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How automated vehicles should operate to avoid fatal crashes with cyclists?

Roni Utriainen *, Markus Pöllänen

Transport Research Centre Verne, Tampere University, P.O. Box 600, FI-33014 Tampere, Finland

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ABSTRACT

The study assesses what kind of features would allow highly automated vehicles' (HAVs) safe operation in encounters with cyclists and allow avoiding fatal crashes between cyclists and passenger cars. Five features of HAVs' capabilities are formed based on previous studies and evaluated qualitatively using data from fatal crashes between driver-managed passenger cars and cyclist in Finland. By analysing these crashes, it is assessed which features HAVs should have in order to avoid each crash in a hypothetical setting, in which driver-managed cars would be replaced by HAVs. The necessary features of HAVs for crash avoidance are analysed crash-by-crash by considering the obligation to yield, visual obstacles at the crash scene and driver's behaviour prior to the crash. In order to avoid different types of fatal crashes with cyclists, the HAVs should be able to recognize nearby cyclists (feature 1), be aware of the priority rules in various intersections and traffic situations (2), indicate its intentions to cyclists (3), maintain safe driving patterns and anticipate future situations (4), and assess cyclists' intentions (5). Albeit the number of different features to allow crash avoidance is only five, implementing these features is a considerable challenge for HAVs' programming and design, as these should function in various and complex traffic situations. The study discloses the complexity in the encounters between HAVs and cyclists, which are to be considered in further studies and real-world implementations.

1. Introduction

Increased safety is one of the benefits highly automated vehicles (HAVs) are expected to deliver. Especially, safety of motor vehicle traffic would be enhanced, when human drivers are replaced by driving automation (Fagnant and Kockelman, 2015). Even if the HAVs would become mainstream as forecasted e.g., by 2050 or by 2060 (Litman, 2020), humans will still remain as important and visible road users as cyclists and pedestrians. In the encounters between HAVs and other road users, interaction is an essential factor to consider from safety perspective (Merat et al., 2018). However, as HAVs are mainly operated under test environments, knowledge on the encounters with other road users, and especially with cyclists, is currently deficient.

Studies on drivers' yielding behaviour have shown a great challenge in the encounters with the cyclists due to inconsistency as the drivers sometimes obey the priority rules, but in some cases, the drivers may ignore their obligation to yield to the cyclists (Räsänen and Summala, 2000; Silvano et al., 2016). Even though the rules would obligate the cyclist to give way, the drivers may yield to cyclists at intersections (Silvano et al., 2016; van Haperen et al., 2018), and sometimes the drivers may not yield to cyclists, albeit the drivers should give way. HAVs are likely designed and programmed to obey formal traffic rules (e.g., the obligation to yield), which would supposedly make the encounter more predictable from cyclists' perspective. However, the cyclists may not always obey their obligation to yield (Räsänen et al., 1999), and therefore the question arises whether HAVs could and should be programmed to recognize and anticipate these situations to ensure safe encounters. In order to manage this task, the HAVs should be able to assess the cyclists' as well as other road users' intentions, which is likely to be a challenge for the HAV's operation (Botello et al., 2018).

So far, there are only a few studies, which have focused on the interaction between HAVs and cyclists. According to a photo experiment made by Hagenzieker et al. (2020), cyclists were not more confident to be noticed by HAVs compared to manually driven cars in bicycle-car interactions. Cautiousness towards HAVs was evident as the cyclists were found to be similarly sure that the driver or the HAV would stop for them. In addition, it was found that the appearance of the HAV is important for the interaction from cyclist's point of view. Merat et al. (2018) studied the interaction between cyclists and pedestrians and an automated shuttle bus (ASB) in a shared space area without lane markings and concluded that other road users thought that the ASB should yield and have an external way to communicate in the

* Corresponding author.
E-mail address: roni.utriainen@tuni.fi (R. Utriainen).

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encounters. Tengvall (2018) noticed that interaction with the ASB of the same type was considered to be simpler compared to a human driver as the ASB either reacted clearly (e.g., decelerated or stopped) while in collision course with other road users or the ASB ignored others and continued moving. Tengvall's (2018) study did not recognize clear safety benefits from the perspective of cyclists or other road users in case of ASB encounters. Rodriguez et al. (2016) found that cyclists felt the interaction with the ASB at unsignalised intersections less safe compared to a driver-managed vehicle. These studies suggest that an HAV may simplify the interaction and encounters from the perspective of cyclist and other road users, but acceptable and practical procedures should be developed for the interaction.

