preferred level of risk, then the individual will adapt his/her behavior in a way that increases the perceived level of risk. Some problems risk homeostasis encountered were being to general and not testable (Wilde, 1988). According to Ewing and Dumbaugh (Ewing & Dumbaugh, 2009), conventional traffic safety theories, that state that more 'forgiving' road designs only increase safety, do not account for the fact that human behavior can change too. By designing a road to be more forgiving towards road users, they are given the possibility to take more risks. This is what potentially causes an adverse effect. In addition, measures inside vehicles also elicit behavioral adaptation.

Research shows that driver assistance systems can lead to negative behavioral adaptation. Hoedemaeker and Brookhuis (Hoedemaeker & Brookhuis, 1998) noted that adaptive cruise control (ACC) was liked by the majority of participants in a driving simulator study because of its helpfulness. The participants took more risks when driving with ACC than they did without ACC in the form of smaller time headways, higher deceleration rate and higher speeds. A meta-analysis showed that different kinds of ACCs have different effects on behavior and that it may not be possible to conclude how ACCs in general will create behavioral adaptation (Dragutinovic, Brookhuis, & Hagenzieker, 2005). However, there seems to be a positive relation between the amount of support ACC provides and behavioral adaptation. Another review on psychophysiological effects of ACC and highly automated vehicles on drivers' performance showed that there are some indications that heart rate is reduced by driving in an AV (De Winter, Happee, Martens, & Stanton, 2014). Not all studies included in the analysis reached the same conclusion, thus, no clear conclusion can be drawn without more research into this area. However, it is clear that drivers adapt to the system and that it does not necessarily increase safety (De Winter et al., 2014; Dragutinovic et al., 2005; Hoedemaeker & Brookhuis, 1998). These findings indicate how drivers adapt to AVs. The question remains on how

VRUs will adapt to these vehicles over time. AVs could behave in a very defensive manner to increase the safety of an interaction with another road user. This could lead to a behavioral adaptation in the form of abuse of this defensive driving style. In addition, it is unclear how VRUs are going to adapt to the lack of eye contact.

Rudin-Brown and Noy presented a qualitative model (C.M. Rudin-Brown & Noy, 2002), in which behavioral adaptation of an individual depends on one's personality, control seeking, one's mental model, and trust. If an individual gets in contact with a change to one's environment and learns new behavior through feedback, he or she will adapt his or her trust level. They tested this model in a number of driving simulator studies, and field tests on a track (Christina M Rudin-Brown & Parker, 2004). The conclusions drawn from these studies were that too much trust in a system induces risky behavioral adaptation, and particularly when this trust is false. In addition to trust, learning and feedback allow behavioral adaptation to occur and therefore need to be incorporated in our model.

2.3 Trust

Trust defined as "the attitude that an agent [in this case AVs] will help achieve an individual's goal [in this case the VRU] in a situation characterized by uncertainty and vulnerability" (Lee & See, 2004) could be seen as a cause of road users' behavior or an outcome of an interaction with AVs (Madhavan & Wiegmann, 2007). Many studies have been performed on the dynamics of trust. Hoff and Bashir (Hoff & Bashir, 2015), for example, proposed a model that represents 29 factors that influence trust, such as experience, attitudes, and understanding of the system. It explains how trust is affected by different factors depending on the kind of trust, and how the reliance on systems changes prior and during interactions. This model is not the only one with an extensive list of factors affecting trust. In a human-automation interaction trust influences the reliance on automation, but it does not determine it. Principally, trust influences reliance in situation where uncertainty is present and where resources to explore all alternatives are lacking (Lee & See, 2004).

During human interactions with a system, its performance is the most important factor affecting humans' reliance. Muir (Muir, 1994) specifies how experience with a system changes trust. He concludes that a user can have appropriate (dis)trust towards an automation, if the user trusts automation and it is of high quality, but also if the user distrusts automation or when it's of low quality. However, a user can also wrongly mistrust automation. Particularly, in cases where automation is wrongly mistrusted this can lead to accidents or inefficient interactions (Lee & See, 2004) in the case of AVs. Therefore, the trust people have in automation and their reliance on AVs must be taken into account in contemporary research on VRUs-AVs interaction and carefully examined.

