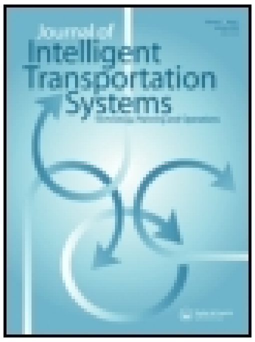

Journal of Intelligent Transportation Systems
Technology, Planning, and Operations

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/gits20

The potential impacts of automated vehicles on pedestrian safety in a four-season country

R. Utriainen

To cite this article: R. Utriainen (2020): The potential impacts of automated vehicles on pedestrian safety in a four-season country, Journal of Intelligent Transportation Systems, DOI: 10.1080/15472450.2020.1845671

To link to this article: https://doi.org/10.1080/15472450.2020.1845671

JOURNAL OF INTELLIGENT TRANSPORTATION SYSTEMS
https://doi.org/10.1080/15472450.2020.1845671

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

The potential impacts of automated vehicles on pedestrian safety in a four-season country

R. Utriainen

Transport Research Centre Verne, Tampere University, Tampere, Finland

ABSTRACT

Automated vehicles (AVs, level 4) are coming on the market in forthcoming years, but it is unsure what is the operational capability of these vehicles in the first place. Especially in four-season countries, winter conditions, such as snowfall and minor amount of daylight hours, increase the operational requirements of AVs. In this study, the potential impacts of AVs on pedestrian safety are evaluated in Finland. The study evaluates which in-depth investigated 40 fatal crashes between pedestrians and driver-managed cars could have been avoided in the best possible situation had the cars been replaced by the AVs. The maximum safety impacts are evaluated in three scenarios. The scenarios are based on the AV's potentially varied abilities to operate in snowy and low-light conditions, and without lane markings. In addition, a time-to-collision analysis was made for each crash. According to the analysis, 28-73% of the pedestrian crashes are avoidable in the different scenarios. In the basic scenario, in which the operational capability of AV (level 4) is limited, solely 28% of the crashes are avoidable. In a full automation scenario (level 5), 73% of the crashes are potentially avoidable. In reality, some drivers would probably like to drive manually instead of automated driving, which would likely reduce the potential safety impacts. This hypothetical scenario is analyzed and discussed. In the countries with varied weather and road conditions, the operational requirements of the AVs are demanding. In order to ensure the maximum safety potential of the AVs in different countries, the AVs should be able to operate in various conditions and environments.

ARTICLE HISTORY
Received 29 September 2019
Accepted 26 October 2020

KEYWORDS
Automated vehicle; pedestrian; safety impact; weather; scenario

Introduction

Automated vehicles (AVs) are said to enhance traffic safety of all road users by eliminating human errors (e.g., Fagnant & Kockelman, 2015). In this study, a term AV is related to SAE. (2018) level 4 and 5 of driving automation. Especially, pedestrians are affected when AVs are introduced, as the pedestrians typically communicate with the driver (e.g., by an eye contact) before making a decision to cross the street (Rodríguez Palmeiro et al., 2018). However, the pedestrians do not typically show a clear message (e.g., a hand gesture) before they are about to cross the street (Dey & Terken, 2017). Because understanding the pedestrian's intention in various situations is probably difficult by an automated driving system, the system should likely be programmed to avoid all collisions. Previous studies on the AVs and the pedestrians have mainly focused on an interaction in the encounters (e.g., Ackermann et al., 2019; Lundgren et al., 2016; Rothenbücher et al., 2016). Very few studies have assessed AVs' potential safety impacts on pedestrians. Combs et al. (2019) estimated that in 36% to 98% of fatal pedestrian crashes in the United States, the pedestrian could have been recognized by sensors and the crash could have been avoided by the features of the AV. The range is depend on the utilized sensor technology (e.g., camera, LiDAR or radar), which are operational in different conditions. For instance, camera sensors are assumed ineffective in low-light and adverse weather conditions. Detwiller and Gabler (2017) evaluated that AVs could prevent 95% of the pedestrian injury crashes in the United States, because a driver violation caused the crash or the pedestrian was visible more than one second before crossing the street. Some other studies have evaluated the safety potential of automatic emergency braking (AEB) systems, which are not fully comparable to operation of AV. For instance, according to Lubbe and Kullgren (2015), 25-26% of road crash casualty costs in car-to-pedestrian injury crashes could be decreased by AEB. The study was based on simulations and test scenarios with pedestrian dummies.

CONTACT R. Utriainen roni.utriainen@tuni.fi Transport Research Centre Verne, Tampere University, Tampere, Finland.