The aim of this paper is to qualitatively assess, what features would allow HAV's safe operation in encounters with cyclists and allow avoiding fatal crashes between cyclists and passenger cars. Related to the aim, the key questions this paper aims to answer are:

1) What features should an HAV (i.e., a passenger car with an automated driving system) have in order to manage safe encounters with cyclists?
2) How would these features help to avoid crashes, which have resulted to fatalities in actual crash scenes between cyclists and driver-managed passenger cars?

2. Materials and methods

Firstly, this section describes the different features related to HAVs' design and operation, which would allow HAVs' safe operation in the encounters with cyclists. The features are described based on findings from previous studies and a preliminary analysis of the crash data. Secondly, data on fatal crashes between cyclists and passenger cars are presented. Finally, the method to analyse the needed HAVs' features to avoid each studied crash is presented.

2.1. Features of HAVs to acknowledge cyclists and provide cycling safety

As the HAVs are still mostly non-existing in real traffic settings and the knowledge on the encounters between the HAVs and the cyclists is limited, this section refers mostly to studies, which discuss the interaction between driver-managed cars and cyclists. The few existing studies on interaction between HAVs and cyclist are also referred. The findings from previous studies and a preliminary analysis of the crash data were used to define the features of HAVs, which would be needed to manage safe operation in the situations which have led to fatal cycling crashes. Motivation for this chosen approach is to recognize the features which would result to safe encounters between cyclists and HAVs as there is little previous knowledge on the needed features. The preliminary analysis of the crash data was used to gather understanding on the occurrence of crashes by analysing crash types, crash descriptions and other variables (e.g., speed, visual obstacles etc.) that enable identifying key factors associated to undesirable outcomes. Features are presented in a numerical order following a paragraph, which describes and reasons the features. The features relate to cyclist recognition (section 2.1.1), following the rules and indicating intention (section 2.1.2), and safe behaviour and situational awareness (section 2.1.3).

2.1.1. Features related to cyclist recognition

Feature 1 (recognize): HAVs should always recognize all road users which may end up on a collision course

In order to operate safely, the HAV should be able to recognize all nearby road users, which may end up on a collision course in all situations, including also e.g., bad weather. One essential factor related to yielding behaviour is whether the driver notices the crossing cyclist (Räsänen and Summala, 2000). Even if the driver should yield to the cyclist (e.g., when exiting a roundabout), the driver does not always yield as the driver may not recognize the cyclist due to the lack of attention or poor visibility (Silvano et al., 2016). For instance, when the driver is approaching an intersection, the driver may pay attention only to other motor vehicles and fail to recognize the cyclists (Räsänen and Summala, 2000).

2.1.2. Features related to following rules and indicating intention

Feature 2 (follow rules): the HAV's yielding behaviour should be based on formal priority rules and the HAV should accurately obey its obligation to yield in all traffic situations and different types of intersections

Räsänen and Summala (2000) discussed three driver-related factors, which have an impact on the yielding behaviour: 1) is the cyclist noticed, 2) are the priority rules known, and 3) is the driving style (e.g., speed) safe. According to Silvano et al. (2016), drivers consider time distance to the intersection, vehicle speed and the proximity of cyclists, when making the yielding decision. Even if Räsänen and Summala (2000) mentioned the priority rules as one factor, formal yielding rules do not seem to have a major effect on the yielding behaviour, or they are not more important than some other factors. Sakshaug et al. (2010) have stated that formal rules (e.g., priorities at intersections) have only a minor effect on the yielding behaviour. The HAVs should follow formal rules, which would make the rules a stronger basis for the yielding behaviour contrary to present procedures in operations by human drivers. The accurate compliance would likely increase cyclists' trust on HAVs, because the cyclists seem not to be more confident that the HAVs would yield more often than the drivers, even if the law would obligate them to give way (Hagenzieker et al., 2020). In addition, Vlakveld et al. (2020) found based on video experiments that the less cyclists trust on HAVs, the more likely they decelerated in conflicts with the HAVs at intersections even if they had a priority.

Feature 3 (indicate intentions): the HAV should indicate its intentions to cyclists in a clear and a consistent manner

It is also important to examine the encounter from the cyclist's point of view. At intersections, the cyclist may sometimes think that the driver has recognized them (Silvano et al., 2016), but decreasing vehicle speed as a potential clue of the recognition may not be a result of detecting the cyclist (Kovácsová et al., 2018). From the perspective of the cyclist, it is sometimes difficult to find proper signals in the behaviour of the driver or the manoeuvres of the vehicle, which would indicate to the cyclist that they can safely cross the street first. As an answer to the problem, the HAV should be designed to indicate its intention in the encounters with other road users by e.g., decreasing vehicle speed or by light or text signals, as Ackermann et al. (2019) have studied from the pedestrians' point of view. For instance, the HAV could indicate that the cyclist is recognized and whether the HAV is yielding or not.

