C-V2X-enabled Use Cases for Powered Two-Wheelers with a Focus on Safety Aspects

5GAA Automotive Association
Technical Report

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Contents

Foreword

This Technical Report has been produced by 5GAA.

The contents of the present document are subject to continuing work within the Working Groups (WG) and may change following formal WG approval. Should the WG modify the contents of the present document, it will be re-released by the WG with an identifying change of the consistent numbering that all WG meeting documents and files should follow (according to 5GAA Rules of Procedure):

x-nnzzzz

1. This numbering system has six logical elements:
   a. x: a single letter corresponding to the working group:
      where x =
      T (Use cases and Technical Requirements)
      A (System Architecture and Solution Development)
      P (Evaluation, Testbed and Pilots)
      S (Standards and Spectrum)
      B (Business Models and Go-To-Market Strategies)

   b. nn: two digits to indicate the year. i.e. ,17,18 19, etc
   c. zzzz: unique number of the document

2. No provision is made for the use of revision numbers. Documents which are a revision of a previous version should indicate the document number of that previous version.

1. Scope

The Connected Motorcycle Consortium (CMC) has developed and published a Basic Specification related to the incorporation of Powered Two-Wheelers (PTW) in Cooperative Intelligent Transport Systems (C-ITS), with the goal of enhancing rider safety. The resulting 'CMC Application Roadmap' indicates C-ITS applications for PTWs in the future. The most important one in terms of safety benefits for motorcycle riders is the so-called 'See and Be Seen by Others" application. In the other two categories, 'Ride with Less Stress' and 'Be Aware of the Unexpected' are more like the equivalent applications in cars. Specifications for cars cannot simply be transferred to PTWs because of the different characteristics, such as vehicle size and dynamics. This means that C-ITS and the applications for cars need to be specially tailored to PTWs. For this reason, CMC has reviewed and published comments on relevant standards/ specifications:

- ETSI EN 302 637-2 V1.4.1 (2019-04) CAM
- ETSI TR 103 562 V2.1.1 (2019-12) CPM
- C2C-CC BSP

5GAA has already conducted important work relating to PTWs, namely through its VRU White Paper published in September 2020. That Paper included key recommendations and challenges that should be addressed in further VRU protection-related activities.

The current Technical Paper has a declared special focus on safety, but it is not limited to that area (e.g., it also addresses comfort and other issues). It includes use cases enabled by external connectivity or sensors (e.g., from roadside infrastructure and/or network, not only V2V-based). It also covers use cases that may profit or be enabled by the presence of an external computing power (a roadside unit (RSU) or a network edge) which presents an attractive potential market even in low V2X penetration. The WI first addresses the use cases with a technologically neutral description in terms of PC5 and Uu connections, then identifies specific solutions enabled by Edge Computing, Mobile Devices and 5G-V2X direct. The scope of the WI initially focuses on motorcycles, then potentially expands to all L category vehicles.

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3. Abbreviations

3.1. Abbreviations

For the purposes of the present document, the following abbreviations apply:

AEB	Autonomous Emergency Braking
AEVW	Approaching Emergency Vehicle Warning
AWW	Adverse Weather Warning
CAM	Cooperative Awareness Message
C-V2X	Cellular Vehicle-to-Everything
C-ITS	Cooperative Intelligent Transport Systems
CMC	Connected Motorcycle Consortium
CPTW	Connected Powered Two-Wheelers
DCW/CSW	Dangerous Curve Warning / Curve Speed Warning
DENM	Decentralised Environmental Notification Message
DNPW	Do Not Pass Warning
EEBL	Electronic Emergency Brake Light
FCW	Forward Collision Warning
GIDAS	German In Depth Accident Study
GIDAS-PCM	Pre-Crash-Matrix
GLOSA	Green Light Optimal Speed Advisory
HLN	Hazardous Location Notification
IMA	Intersection Movement Assist
IVS	In-Vehicle Signage
LCW/BSW	Lane Change Warning / Blind Spot Warning
LMA	Lane Merge Assist
LTA	Left Turn Assist
MAIDS	Motorcycle In-depth Accident Study
M1/N1 vehicle	Passenger car/light commercial vehicle
PKI	Public Key Infrastructure
PTW	Powered Two-Wheeler
RSU	Roadside Unit
RWW	Road Works Warning
SCMS	Security credential management system
SSVW	(Stop) Sign Violation Warning
SVW	Stationary Vehicle Warning
TTC	Time to collision
TJW	Traffic Jam Warning
TLVW	Traffic Light Violation Warning
VRU	Vulnerable Road User
WWD	Wrong Way Driving

4. Background and Objective

4.1. High-Level Crash Statistics, Motorcycle Crashes

Motorcycles are used for a variety of purposes. According to a survey conducted in Europe, the primary use of motorcycles is leisure riding, accounting for 49% of the total. The second most significant use is commuting (30% of the total). Motorcycles have great potential in the future of mobility beyond their predominant use for leisure. They will also have a growing role in commuting due to their greater efficiency in urban traffic as a result of their small size and environmental footprint.