So far a conversation about the safety benefits of AVs has mostly focused on the elimination of driver errors, which is a key factor in terms of accident prevention. However, it is still unsure when the operational capability of the AVs is advanced enough that they are able to operate in adverse weather conditions and are able to interact with other road users, especially with pedestrians and cyclists. It is predicted that AVs may become mainstream by 2040 or 2050 (Litman, 2019). At the initial stage of AVs' implementation, the AVs are probably operating on roads without complex intersections (Combs et al., 2019), when impacts on pedestrians are potentially minor. Before the AVs are capable of operating in various conditions, the role of human drivers is going to remain and there are still possibilities for human errors.

This study aims to evaluate the potential impacts of SAE level 4 and 5 AVs on pedestrian safety in the traffic and weather conditions of Finland, in which four seasons and especially winter conditions make the operation of the AVs more difficult. The Potential safety effects are evaluated as the maximum safety potential, e.g. in the hypothetical best situations in terms of AV's operation. It is considered in the analysis the AV may not be able to operate in various weather conditions in forthcoming years, when first AVs come on the market. It is also considered that some drivers would like to drive themselves despite of a possibility of the automated driving. If the drivers were allowed to bypass the automated driving system, the potential safety benefits would be reduced.

Data and method

The potential safety impacts of AVs (SAE level 4 and 5) on pedestrian safety are evaluated by analyzing in-depth investigated fatal crashes from years 2014–2016 from Finland. The data consist of 40 crashes between pedestrians and driver-managed passenger cars, which are provided by the Finnish Crash Data Institute. The number of pedestrians who were killed in 40 crashes is 41. All fatal pedestrian crashes, in which a passenger car was involved during the years 2014–2016, are included in the study, almost as all fatal crashes are in-depth investigated in Finland. The data include crash descriptions and other characteristics on vehicles, road infrastructure and weather conditions, which are based on the investigations by multidisciplinary crash investigation teams. The investigation of fatal road crashes has been mandated by law in Finland (Finlex, 2016).

It is predicted that AVs (level 4) are coming on the market in a near future, but the first versions of the AVs are probably able to operate only under limited conditions (operational design domain, ODD). Especially, in Finland, winter conditions (e.g., snowfall and snowy road surface) increase the level of difficulty in the operation of AVs. It is possible that the first AVs, which are replacing the conventional passenger cars, are not able to operate in adverse weather conditions. Currently, the visibility of lane markings is a requirement of certain driver assistance systems (e.g., lane keeping assistance) and it may be possible that fully visible lane markings are required for some AVs level 4). In addition, the AV may not be able to assess pedestrians' intention in potential conflict situations (e.g., whether a pedestrian is about to cross a street) due to restrictions in current technology and algorithms (Rasouli & Tsotsos, 2019). If pedestrians' intentions cannot be assessed before the pedestrian is identified in a collision course or stepping on a roadway, a collision avoidance feature can only be activated, when it is evident that a conflict will occur. The lack of anticipation of the automated driving system increases a difficulty to avoid a collision in conflict situations. As the forthcoming future involving the development of the AVs is uncertain, this study considers hypothetically varied ODDs of AVs.

Three different scenarios on the operational capability of AVs are formed and their potential safety impacts are evaluated in this study (Table 1). In the basic scenario (1), the AV (level 4) is not able to operate in adverse conditions and without visible lane markings. In the advanced scenario (2), the AV (level 4) is capable of operating in low-light conditions and without lane markings, but it is not able to operate in adverse weather conditions (e.g. on rain or snowy road surface). In the full automation scenario (3), the AV (level 5) can theoretically operate in various weather and traffic conditions. In addition, each of the three scenarios are divided to two groups: whether the driver cannot bypass the system (A) or the driver is allowed to bypass the system and take the control of the vehicle (B). This hypothetical analysis is based on the assumption that a driver who exceeded a speed limit by 15 km/h or more to reduce travel time would like to take the control of the vehicle from the automated driving system (B). Even though this is a hypothetical estimate on the potential drivers who would potentially like to bypass the automated driving function, the analysis indicates how the potential safety effects would change, if the drivers who clearly exceeded the speed limit were allowed to bypass the

Table 1. Three scenarios on the operational capabilities of AVs and whether a driver has a possibility to bypass the system (A or B).