The feature to indicate intentions has also been identified necessary in previous studies on HAVs, as Merat et al. (2018) concluded that the HAVs should have an external way to communicate in the encounters with cyclists and other road users. Lee et al. (2020) also suggested that some way to communicate is needed, when the HAVs replace the role of drivers.

2.1.3. Features related to safe behaviour and situational awareness

Feature 4 (safe driving patterns and situational awareness): the HAV should use safe speed and maintain safe driving patterns by considering the traffic situation

Maintaining safe driving patterns and being consistent in yielding behaviour is a crucial part of HAV's operation for the cyclists to be able to anticipate the HAV's behaviour. In some occasions, where the drivers should give way, the drivers do not always yield to cyclists (Silvano et al., 2016). It has been found that high speed of the car increases the probability not to yield to cyclists (Räsänen and Summala, 2000). Obeying the obligation to yield or maintaining safe speed should not be a problem in the programming and designing of HAVs. Safe speed refers to obeying the speed limit and choosing lower speed in interaction situations with cyclists (OECD, 2018). Anticipation is important for safety, if the automated driving systems cannot be sure that the cyclist is going to yield.

Similarly, if a visual obstacle in the traffic environment restricts the view to potential cyclists or other road users at intersections approaching from other directions, speed should be lowered to prepare for making an evasive action, if a road user should appear behind the obstacle. Zao et al. (2019) indicated that speed reduction by the automatic emergency braking system would typically have been small in car-cyclist collisions, when a visual obstacle restricted the view to the cyclist and hence, the visual obstacles should be able to consider in the HAV operation. HAVs should be designed in a way that they are always able to stop for any foreseeable obstruction, which sometimes means lower speed than the speed limit indicates (OECD, 2018). As the HAVs should be able to consider these types of obstacle and potential conflicts in its operation, implementing situational awareness (see Endsley, 1995) as a feature of HAVs may not be easy. Considering the potential conflicts is important as according to the principles of vision zero and safe system approach (OECD, 2018), it should be recognized and emphasised that people will always make mistakes, but these mistakes should not lead to serious consequences.

Feature 5 (assess cyclist's intention): even if the priority rules state that the cyclist should yield to the HAV, the HAV should assess cyclists' intentions and choose its speed so that it is prepared for the cyclist not yielding

The safe driving patterns and situational awareness discussed related to feature 4 are probably not always enough to avoid collisions with cyclists. For instance, as the cyclist may not always obey their obligation to yield, the HAV should anticipate such behaviour of the cyclist and take evasive action to avoid a possible crash. Decreasing the speed is probably needed in most of the encounters with cyclists in the early phase of the HAV's deployment, because intention estimation is assessed to be difficult (Botello et al., 2018). Lower speed enables more time to make the evasive action and to avoid the collision.

Cyclists do not always pay attention to cars (and turn their heads towards the car) at intersections, if they can be sure that there will not be a conflict (Kovácsová et al., 2018). This suggests that HAVs cannot solely rely on cyclist's head movements when assessing the cyclists' intention. As it is not always possible to assess cyclists' intentions in various situations, HAVs should choose safe speed to anticipate the possibility that cyclists would come into collision course, e.g., by crossing the street, albeit the cyclist has the obligation to yield.

2.2. Crash data

In order to analyse HAVs' possibilities to safe operation in situations, in which fatal crashes have occurred, Finnish data from years 2014–2016 considering all 24 fatal crashes between cyclists and driver-managed passenger cars were studied. For study purposes, data on in-depth investigated crashes was received from Finnish Crash Data Institute. The in-depth investigations are based on crash scene investigations, reconstructions, interviews, and medical reports (Finnish Crash Data Institute, 2021). The data received included crash descriptions and descriptive factors on the crashes based on the investigations by multi-disciplinary crash investigation teams, in which investigators represent different areas of expertise (police, road engineering, vehicle technology, medicine, and behavioural sciences).

In this study, the crashes between cyclists and passenger cars were chosen as the crashes to be studied in order to reduce the heterogeneity of vehicle and crash characteristics to be considered. The amount of cycling crashes is relatively low in Finland as the total number of fatal crashes in Finland in 2014–2016 was 721, of which 80 (11 %) were cyclist crashes (Finnish Crash Data Institute, 2019). In addition to the 24 crashes between cyclists and passenger cars, the fatal cycling crashes include 31 single-bicycle crashes, 23 collisions between cyclists and other motor vehicles than passenger cars and 2 collisions with other cyclists or with pedestrians. The analysed 24 fatal crashes between cyclists and passenger cars include 17 crashes in cycle crossings or at intersections and seven other crashes, which were rear-end crashes or crashes, in which the cyclist crossed the lane without a cycle crossing.