2.4 Expectations

Expectations have been proven to be an important factor affecting behavior (Houtenbos, 2008; Theeuwes & Hagenzieker, 1993). Studies found that road users are quite good at adapting to unexpected situations, one of them is Houtenbos' study. Houtenbos (Houtenbos, 2008) studied the interactions between car drivers at intersections, and provided insights on how expectations affect drivers' interaction behavior. She proposed a framework which describes how drivers' interactions depend on their expectations, information processing, (road) environment and interaction space. This framework provides insights on expected changes in behavior due to changes in expectations. Houtenbos' framework takes into account the short and long term expectations (Knapp, 1998). Short term expectations are expectations that are enriched with the information one has at that particular moment, in addition to the long term expectations. Long term expectations are a priori ideas about certain situations, such as expectations about how the driving behavior of other road users will be on a highway. Expectations and reduction of uncertainty play a major role in "self-explaining roads" (Theeuwes & Godthelp, 1995), which is part of the Dutch road safety approach (Wegman, Aarts, & Bax, 2008). This way of designing roads is devised to increase road users' performance by helping them forming accurate expectations . Research has shown that road users' expectations, about how they should behave in a certain situation and road lay out, guides their behavior, whether they are correct or not (C. Rudin-Brown, Jonah, & Boase, 2013). Therefore, roads, including their specific design characteristics and the presence of various road users, should help road users create the right expectations so that they behave adequately. In TPB expectations are also important: Perceived behavioral control is one's expectation of the probability of performing a certain behavior successfully, which is closely related to "self-efficacy" (Bandura, 1986). We assume that perceived behavioral control is derived from general expectations about the situation. Thus, expectations should be part of our proposed framework and precede perceived behavioral control.

AVs could make VRUs create different expectations or change their expectations. For example, by using communication displays, the intent of the vehicle could be communicated to the VRU manipulating the VRU to behave in a manner that fits the situation. In addition, AVs are expected to behave more consistent as their behavior will be programmed, which would help VRUs to create more accurate expectations. However, VRUs could fail to create accurate expectations, for example, when different AVs use different signs to indicate the same intent, or when an AV is not recognizable as such.

3 Theoretical framework

The literature described in this paper gives insights into the knowledge gaps related to the interactions between VRUs and AVs, which are in line with previous reviews (Parkin, Clark, Clayton, Ricci, & Parkhurst, 2016; Vissers et al., 2016). TPB has been used in various traffic related studies but has not been used to investigate the behavior of road users interactions with AVs. In addition, the literature on road user behavior points out that also other factors influence road users' behavior. Studies have suggested that TPB can be expanded to increase its predictive validity. In addition, the short term and long term of the interactions need to be targeted by researchers. Behavioral adaptation could affect the road users' behavior and in that case, undermine the safety or efficiency of AVs. This can be related to differences in trust and expectations. Rothenbücher et al. found that a difference exists between trust and expectations now and in the future (Rothenbücher et al., 2016). More research is needed to understand how these constructs influence the behavior of the road users and thus the interactions with AVs and how these constructs are affected by AVs' characteristics, such as the driver absence, distinguishableness as an AV, communication capabilities, physical appearance and level of automation. In conclusion, some studies have already targeted the interactions between AVs and VRUs but many questions remain. Therefore, we propose a theoretical framework combining the literature on factors that influence road users' and TPB to better understand what the effects of AVs could be on road users' behavior.