	1. Basic (Incapable of operating in adverse and dark conditions)		**2. Advanced** (Capable of operating in dark conditions and without lane markings)		**3. Full automation** (Capable of operating in adverse conditions)	
Features of AVs	A	B	A	B	A	B
AV is able to operate:						
-during rain, snowfall, sleet or fog	No	No	No	No	Yes	Yes
-on snowy road surface	No	No	No	No	Yes	Yes
-in dark conditions	No	No	Yes	Yes	Yes	Yes
AV is able to operate without visible lane markings	No	No	Yes	Yes	Yes	Yes
If a driver exceeded a speed limit by 15 km/h or more, the driver would bypass the automated driving system*	No	Yes	No	Yes	No	Yes

*Two options are considered in the case of excessive speed; the driver is allowed to override automated driving system and maintain excessive speed, when the crash is assumed unpreventable (B) or the driver is not allowed to bypass the system, when the crash may be preventable depending on the other conditions (A).

system. In these cases, the safety impacts of the AVs are not realized, because the automated driving technology is overridden. In addition, it is unlikely that a driver assistance system (e.g., automatic emergency braking (AEB) with a pedestrian detection system) would prevent pedestrian crashes in which a car's speed was excessive, because AEB is unlikely able to prevent crashes with vehicle speed of 60 km/h or more (see e.g., Lubbe & Kullgren, 2015; Sander, 2017). Consequently, it is assessed that any driver assistance system would not be able to prevent a crash, in which a driver had bypassed the automated driving technology and exceeded the speed limit by 15 km/h or more.

By using the data on fatal crashes between driver-managed cars and pedestrians in Finland, it is evaluated which fatal crashes could have been prevented had the driver-managed cars been replaced by the AVs. Each 40 crashes are analyzed individually in different scenarios by taking into account variables presented in Table 2. Each variables are outcomes from crash investigations made by the crash investigation teams. For instance, vehicle speed has been estimated based on crash scene investigations, reconstructions and interviews.

Each crash is evaluated potentially preventable in different scenarios, if an AV is able to operate in the road and weather conditions at each crash site. The operational capability of the AV is described in scenarios 1-3. In addition, a time-to-collision (TTC) analysis was made to evaluate a possibility of the AV to avoid a crash by a collision avoidance system. It is assumed the AV would apply the brakes, when a pedestrian stepped to a roadway from a pavement or other area outside the roadway. The AV could potentially have avoided the crash, had the AV had enough time to stop the vehicle prior to a collision. To analyze the crash reduction potential TTC_{AV} (1) and TTC_P (2) were calculated. TTC_{AV} is a time distance between a collision point and a point, in which an AV would recognize the pedestrian stepping to a roadway. TTC_P is a pedestrian's time distance between a collision point and the edge of the roadway.

$$TTC_{AV} = \frac{v_{AV}}{a} \tag{1}$$

TTC_{AV} is calculated by considering vehicle speed (V_{AV}) prior to a collision and an average deceleration value (a) of the collision avoidance system. The deceleration value of 6.0 m/s^2 was used in this study, which is based on the values in the previous studies involving the AEB systems (e.g., Grover et al., 2008; Strandroth et al., 2012; Winner, 2016).

$$TTC_P = \frac{s}{v_P} \tag{2}$$

TTC_P considers (2) a distance that a pedestrian walked between a collision point and an edge of the roadway (s), and an assumed pedestrian speed (V_P). V_P is assumed 1.2 m/s, which is based on the values in previous studies (e.g., Onelcin & Alver, 2017; Rastogi et al., 2011). Finally, TTC_{AV} and TTC_P values are compared to investigate the possibility of the AV to avoid the crash. If TTC_{AV} was shorter than TTC_P, the crash could have been avoided, because the AV had potentially been able to stop the vehicle prior to a collision point. Albeit the TTC analysis indicates that the crash would be preventable, ODDs in scenarios 1-3 are also taken into account. If the AV cannot operate under the prevailing conditions, the crash could not be avoided, albeit TTC_{AV} was shorter. When an AV is

Table 2. Variables and observational units in the analysis. An asterisk (*) involves a condition or a factor, which would prevent an operation of the AV in scenario 1. Factors without the asterisk are considered as normal conditions, in which the AV is able to operate in each scenario.

Variables in the evaluation of scenarios 1-3 (A)				
Weather conditions:	Road conditions:	Lightness:	Visibility of lane markings:	
-Clear	-Dry road surface	-Daylight	Fully visible lane markings	
-Cloudy, dry weather	-Wet road surface	-Dim light	Partially visible lane markings:	
-Drizzle	-Icy road surface	-Dark*	-Partially worn-out markings	
-Rain*	-Snowy road surface*		-Partially covered by dirt	
-Snowfall*	-Other/not available		-Partially covered by snow/ice	
-Sleet*			Invisible lane markings:	
-Fog*			-Fully covered by dirt*	
-Other/not available			-Fully covered by snow/ice*	
			-Lack of lane markings*	
			-Deficient markings*	
Additional variables in the evaluation of scenarios 1-3 (B)				
Estimated vehicle speed:	Speed limit:			
-A continuous variable (km/h)	−30 km/h			
	−40 km/h			
	−50 km/h			
	−60 km/h			
	−70 km/h			
	−80 km/h			
	−100 km/h			
	−120 km/h			
Variables in a TTC analysis				
Estimated vehicle speed:	Width of a road surface:	Number of traffic lanes:	Sight distance:	A collision point:
-A continuous variable (km/h)	-A continuous variable (m)	-A discrete variable	-A continuous variable (m)	-A collision point on the roadway

able to operate, it is assumed the AV would always recognize nearby pedestrians, and the AV would immediately apply the brakes, when the pedestrian steps to a roadway. In calculations, a collision point is assumed to be in the middle of the front part of a car.