2.3. Case-by-case evaluation

Using the crash data, it is evaluated qualitatively, which features should the HAV have in order to be able to prevent crashes with cyclist in the hypothetical scenario that HAV would be involved vehicle instead of a driver-managed car. The crash data enables evaluation of the factors, which caused or enabled the crash and thereafter enables considering, what kind of HAV design and operation could make preventing the crashes possible. The needed HAV features and behaviour to allow crash avoidance is evaluated broadly prior to the crash instead of just assessing the possible operation in the immediate crash situation as the HAV would assumedly operate differently from driver's actions prior to the crash.

The needed HAV features for crash avoidance are evaluated qualitatively using three questions related to each crash as depicted in Fig. 1. First, it is evaluated, whether the passenger car or the cyclist had the obligation to yield. Second, it is studied, whether there was a visual obstacle (e.g., a building or other vehicles), which blocked the possibility to recognize the cyclist. If the cyclist should have yielded, the required features of the HAV to avoid the crash can be recognized based on this information. If the car had the obligation to yield, it is further assessed, did the driver behave dangerously by violating some other rules than an obligation to yield (e.g., passed traffic island from wrong side as in one of the studied crashes).

In Fig. 1, cases CN1 and CN2 represent different needs in HAV's features in intersection (CN1) and rear-end or same driving direction crashes (CN2). However, in most of the cases the location of the crash had no effect on the required features. As an example, an intersection crash without any visual obstacles and when the driver had obligation to yield and drove dangerously (case DNY), could be avoided by the HAV with features 1 (recognize), 2 (follow rules) and 4 (safe driving patterns). This means that to avoid similar crashes, HAVs should recognize the cyclist, follow priority rules at intersections and maintain safe driving patterns (e.g., not violate any rules). Similarly, all crashes are evaluated case-by-case to assess the features, which the HAV should have to be able to avoid each crash.

The analysis in Fig. 1 assists to evaluate the potentially needed HAV's features, but some of the cases may be difficult to avoid despite of the HAV's features due to a short time margin to the collision, when the cyclist is recognized. Therefore, we conducted a time-to-collision (TTC) analysis to evaluate HAV's possibilities to avoid the crashes assuming a similar crash scene and characteristics to the actual crash. TTC was calculated as presented in Eq. 1.

$$\text{TTC} = \frac{X_{CY}}{V_{CY}} \tag{1}$$

In Eq. 1, X_{CY} presents a distance between a trigger point and a collision point. The trigger point is a point in which the cyclist enters the roadway from a cycle path at cycle crossings (e.g., the cyclist passes a kerb) or the cyclist turns to car's trajectory from the side of the roadway in the crash type of same running directions. In one case, the depicted distance could not be analysed, because the cyclist was already on the collision point, when the cyclist could firstly have been recognized. In this case, TTC is based on the car's speed and the sight distance, when the cyclist could be firstly recognized. V_{CY} presents cyclist's speed.

In many cases, speed of the cyclist was not available in the data as it could not be defined by the crash investigation teams and hence, TTC was calculated by using two different cyclist's speeds as assumptions: 5 km/h and 15 km/h. Consequently, two different TTC values are presented, when the cyclist's speed is not known. The depicted TTC analysis enables to evaluate the time distance to the collision point, when it is likely that the trajectories of the car and the cyclist are going to intersect. The HAV could apply the brakes before the cyclist goes to the roadway