Figure 1: A variety of Powered Two-Wheelers

According to the latest data, when looking at the fatality rate (e.g. Figure 2 from Great Britain), motorcycle riders are more likely to be killed or seriously injured in an accident than other types of road users. The reported number for motorcycle riders' fatality is high and they are therefore typically included in the Vulnerable Road Users (VRU) group along with pedestrians and cyclists. However, motorcycle riders are considered to be a special case of VRU because they share the same roads with cars and travel at similar speeds.

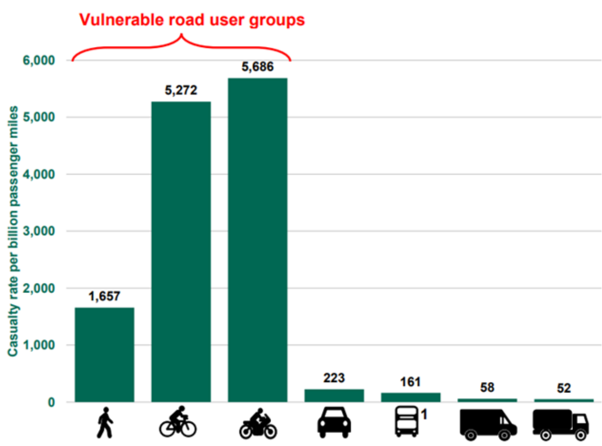


Figure 2: Casualty rate per billion passenger miles by road user type, Great Britain

The main cause of motorcycle accidents is that motorcycles are overlooked by other vehicles. As shown in Table 1, other vehicles are the primary cause of motorcycle accidents in more than 50% of total accidents, according to the study conducted by the European Association of Motorcycle Manufacturers (ACEM). Because of this, it is crucial that drivers of other vehicles pay particular attention to motorcycles.

Table 1: Primary accident contributing factor

Factor	Percentage
Human – other vehicle driver	50.5
Human – motorcycle rider	37.4
Environmental	7.7
Vehicle	0.3
Other failure	4.1
Total	100

Even though motorcycle safety features have been enhanced in recent years, rider fatalities still accounted for 28% of the 1.35 million traffic deaths worldwide in 2016 (see Figure 3). It can be observed that motorcycle category is the highest in the South-East Asia and Western Pacific respectively.