It should be noted that an AV could potentially recognize an approaching pedestrian earlier than the pedestrian steps to a roadway. However, it is not considered in this study the AV could anticipate that the pedestrian in a pavement is going to cross the road. In this study, the AV would only apply the brakes, when the pedestrian steps on the roadway.

In cases, in which a pedestrian was standing on the roadway or moving parallel to a roadway, TTC_P as presented in an equation 2 cannot be calculated, because the pedestrian is already on a collision course on the roadway, when an AV could recognize the pedestrian. Instead of a distance (s), a sight distance (s_d) of the AV is used to identify a distance to a collision point. The sight distance is a distance the AV moves between the collision point and a point, when the AV could firstly recognize a pedestrian. The sight distance is used to calculate TTC_P in cases 19, 24, 33 and 34 in Appendix Table A1. In some crashes related to e.g., crashes in parking areas and crashes due to drifting out of a lane, TTC values could not be calculated due to different pre-crash events. It is assumed that the AV could avoid these crashes by normal and safe behavior (e.g., obeying speed limits in drift out of lane cases and recognizing pedestrians nearby the vehicle in parking area crashes). In cases, 25-32 and 36-40 TTC values could not be analyzed.

The data includes 13 crashes on pedestrian crossings, 11 crashes in road areas outside the crossings and 16 uncategorized crashes including crashes e.g., in parking areas or crashes, in which a vehicle drifts out of a lane and hit a pedestrian. In the pedestrian crossing crashes, a driver did not typically observe the pedestrian early enough or at all. In the crashes in other road areas, a pedestrian crossed the road by not using the pedestrian crossing and the driver did not recognize the crossing pedestrian. In total, 11 crashes occurred in dark conditions and seven crashes during snowfall, rainfall or on snowy road surface. In 14 crashes, the lane markings were not visible due to lack of the markings, snow-covered markings or the detrition of the markings. A driver exceeded a speed limit by 15 km/h or more in seven cases.

Results

According to the analysis, 8-11 (20-28%) of 40 fatal pedestrian crashes could potentially have been avoided by level 4 AVs in the basic scenario (Table 3). Advanced AVs (level 4) may have prevented 19-24 (48-60%) and fully automated vehicles (level 5) 22-29 (55-73%) of the crashes. A range is depending on whether the bypass of an automated driving system is allowed in cases in which a driver exceeded a speed

Table 3. The amount and share of potentially preventable crashes in three scenarios and in different locations or crash types. The results are presented by the options whether the bypass of the system is not allowed (A) or is allowed (B).

The amount of potentially preventable crashes:

Scenarios 1-3	A: a driver cannot bypass the system	B: a driver bypasses the system
1. Basic (level 4)	**11 of 40 (28%)**	**8 of 40 (20%)**
-Pedestrian crossing crashes	7 of 13 (54%)	5 of 13 (38%)
-Pedestrian crashes outside the crossing	0 of 11 (0%)	0 of 11 (0%)
-Uncategorized crashes	4 of 16 (25%)	3 of 16 (19%)
2. Advanced (level 4)	**24 of 40 (60%)**	**19 of 40 (48%)**
-Pedestrian crossing crashes	8 of 13 (62%)	5 of 13 (38%)
-Pedestrian crashes outside the crossing	6 of 11 (55%)	6 of 11 (55%)
-Uncategorized crashes	10 of 16 (63%)	8 of 16 (50%)
3. Full automation (level 5)	**29 of 40 (73%)**	**22 of 40 (55%)**
-Pedestrian crossing crashes	10 of 13 (77%)	7 of 13 (54%)
-Pedestrian crashes outside the crossing	7 of 11 (64%)	6 of 11 (55%)
-Uncategorized crashes	12 of 16 (75%)	9 of 16 (56%)

limit by 15 km/h or more. The characteristics of each crashes are presented in Appendix Table A1.

In crashes on pedestrian crossings, low-light conditions in three crashes and snowfall or rainfall in two crashes limited the operational capability and the crash reduction potential in scenarios 1 and 2. In three cases, a difference between TTC_{AV} and TTC_P was negative and hence, crashes were not potentially preventable in any scenarios.