Figure 2 presents our proposed theoretical framework, which combines TPB and constructs that affect VRUs' behavior and in which we assume will be relevant when studying the interactions between AVs, VRUs and road design. The core of this framework is the interaction of VRUs with AVs with various characteristics taking into account the environment in which they interact, in particular the road design. The characteristics of VRUs, AVs and road design that we think are important to be taken into account are as following:

(1) Characteristics of the road design: the number of lanes, type of intersections, presence of road signs, presence of crossing facilities for VRUs and communication capabilities of and to the road design.
(2) Characteristics of AVs: their programmed 'driving' behavior, communication capabilities with the road and other road users, presence of a driver, distinguishableness as an AV, and level of automation.
(3) VRUs' characteristics: mode of transport, a priori expectations, trust levels, and experience with AVs. Demographics, age and gender have also proven to correlate with certain behavior however, TPB assumes these factors affect the TPB constructs instead of directly having an effect on behavior.

Following our proposed theoretical framework, road users' behavior depends on their behavioral intentions and perceived behavioral control, which is adopted from the Theory of Planned Behavior (Ajzen, 1991). The behavioral intentions depend on the attitude towards the behavior, the perceived subjective norm and the perceived behavioral control, and these three factors also affect each other (Ajzen, 1991). We added the assumption that perceived behavioral control is affected by trust in AVs and by expectations about the situation in general, such as expectations about who has the right of way, trajectory and speed of the other road user, and about safety. Finally, we assume that the expectations are affected through feedback obtained from previous interactions, and by feedback provided by the road design and AVs. The effect feedback will have on behavior depends on the feedback's nature, such as amount, and intensity. VRUs are more likely to change their behavior if they receive a high amount of feedback, due to, for example, a high penetration rate of AVs. In addition, it is likely that VRUs change their behavior after an accident with an AV, which we see as an extreme form of feedback. Trust is, in this framework, assumed to have an effect of expectations, which have been created by the interactions through feedback, and a cause affecting behavior through influencing one's perceived behavioral control. Feedback of the interaction has a direct effect on expectations as the VRU uses this feedback to assess its performance and changes its expectations accordingly and on trust (Heikoop, de Winter, van Arem, & Stanton, 2015), but in the long term it will probably also have effects on attitudes, perceived subjective norms, AVs and road design. For the latter two it could come in the form of, for example, updates for AVs software and changes in the road design.