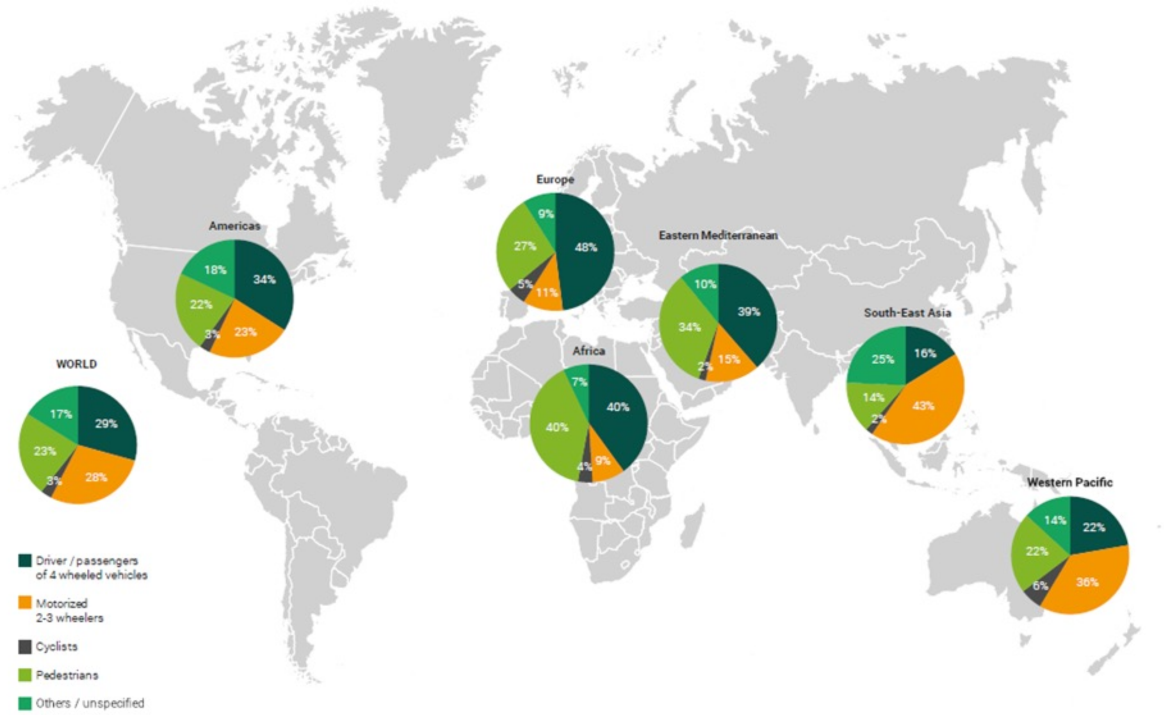


Figure 3: Distribution of deaths by road user type

In the European Union in 2016, the total number of fatalities was 25,651, of which 3,657 were motorcycle riders or more than 14% of the total road fatalities. As shown in Figure 4, the rate of motorcycle rider fatalities had been declining year by year (which could be associated with the adoption of safety solutions by motorcycle manufacturers), however in recent years the rate of decline has slowed down.

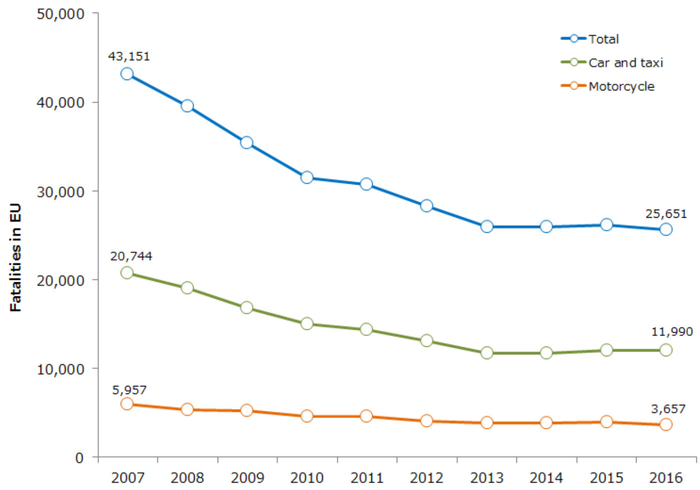


Figure 4: Annual number of fatalities in EU

One conclusion that could be drawn from the data is that the primary cause of accidents involving motorcycles is other road users failing to see them in traffic overlooking them in traffic.

One example of a typical accident scenario is shown in Figure 5. This photograph is taken from the viewpoint of a car. The car is turning left while a motorcycle is approaching from the front, but the car driver is not aware of the presence of the motorcycle. This situation results in a crash. Since motorcycles do not offer the same level of protection to their riders as cars to their occupants, there is a higher risk of serious injury for motorcycle riders than for car drivers. In this situation, the most important role of C-ITS technology is to notify other vehicles of the presence of the motorcycles that drivers can take action to avoid potential crashes.

Figure 5: Difficulty seeing the motorcycle from car-driver's perspective

An in-depth accident analysis has been conducted by CMC based on the GIDAS database and German national accident statistics. The example in Figure 6 shows an analysis of the frequency of each type of accident scenario, separated by accident causer (i.e., either the motorcycle or the other road user).

The outcomes show that in the 'Crossing traffic' scenario, the other road user is most frequently the cause of the accident. Often, the other vehicle driver overlooks the motorcycle rider or misinterprets the speed and/or distance of the motorcycle. In that regard, this situation is similar to the 'Lane change', 'Left turn' and 'U-turn' scenarios with more strict latency requirements.