In crashes situated on other road section than on pedestrian crossings, many factors would have an impact on crash avoidance. Six of these crashes occurred on dark conditions, lane markings were not visible in four cases and weather conditions were adverse in three cases. Due to weather and road conditions, any of the aforementioned crashes could not potentially have prevented in scenario 1. In addition, in four cases, a difference between TTC_{AV} and TTC_P was negative.

In uncategorized crashes, deficiencies in lane markings' visibility in eight cases would have an impact on the crash prevention in scenario 1. The deficiencies in the lane markings' visibility were typically due to a lack of the lane markings (e.g., in parking area crashes) or the lane markings were covered by snow or ice. In one case, in which a difference between TTC_{AV} and TTC_P was negative, the crash was not potentially preventable by an AV. In addition, three other crashes (37, 38 and 40 in Appendix Table A1), which are classified as uncategorized crashes, would theoretically remain unpreventable. These three pedestrian crashes consist of one case with a pedestrian's suicidal behavior and two cases in which a parked car started moving without a driver and hit a pedestrian. It is unlikely that these crashes could be avoided by the AV.

The aforementioned results are based on the potential impacts of crash avoidance technology of the AV. In crashes in scenario B, in which it is assumed that a driver would take a control of the car when the driver exceeded a speed limit by 15 km/h or more, the safety potential of the AV would be smaller. In total, in seven crashes the driver could potentially override the system and hence, the safety potential would be lower in all scenarios (1-3).

Discussion

Many car manufacturers and technology companies develop automated driving functions, but it is not sure what will be an operation capability of the SAE level 4 AVs in the first place. Currently, driver assistance systems are becoming widespread, but in these vehicles, human drivers are responsible of the driving tasks. It is unsure whether the first automated vehicles, in which the system is responsible for a driving task, are able to operate in complex traffic situations and adverse weather. Consequently, it is also necessary to evaluate the safety impacts of AVs, which are not able to operate in various weather, traffic and road conditions. Adverse weather conditions are not the only challenge in the development and programming of the AVs. The AVs should also be able to recognize nearby pedestrians and other road users, and assess their intentions in the encounters in order to avoid conflicts. The assessment of the pedestrians' intentions is one of the challenge in the development of a technology (Rasouli & Tsotsos, 2019), which is considered in this study. In the analysis, a crash avoidance technology is assumed to activate, when the pedestrian is recognized on a roadway in a collision course. In this study, an AV is not assumed to apply the brakes, when a pedestrian is walking on a pavement, albeit the pedestrian is going to cross a street, because the anticipation of other road users' movement seems to be a restriction in the current technology development. This study evaluated the possibility of SAE level 4 and 5 AVs to prevent fatal crashes, which have occurred between pedestrians and driver-managed cars.

Level 5 AVs (scenario 3), which are capable of operating in various conditions, could theoretically have prevented 73% of occurred pedestrian crashes in Finland, if the driver-managed vehicles had been replaced by the AVs. However, if the adverse weather conditions, low-light conditions and lane markings' poor visibility (scenario 1) would restrict automated driving, solely 28% of the pedestrian crashes had potentially been avoided. The results emphasize challenges especially in four-season countries, such as in Finland[1], in which snowy conditions and only a few daylight hours in winters should be considered in the operation of AVs. In addition, if the visibility of lane markings will be an essential requirement of the AVs, automated driving will not be possible in many road sections, because about 35% of road network in Finland are gravel paved-roads (Finnish Transport Infrastructure Agency, 2019).

The operational capability (e.g., ODD) of the AVs was one part of the analysis. In addition, a TTC analysis was made in each case. The AV was assumed to apply the brakes, when the pedestrian stepped to a roadway or when the pedestrian was firstly recognized, if the pedestrian was already situated on the roadway. The analysis enabled to evaluate the possibility to prevent a collision by considering an estimated vehicle speed and a distance to a collision point in the actual crash, in which a collision occurred between a pedestrian and a driver-managed car. Some assumptions were made in the analysis, which may have an impact on the crash reduction potential. A velocity of a pedestrian and a deceleration value of an AV was assumed constant, and the values were determined according to previous studies. In some cases, e.g., in winter, a low coefficient of friction may have an impact on stopping distances, but the potential changes in the coefficient of friction (e.g., between icy and dry road conditions) were not considered in the analysis.