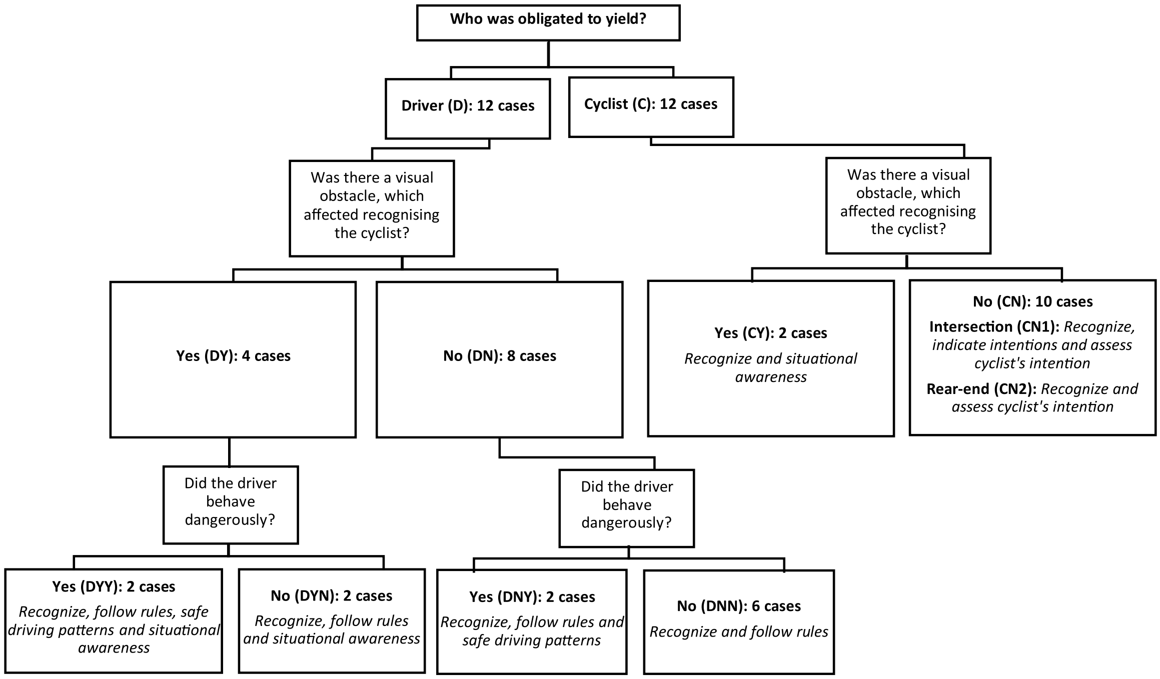

Fig. 1. The questions, which were considered in evaluating crash avoidance possibilities and different HAV features. Code in the parenthesis (e.g. DYY) represents different crash types between driver-managed cars and cyclists, and the italic text presents the features, which the HAV should possess to be able to avoid the crash.

from the cycle path (e.g., passes the trigger point), but it is not sure whether the HAV is able to anticipate that the approaching cyclist is going to cross the street, before the cyclist passes the trigger point. The TTC analysis is not applied when the driver broke the law (e.g., passed the traffic island from the wrong side), because the HAV is assumed to obey the law and it would enable avoiding these crashes.

3. Results

3.1. Crashes in cycle crossings and at intersections

The analysed 17 cycle crossing or intersection crashes typically occurred as the car driver, the cyclist or both of them were not able to recognize the other involved party before the collision. This led to the situation, in which the road user, who would be obliged to give way, did not yield. In some of the studied crashes, the driver or the cyclist assumed the other road user would yield. The studied cycle crossing and intersection crashes could be divided to two groups based on the priority rules. In seven crashes, the driver had the obligation to yield and in ten crashes, the cyclist had the obligation to yield. When the passenger car was obliged to yield, features 1, 2, and 4 would be essential for crash avoidance. In the other cases, when the cyclist was obliged to yield, the range of needed features is wider (Table 1). Impact speeds of the cars varied from 12 km/h to 50 km/h in the studied crashes.

Table 1
Fatal cycling crashes in cycle crossings and at intersections, and HAV's features, which would be needed to avoid the crashes. TTC is not applied (NA), when the driver had broken the law as is depicted in section 2.3.

Code for the case as presented in Fig. 1	Amount of crashes and time-to-collision (TTC) values	Crash description	Visual obstacle	Driver's dangerous behaviour (excluding priority rules)	Road user obligated to yield according to priority rules	HAV's features needed for crash avoidance
DYY	1 TTC = NA	The car hit a cyclist when driving straight through and passing another car, which had stopped in front of cycle crossing.	Another car	Yes	Driver	1; 2; 4
DYY	1 TTC = NA	The car turned and passed the traffic island from the wrong side and hit a cyclist.	Another car	Yes	Driver	1; 2; 4
DYN	2 TTC = 1.0–4.0 s	The car turned and hit a cyclist. The driver did not recognize the cyclist.	Another car/ environment	No	Driver	1; 2; 4
DNN	3 TTC = 0.5–1.5 s	The car was exiting a roundabout or turned at intersection and hit a cyclist. The driver did not recognize the cyclist.	None	No	Driver	1; 2
CN1	8 TTC = 0.5–2.5 s in six cases and 2.0–6.0 s in two cases	The car drove straight and hit a cyclist. The driver and/or the cyclist did not recognize the danger, or the driver assumed the cyclist to yield.	None	No	Cyclist	1; 3; 5
CY	2 TTC = 0.5–1.0 s in one case and 6.0 s in one case	The car drove straight and hit a cyclist. The driver did not recognize the cyclist.	Environment	No	Cyclist	1; 4

3.2. Other cycling crashes

In addition to the 17 analysed cycle crossing and intersection crashes discussed in section 3.1, there were seven other crashes between cyclists and passenger cars in the dataset. The crashes presented in Table 2 had occurred, when a car and a cyclist were going to same direction and the car hit the cyclist (5 crashes), or when the cyclist crossed the lane without using a cycle crossing and was hit by a car (2 crashes). Impact speeds of the cars varied from 30 km/h to 50 km/h in four cases and from 60 km/h to 80 km/h in three cases.