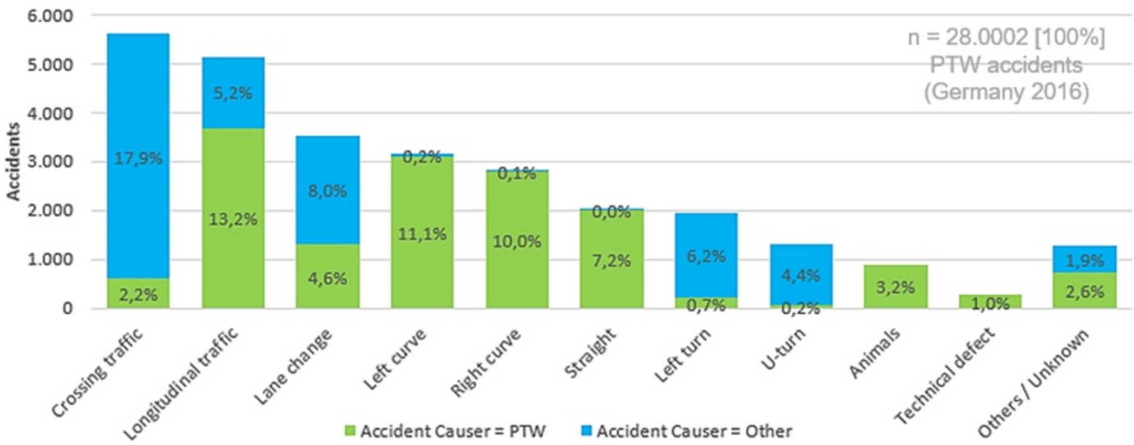


Figure 6: Accident scenario analysis, Germany 2016

4.2. CMC Specifications

The automotive industry is continuously working on active safety features that aim to prevent accidents. C-ITS is an example of a group of safety technologies for cars that also apply to motorcycles. It is a communication technology that allows road vehicles to communicate with each other, with roadside infrastructure and with other road users. These systems are often referred to as Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), or Vehicle-to-Network (V2N) communication. Assuming interoperability with other vehicles is ensured, C-ITS has a high potential to prevent accidents before they occur by proving situational awareness to road users. Motorcycles are often overlooked in traffic and their riders are much more vulnerable than car occupants. Nevertheless, the role of C-ITS for motorcycles has not been well considered in the past.

The safety benefit of C-ITS applications improves as the number of active users and devices increases because these technologies rely on information exchange among road users. Therefore, the penetration of C-ITS technology is a critical factor for road safety. According to the impact assessment of C-ITS conducted by the European Commission, annual deployment is predicted to increase rapidly for new vehicles, aftermarket and infrastructure, as shown in Figure 7. An increase of C-ITS systems in the market is expected to enhance overall road safety.

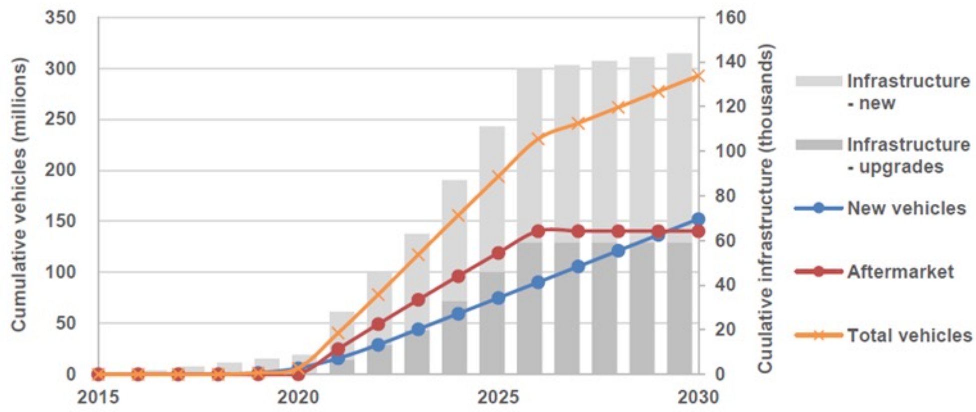


Figure 7: Annual deployment for new vehicles, aftermarket and infrastructure

While C-ITS technology has great potential to improve safety for both cars and motorcycles, specifications for cars cannot simply be transferred or adopted by motorcycles because of the different characteristics, such as vehicle size and dynamics. This means that C-ITS systems and the applications for cars need to be specially tailored to motorcycles. CMC analysis indicates that motorcycle rider safety could be enhanced through the following three categories.

A) See and Be Seen by Others

It is important to make motorcycles visible to drivers of other vehicles, especially cars, to realise and detect the presence of motorcycles in order to avoid accidents. As the accident data indicates, around half of all accidents are caused by a car and can be potentially avoided by detecting motorcycles beforehand.

B) Be Aware of the Unexpected

It is also important for motorcycles to notice and be aware of potential hazards that are unexpected or 'out of the ordinary', so that the rider can take action to prevent them developing into critical situations.

C) Ride with Less Stress

Reducing rider stress levels also has an influence on safety, although its contribution cannot be directly extracted from accident data and requires additional rider state-of-mind analysis and correlation analysis between risky rider behaviour.