In cases, in which a difference between TTC_{AV} and TTC_P was more than zero, a crash was assumed potentially preventable by an AV. In total, in eight crashes, the difference was negative and hence, these cases were evaluated to be unpreventable. However, in four of these crashes crash consequences could potentially have been mitigated, because the difference was -0.5 s or -1.0 s, which would be equal to a collision at impact speed of 11-22 km/h. According to Rosén and Sander (2009), the fatality risk at impact speed of 30 km/h is small. For instance, the risk is more than five times higher at impact speed of 50 km/h than 30 km/h in collisions between a pedestrian and a passenger car. Consequently, a fatal outcome could potentially have been avoided in 33 of 40 (83%) crashes, but the collision could only have been avoided in 29 (73%) crashes in scenario 3. In two cases (#5 and #6 in Table A1), a difference between TTC_{AV} and TTC_P was zero. These cases were categorized as preventable crashes, albeit the avoidance of the crash is not sure due to the tight time margin and assumptions made in the analysis. However, it is likely that fatal consequences could be avoided, because the impact speed would be low, if the collision would occur in these two cases.

According to results, the operational capability of the AV seems to be an important factor, because a difference between three scenarios is clear in terms of the safety potential. In scenario 1, 28% of crashes could potentially be avoided, but in scenario 3 the crash reduction potential is 73%. The AVs should not be developed to follow lane markings, because a poor visibility of the markings was a typical restriction in crashes outside the pedestrian crossings and in uncategorized crashes. A positioning of the vehicle should be based on digital lane markings and high definition maps (see e.g., Kühn et al., 2017), which would diminish restrictions related to road infrastructure and conditions. In addition, in four-season countries, snowy and low-light conditions are more common than in other countries, which causes further requirements for the operation of AVs, because the vehicles should also be able to operate under adverse conditions. In 16 of 40 crashes, weather conditions were adverse or lightness was low, which emphasize the typical conditions of Finland and other four-season countries.

According to this study and previous studies, fully automated vehicles (level 5) with 100% penetration in car fleet would have a significant impact on the amount of pedestrian crashes. However, the situation, in which all vehicles would be fully automated, may not be a likely future. Albeit the automated driving would be available, some people may still choose to drive by themselves, if the manual driving is not prohibited. If some drivers and especially those drivers, which have broken the law by e.g., exceeding the speed limit, would choose to drive manually, the potential safety impacts would clearly be reduced in each of the three scenarios discussed in this study. It is unclear, which people would like to drive manually, but some people may want to drive without automated driving technology. This study discusses one hypothetical case, in which a driver would potentially choose a manual driving mode instead of automated driving mode, and indicates the potentially reduced safety impacts compared to cases, in which the driver is not allowed to bypass the technology. The analysis indicates clearly reduced safety potential, if drivers, who exceeded the speed limit by 15 km/h or more, would always bypass the system. It is important to design a possibility to override the automated driving system carefully.

There are some limitations in this study to discuss. Results can be considered as the maximum safety potential, because it was assumed that AVs are able to recognize nearby pedestrians and operate without errors in different traffic situations, if the operational capability related to different scenarios allowed to operate in certain conditions. In reality, error-free operation may be too difficult to achieve. Errors could increase the number of crashes. Especially, the operation in adverse weather conditions is likely more difficult, which may increase the possibility of the error and the crash. In addition, an interaction between a pedestrian and a driver will change, because the driver is no longer responsible for the driving task in AVs. Changes in the interaction will probably cause conflicts and hence, an AV should always be able stop the vehicle in these encounters. It is important to consider that a crash avoidance action of the AV could increase a risk of a rear-end crash due to an emergency braking or a sideswipe collision due to a swerve. These crashes due to an evasive action were not considered in this study, because the focus is on the pedestrian safety. Albeit the crash data include almost all fatal crashes between pedestrians and passenger cars, the number of analyzed crashes is relatively small. Results on the safety potential could be different in other countries. However, this study also indicates potential differences in the safety potential, when an operational capability is limited, e.g., an AV is not able to operate in adverse weather conditions. It is also necessary to investigate the potential safety impacts in a four-season country, in which weather conditions are more challenging compared to many other countries. Because the AVs are not common in any part of the world, we do not know the details of the automated driving technology. Consequently, larger data set related to crashes of driver-managed cars and pedestrians would not necessary provide much better outlook on the potential safety effects.

Conclusions

The safety of vulnerable road users, such as pedestrians and cyclists, should receive more attention in the discussions about the potential safety impacts of AVs. Similarly, it is essential to take into account that not all vehicles will be equipped with automated driving systems in forthcoming years and some drivers would still like to drive a car in spite of the AVs. It does not seem to be a likely outcome that most of the vehicles will be in an automated driving mode in a near future. Consequently, the behavior of the drivers and human errors remain as key areas in traffic safety research. It should be acknowledged that new technology and driver assistance systems, such as automatic emergency braking systems, enhance pedestrian safety before AVs (level 4) become more common.