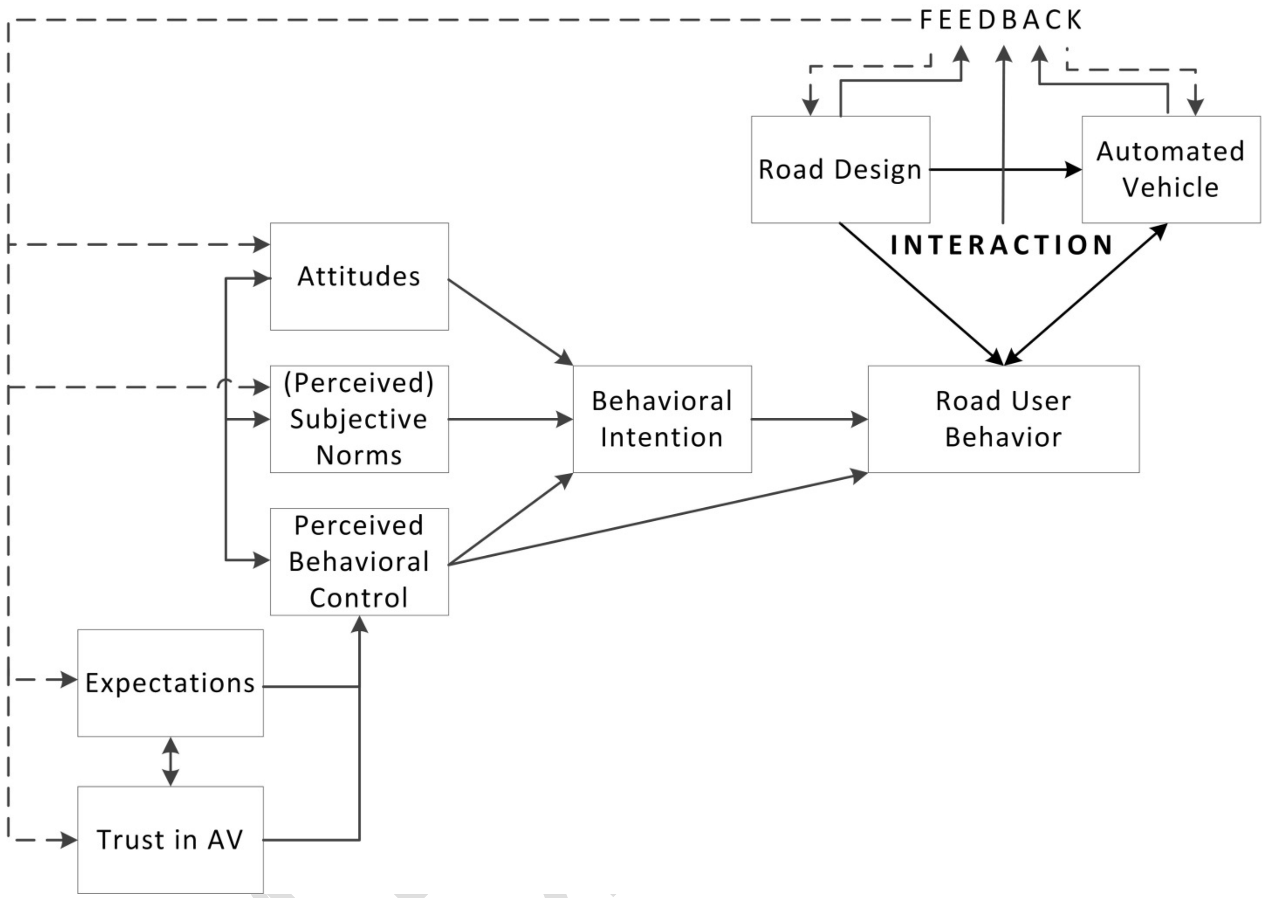

Figure 2: The proposed theoretical framework. The dashed lines represent how behavior could be affected after an indefinite number of interactions depending on the feedback's nature.

4 Discussion and conclusion

Our proposed theoretical framework is designed to provide a better understanding of the mechanisms that affect road users' behavior when interacting with AVs, and in a later stage predict road users' behavior in such interactions. We have chosen the TPB as a basis for our proposed theoretical framework and extended it by adding the constructs of trust and expectations as we assume that these affect the perceived behavioral control. In addition, a feedback loop resulting from the interactions has been added to the framework.

The proposed theoretical framework contains the dominant relations that affect behavior when a road user interacts with an AV. Future changes in road design and AVs could affect specific elements in our model, and the way our model performs. For example, if at some point communication capabilities are implemented that make it possible to communicate with road design, AVs, and other road users, a two-way arrow should be added to the model between 'road design' and 'road user behavior', and between 'road design' and 'automated vehicle'. Also, the penetration rate of AVs affects (the outcomes of) this model. If there are just a few AVs on the road it is possible that other road users do not interact frequently enough with AVs to learn from these interactions. If the penetration rate is high, and lots of AVs are on the road then the feedback would have more effect on road users' behavior. In contrast, software updates of AVs could influence, negatively or positively, the learnt behavior of road users, particularly when the updates would change AVs' behavior. For example, allowing less space between them and VRUs could result in a higher perceived unsafety by the VRUs. Further, not all road users have the same level of expectations and trust when they start interacting with AVs and thus this should be taken into consideration. Further research would be needed to investigate how feedback affects expectations and trust. As mentioned earlier, there are few studies on the interactions between VRUs and AVs, but none of these studies until now has focused on how VRU behavior would changes over time, and how this change in behavior is established, which is not surprising given that AVs are not common on the road yet.

In our following studies we will apply this model to explore its usability. Studies could include longitudinal experiments that investigate the changes in trust, expectations, TPB constructs and behavior over time with the help of, for example, questionnaires, video recordings and field tests.

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