3.3. Summary on the needed features

To summarise the analysis presented in sections 3.1 and 3.2, the most important feature to allow crash avoidance was feature 1 (recognize), which relates to all 24 studied crashes, and can thus be characterised as a basic feature. Feature 2 (follow rules) is an essential requirement in all 12 cases, in which the driver had an obligation to yield. In addition, features 3, 4 and 5 were recognized necessary in eight, eight, and ten crashes, respectively. Cases with cyclist's obligation to yield at intersections (CN1) and cases with driver's obligation to yield without a visual obstacle or the driver's clear risky behaviour (DNN) cover more than half of the cases (14 crashes). Due to difference in the obligation to yield, the cases vary greatly from the perspective of required features in the HAV's operation.

4. Discussion

4.1. Crashes in cycle crossings and at intersections

In order that HAV can take evasive action in potential conflicts with the cyclists, the realization of feature 1 is required. Another basis for HAV's safe operation and crash avoidance is the feature to obey priority rules (feature 2). If there is additionally a visual obstacle, which may delay recognizing the cyclist when turning at an intersection, the HAV should anticipate taking evasive action in case the cyclist comes out behind an obstacle (feature 4). In cases, in which the driver had broken the law, the HAV would avoid the crashes by following the rules and maintaining safe driving patterns. With this feature, the HAV would not pass a stopped car in front of the cycle crossing without stopping first, neither would the HAV pass a traffic island from the wrong side as had happened in one crash. If formal traffic rules are obeyed, an obstacle (e.g., a stopped car) blocking recognizing the cyclist would not be a problem for HAV's safe operation and crash avoidance. According to the Finnish law (Finlex, 2018), road users should anticipate other road users' actions to avoid conflicts and collisions.

The crashes, when the cyclist did not yield to the car even though being obliged, are more demanding to be avoided by an HAV. It is important that the HAV recognizes the approaching cyclist (feature 1), but it should additionally be able to assess cyclist's intentions (feature 5), i.e., whether the approaching cyclist will cross the street or stop prior to crossing and yield to the car. To anticipate potential conflicts related to cyclists' surprising manoeuvres and cyclists not yielding, the HAV should choose a safe speed. As it may be impossible to reliably assess cyclist's intentions in every situation, the HAV should decelerate as a precaution in unclear situations (feature 5), e.g., when the cyclist is recognized near the intersection with a possible colliding course. Another solution could be that the HAV would indicate its intentions to the cyclist that it is not going to yield as it has the priority (feature 3). However, at the same time, the HAV should choose a safe speed to prepare for cyclist's surprising actions, if the risk of fatal crashes is strived to be minimized. Additionally, there could be obstacles restricting recognizing the other party early enough and thus preventing assessing the intentions, too. In these circumstances, the HAV should consider the traffic situation and anticipate that cyclists or other road users may come out behind nearby obstacles (feature 4).

4.2. Other cycling crashes

HAV's basic function is the feature of recognizing nearby cyclists on the roadway (feature 1). The HAV should pass the cyclist travelling on the roadway from a distance far enough or slow down if there is not enough space to pass the cyclist safely (feature 2). Unlike some cases in the crash data, the HAV would not hit cyclists intentionally and the HAV should be able to keep the vehicle between the lane markings and avoid drifting outside of an edge line (feature 4). Thus, it should be safe to cycle on road shoulders with HAVs sharing the road.

Crashes, where the cyclist neglected their obligation to yield, are challenging to avoid from the perspective of an HAV. When a cyclist travelling on the roadway moves from the other side of the lane to the other in front of the HAV, the HAV should be able to take evasive action. However, as the cyclist is travelling to the same direction, it may be difficult to assess the cyclist's intention (feature 5) to change lane position, unless the cyclist gives a clear sign. Similarly, the cyclist cannot assess the HAV's intentions by interpreting the HAV's external signals without a rear mirror (not required by law and rarely as an accessory in Finland) unless the cyclist would glance behind or the signal would be e.g., a loud audio signal. To maximise the safety of HAV's operation, all signs, even minor ones, should be recognized to ensure that possible changes in cyclists' position can be anticipated and evasive actions can be taken.