In countries with varied weather and road conditions, automated driving may not become mainstream similarly and as quickly as in countries with mostly summery weather conditions. This may even delay the development of transportation systems, if new mobility services, such as automated taxis and shuttle buses, are not able to operate in some countries or in some seasons. Delay in the introduction of the AVs would also mean unequal progress in traffic safety between different countries. If large car manufacturers and technology companies do not focus on developing AVs, which are capable of operating in various conditions, smaller companies and authorities from countries with challenging conditions should allocate their resources to the development of AVs, which are able to operate in various conditions.

Notes

1. Winter lasts about 100 days in Southern Finland and 200 days in Northern Finland. Here winter is defined as a period, when the mean temperature remains below 0 °C in almost every day. In northern part of Finland, the sun does not rise above the horizon during 51 days in winter. In Southern Finland, the shortest day lasts about six hours. (Finnish Meteorological Institute, 2019)

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

R. Utriainen http://orcid.org/0000-0002-2466-9660

References

Ackermann, C., Beggiato, M., Schubert, S., & Krems, J. F. (2019). An experimental study to investigate design and assessment criteria: What is important for communication between pedestrians and automated vehicles? *Applied Ergonomics*, *75*, 272–282. https://doi.org/10.1016/j.apergo.2018.11.002

Combs, T. S., Sandt, L. S., Clamann, M. P., & McDonald, N. C. (2019). Automated vehicles and pedestrian safety: Exploring the promise and limits of pedestrian detection. *American Journal of Preventive Medicine*, *56*(1), 1–7. https://doi.org/10.1016/j.amepre.2018.06.024

Detwiller, M., & Gabler, H. C. (2017). *Potential reduction in pedestrian collisions with an autonomous vehicle* [Paper presentation]. 25th International Technical Conference on the Enhanced Safety of Vehicles, Detroit, MI.

Dey, D., & Terken, J. (2017, September). *Pedestrian interaction with vehicles: Roles of explicit and implicit communication* [Paper presentation]. International Conference of Automotive User Interfaces and Interactive Vehicular Applications (pp. 109–113). Oldenburg, Germany.

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transportation Research Part A*, *77*, 167–181.

Finlex. (2016). *Law on investigations of road and off-road accidents (Laki tie- ja maastoliikenneonnettomuuksien tutkinnasta)*. http://www.finlex.fi/fi/laki/smur/2001/20010024

Finnish Meteorological Institute. (2019). *Seasons in Finland*. https://en.ilmatieteenlaitos.fi/seasons-in-finland

Finnish Transport Infrastructure Agency. (2019). *Road network*. https://vayla.fi/web/en/road-network#.XYxm3WNS_DA

Grover, C., Knight, I., Okoro, F., Simmons, I., Gouper, G., Massie, P., & Smith, B. (2008). *Automated emergency brake systems: Technical requirement, costs and benefits*. TRL Limited. PPR 27.

Kühn, W., Müller, M., & Höppner, T. (2017). Road data as prior knowledge for highly automated driving. *Transportation Research Procedia*, *27*, 222–229. https://doi.org/10.1016/j.trpro.2017.12.011

Litman, T. (2019). *Autonomous vehicle implementation predictions. Implications for transport planning*. Victoria Transport Policy Institute.

Lubbe, N., & Kullgren, A. (2015). *Assessment of integrated pedestrian protection systems with forward collision warning and automated emergency braking* [Paper presentation]. IRCOBI Conference 2015. IRC-15-51.

Lundgren, V. M., Habibovic, A., Andersson, J., Lagström, T., Nilsson, M., Sirkka, A., Fagerlönn, J., Fredriksson, R., Edgren, C., Krupenia, S., & Saluäär, D. (2016). Will there be new communication needs when introducing automated vehicles to the urban context. *Advances in Human Aspects of Transportation*, *484*, 485–497.

Onelcin, P., & Alver, Y. (2017). The crossing speed and safety margin of pedestrians at signalized intersections. *Transportation Research Procedia*, *22*, 3–12. https://doi.org/10.1016/j.trpro.2017.03.002

Rasouli, A., & Tsotsos, J. K. (2019). Autonomous vehicles that interact with pedestrians: A survey of theory and practice. *IEEE Transactions on Intelligent Transportation Systems*, *99*, 1–19.

Rastogi, R., Thaniarasu, I., & Chandra, S. (2011). Design Implications of Walking Speed for Pedestrian Facilities. *Journal of Transportation Engineering*, *137*(10), 687–696. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000251

Rodríguez Palmeiro, A., van der Kint, S., Vissers, L., Farah, H., de Winter, J. C. F., & Hagenzieker, M. (2018). Interaction between pedestrians and automated vehicles: A wizard of oz experiment. *Transportation Research Part F: Traffic Psychology and Behaviour*, *58*, 1005–1020. https://doi.org/10.1016/j.trf.2018.07.020

Rosén, E., & Sander, U. (2009). Pedestrian fatality risk as a function of car impact speed. *Accident Analysis and Prevention*, *41*(3), 536–542.