Table 2
Fatal cycling crashes in other road sections than in cycle crossings or at intersections, and HAV's features, which would be needed to avoid the crashes. TTC is not applied (NA), when the driver had broken the law as is depicted in section 2.3.

Code for the case as presented in Fig. 1	Amount of crashes and time-to-collision (TTC) values	Crash description	Visual obstacle	Driver's dangerous behaviour (excluding priority rules)	Road user obligated to yield according to priority rules	HAV's features needed for crash avoidance
DNY	2 TTC = NA	The car drifted outside of the edge line due to driver's decreased alertness and hit the cyclist or the driver hit the cyclist intentionally.	None	Yes	Driver	1; 2; 4
DNN	2 TTC = NA	The car hit a cyclist, who was cycling to the same direction on the side of the roadway. The driver was distracted or a sense of sight was impaired.	None	No	Driver	1; 2
DNN	1 TTC = 4.5 s*	The car hit a cyclist. The driver did not recognize the cyclist, who had fallen of the bicycle.	None	No	Driver	1; 2
CN2	2 TTC = 0.5–2.5 s	Cyclist moved from the other side of the lane to the other. The car hit to the rear of the cyclist.	None	No	Cyclist	1; 5

* TTC analysis is based on a sight distance.

4.3. General discussion

In almost all of the studied fatal crashes, either the driver or the cyclist was not able to recognize the other involved road user, which emphasizes the importance of feature 1 (recognize) for crash avoidance. However, reliable and tireless driving automation does not always guarantee recognizing the cyclist early enough, if the cyclist comes into field of view behind an object (e.g., behind other vehicles or a building) just before the HAV arrives to the possible collision point. Therefore, an important feature of HAV's operation is that it should always maintain safe speed and driving patterns and anticipate that cyclists might approach behind visual obstacles (feature 4). This feature is especially emphasized, when the HAV is obliged to yield to other road users.

Sometimes a cyclist is recognized late and hence, even an HAV may not be able to avoid the collision. To evaluate possibilities for crash avoidance, we also made a TTC analysis. It was found that TTC values were less than 2.0 s in 10–14 (42–58 %) of the analysed crashes depending on the assumed speed of the cyclist. If it is assumed that the HAV would start decelerating after the cyclist is recognized at a trigger point by 6.0 m/s^2, which is the average of deceleration values used in the studies by Grover et al. (2008) and Strandroth et al. (2012), the crash could be avoidable with HAV's speed of 43 km/h or less with TTC of 2.0 s. Considering the crash data and vehicle speeds in the actual crashes, all cases would not be avoidable with this assumption. Consequently, it is important the HAV is able to anticipate cyclists intersecting with the HAV's trajectory before the cyclist passes the trigger point.

One of the most important factors to consider related to crash avoidance analysis is the obligation to yield as it has a great impact on the required features of the HAV. Cases, where the driver has the obligation to yield, are simpler in theory as the HAV should only be able to recognize the cyclist (feature 1) and to obey priority rules (feature 2). However, differences and exceptions in priority rules in various traffic environments complicate a robust and universal implementation of these features. Although recognizing the cyclist and following rules is perhaps the simplest combination of the features, the combination would tackle some of the contemporary key challenges. Currently drivers do not always obey the obligation to yield to cyclists at intersections as the studied crash data and previous studies (e.g., Silvano et al., 2016) indicate. HAV's feature to obey priority rules carefully could make the encounters more predictable for the cyclists.

Related to feature 3, a way to make the encounters with cyclists and other road users more predictable could be an external screen sending text or visual signals (see Ackermann et al., 2019) in front of the HAV. This could help the cyclist to identify, whether the HAV is about to yield or not. The HAV would operate according to priority rules in all circumstances, but an external message could make it easier to anticipate HAV's actions from the perspective of the cyclist. In addition, as informal rules are sometimes followed instead of formal yielding rules, the HAVs should also be able to acknowledge that and communicate with the cyclist to address possible deviant yielding behaviour. A simple light signal could be a suitable solution as it may be difficult to interpret other signals or more complicated messages while cycling. A visual obstacle may also block the view from the cyclist's perspective, and thus it is possible that the cyclist does not see HAV's signal. The realization of feature 3 requires that a universally understandable communication system for these signals is developed.

The analysed crash data and previous studies (e.g., Räsänen et al., 1999) indicate that the cyclists do not always obey their obligation to yield. If the HAVs are designed and programmed to avoid all potential collisions, the cyclist and other road users may change their behaviour to a riskier one. They might e.g., not obey the priority rules as they may assume that the HAV will always give way. HAV's design to maximise safety would also have implications to the traffic flow. If the HAVs should always slow down near cyclists as a precaution, this would cause lots of decelerations. Even if the cyclists' behaviour would not become riskier, some changes in the behaviour are possible compared to encounters with driver-managed cars (Hagenzieker et al., 2020) making the design of HAVs' features more complicated. In addition, when a visual obstacle would be restricting seeing potentially approaching cyclists, the HAV should decelerate as a precaution. Considering the possible high speed of cyclists, the HAV should strongly decelerate in many situations in urban traffic to avoid all thinkable collisions. This would further influence the flow of motor vehicle traffic. In mixed traffic with both driver-managed cars and HAVs, there would be non-uniform practices, which would influence the overall safety and traffic flow outcome.

4.4. Limitations and assumptions

In the analysis, it was assumed that adverse weather conditions or road characteristics would not impact HAV's features, i.e., features were expected to operate in all conditions. Of the 24 analysed crashes, two occurred during rainfall and in one case the road surface was snowy. Four cases occurred in dark conditions. Fourteen of the 24 crashes situated on street network, seven situated on low-volume road network (such as local, connecting and private roads) and three on main roads. For instance, if dark conditions and adverse weather conditions will be obstacles for HAVs' operation, many of the analysed 24 crashes would not be preventable by the HAV.

Of the single features, assessing cyclist's intention (feature 5) may be the most difficult feature to realize in a near future. Intention estimation (e.g., whether a cyclist is about to cross the street or not) made by the HAV may not be reliable enough, as e.g., Botello et al. (2018) and Rasouli and Tsotsos (2019) have discussed regarding the current situation. The reliability of feature 1 (recognize) is the uttermost important to guarantee safe operation. Other features' reliable operation is also needed, but HAVs could compensate possible deficiencies of the other features in unclear situations by slowing down. However, continuous decelerations would eventually influence people's perceptions of the HAVs and hence, developing capabilities to recognize road users' movement and to assess intensions reliably are important tasks for safe automated driving. The features' operational capability should be high-quality, because otherwise the system cannot reliably control the dynamic driving tasks.

The number of the analysed crashes in this study was small, albeit the crash data included all fatal crashes between cyclists and passenger cars in 2014–2016 in Finland. Crashes between cyclists and other vehicles than cars may involve different characteristics and therefore also other features that were recognized in this study may be needed to avoid these. By analysing other crash data sets, additional other features could come up and the relative importance of the features could appear dissimilar. Therefore, further studies should include more analysis of the possible encounters between HAVs and cyclists, and also other types of situation than those, which have led to fatal consequences in current situation with human drivers.

5. Conclusions

The amount of studies related to the interaction between HAVs and cyclists is currently low. This study discloses potentially needed features of HAVs, which would allow safe encounters with cyclists and allow avoiding fatal crashes between cyclists and passenger cars. In order to fulfil the expected safety benefits of HAVs - thinking that HAVs replacing current driver-managed passenger cars would remove the fatal crashes and help to move towards vision zero - also in the encounters with cyclists, the HAVs should have at least the five features discussed in this study. The HAVs should be able to (1) recognize nearby cyclists, (2) be aware of priority rules in various intersections and traffic situations, (3) indicate its intentions to cyclists, (4) maintain safe driving patterns and anticipate the upcoming situations, and (5) assess cyclists' intentions. If all these features are not available, HAV's capabilities for crash avoidance are clearly reduced.

The study increases knowledge on HAVs' features from the perspective of cycling safety. Albeit the number of features (five) recognized in this study is relatively low, the features include various requirements. Implementing these in real world at least in the near future, and especially assessing the intentions (feature 5), will be a great challenge, as well as anticipating future situations (feature 4). All features possess a challenge as cycling and traffic in general are a very complex and take place in varied environments. There is clearly a need to further study the interactions and encounters between cyclists and HAVs, e.g., in real world tests to examine technical requirements and best practices for safe encounters as well as from the perspective of safety and traffic flow. In this study, technical requirements of the five discussed HAV features are not assessed, e.g., what would be required to recognize cyclists in different situations or what should be considered for assessing cyclists' intentions. Therefore, these should be addressed in future studies. It should also be noted that communication systems (e.g., vehicle-to-everything, V2X) were not considered in this study.

Author contributions

Roni Utriainen: Conceptualization, Investigation, Methodology, Project administration, Writing - original draft, Writing - review & editing

Markus Pöllänen: Conceptualization, Methodology, Writing - original draft, Writing - review & editing

Declaration of Competing Interest

The authors declare no conflict of interest.

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