Rothenbücher, D., Li, J., Sirkin, D., Mok, B., & Ju, W. (2016). *Ghost driver: A field study investigating the interaction between pedestrians and driverless vehicles* [Paper presentation]. 25th IEEE International Symposium on Robot and Human Interactive Communication, Columbia University.

SAE. (2018). *Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles*. J3016.

Sander, U. (2017). Opportunities and limitations for intersection collision intervention-A study of real world 'left turn across path' accidents. *Accident; Analysis and Prevention*, *99*(Pt A), 342–355. https://doi.org/10.1016/j.aap.2016.12.011

Strandroth, J., Rizzi, M., Kullgren, A., & Tingvall, C. (2012). *Head-on collision between passenger cars and heavy goods vehicles: Injury risk functions and benefits of autonomous emergency braking* [Paper presentation]. IRCOBI Conference 2012.

Winner, H. (2016). Fundamentals of collision protection systems. In H. Winner, S. Hakuli, F. Lotz, & C. Singer (Eds.), *Handbook of driver assistance systems* (pp. 1149–1176). Springer.

Appendix

Table A1. The characteristics of individual crashes in one row and hypothetically preventable crashes in different scenarios.

Pedestrian crossing crashes:	Dark conditions	Weather and road conditions	Fully visible lane markings	TTC$_{AV}$	TTC$_{P}$	Is TTC$_{AV}$ shorter than TTC$_{P}$?	Driver's behavior	Preventable crashes by scenarios (A):	Preventable crashes by scenarios (B):
1.		Snowfall		2.0s	5.5s	Yes, 3.5 s		3	3
2.	Yes		No	5.5s	2.0s	No, −3.0 s	Excessive speed	–	–
3.				0.5s	2.0s	Yes, 1.5 s		1,2,3	1,2,3
4.	Yes			2.5s	4.5s	Yes, 2.0 s	Excessive speed	2,3	–
5.				1.5s	1.5s	Yes/No, 0.0 s		1,2,3	1,2,3
6.	Yes	Rainfall		2.0s	2.0s	Yes/No, 0.0 s		3	3
7.				1.5s	1.0s	No, −0.5 s		–	–
8.				2.5s	4.5s	Yes, 2.0 s		1,2,3	1,2,3
9.				2.0s	1.5s	No, −0.5 s		–	–
10.				5,5s	10.0s	Yes, 4.5 s	Excessive speed	1,2,3	–
11.				3.0s	4.5s	Yes, 1.5 s	Excessive speed	1,2,3	–
12.				1.5s	4.5s	Yes, 3.0 s		1,2,3	1,2,3
13				1.5s	2.5s	Yes, 1.0 s		1,2,3	1,2,3
Pedestrian crashes outside the crossing:									
14.	Yes			3.0s	4.5s	Yes, 1.5 s		2,3	2,3
15.	Yes		No	3.5s	4.5s	Yes, 1.0 s		2,3	2,3
16.		Snowy	No	3.0s	4.5s	Yes, 1.5 s	Excessive speed	3	–
17.	Yes		No	3.5s	4.5s	Yes, 1.0 s		2,3	2,3
18.				3.0s	1.5s	No, −1.5 s		–	–
19.			No	1.5s	10.5s	Yes, 9.0 s		2,3	2,3
20.				2.5s	1.5s	No, −1.0 s		–	–
21.	Yes	Snowfall		3.0s	1.5s	No, −1.5 s		–	–
22.	Yes			2.5s	4.5s	Yes, 2.0 s		2,3	2,3
23.		Snowy, snowfall		3.5s	1.5s	No, −2.0 s		–	–
24.	Yes			6.0s	10.0s	Yes, 4.0 s		2,3	2,3
Uncategorized crashes:									
25.		Rainfall	No	–	–	–	Excessive speed	3	–
26.				–	–	–	Excessive speed	1,2,3	–
27.			No	–	–	–		2,3	2,3
28.			No	–	–	–		2,3	2,3
29.			No	–	–	–		2,3	2,3
30.		Snowy	No	–	–	–		3	3
31.			No, Parking area	–	–	–		1,2,3	1,2,3
32.				–	–	–		1,2,3	1,2,3
33.	Yes			3.5s	4.5s	Yes, 1.0 s		2,3	2,3
34.				3.5s	5.0s	Yes, 1.5 s		1,2,3	1,2,3
35.			No	1.5s	0.5s	No, −1.0 s		–	–
36.	Yes		No	–	–	–		2,3	2,3
37. Parked car started moving without driver								–	–
38. Parked car started moving without driver								–	–
39. Driver's suicidal behavior, no lane markings								2,3	–
40. Pedestrian's suicidal behavior								–	–