CMC has developed specifications of 19 use cases, as listed in Table 2. In this table, each application is classified and mapped to the categories defined in A) B) C) above.

Table 2: List of C-ITS applications for motorcycles

Abbreviation	Application	Category
IMA	Intersection Movement Assist	See and Be Seen by Others
LTA	Left Turn Assist	
LCW/BSW	Lane Change Warning / Blind Spot Warning	
FCW	Forward Collision Warning	
DNPW	Do Not Pass Warning	
EEBL	Electronic Emergency Brake Light	Be Aware of the Unexpected
HLN	Hazardous Location Notification	
AEVW	Approaching Emergency Vehicle Warning	
AWW	Adverse Weather Warning	
RWW	Road Works Warning	
SVW	Stationary Vehicle Warning	
TJW	Traffic Jam Warning	
DCW/CSW	Dangerous Curve Warning / Curve Speed Warning	
WWD	Wrong Way Driving	
SSVW	(Stop) Sign Violation Warning	
TLVW	Traffic Light Violation Warning	
GLOSA	Green Light Optimal Speed Advisory	Ride with Less Stress
IVS	In-Vehicle Signage	
LMA	Lane Merge Assist	

The category 'See and Be Seen by Others' includes applications that inform road users about the presence of a motorcycle by using wireless messages that it transmits. Therefore, it is important for automobile Original Equipment Makers (OEM) to support these applications and cooperate with motorcycle OEMs to realise the application benefits. For certain applications which trigger Decentralised Environmental Notification Messages (DENM), in the category of 'Be Aware of the Unexpected', the triggering conditions are similar to a car, however some modifications are required for motorcycles due to specific characteristics and accommodations necessary with respect to rider reaction times.

One of the use cases (IMA) is shown in Figure 8. In this scenario involving crossing traffic, the car driver is informed of an approaching motorcycle, even when the driver is unable to see it due to poor weather conditions and/or obstructed view by buildings or other objects, including other road users.

Based on a Cooperative Awareness Message (CAM) transmitted by the motorcycle, if the other vehicle detects a possible crossing with the motorcycle, or if the relative distance between the two vehicles decreases below a certain threshold, a notification or warning is shown to the car driver.

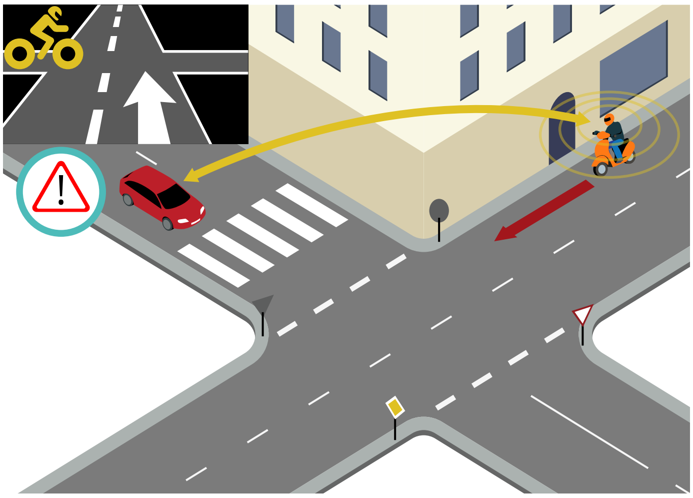


Figure 8: Example use case

Note: It should be taken into account that the introduction of V2X and C-ITS technologies in general, may not necessarily remove all the aforementioned traffic accidents and fatalities because in many cases, multiple factors contribute to an accident. For example, the notion of an impaired driver and/or rider and corresponding accidents cannot be eliminated entirely using C-ITS technologies. However, it is a positive move in that direction.

4.3. Role of Car OEMs

It is important that cars interact with motorcycles through a wireless interface that 'sees through' buildings and objects on the road surface. Specifically, the interoperability between cars and motorcycles is critical to realising the 'See and Be Seen by Others' category. One obvious expectation from car OEMs for motorcycle safety is to transmit CAMs and DENMs, receive safety messages from motorcycles, and notify the driver of the car about the potential danger. An effective human-machine-interface that clearly communicates a motorcycle collision risk would be required for effective mitigation.

4.4. Role of Infrastructure Owners

The role of infrastructure is to transmit any critical information about the road to the vehicles including traffic light signal-phase and timing, and road geometry data. This demand or expectation on infrastructure is higher in the earlier phases of C-ITS adoption, when fewer vehicles support the technology and market penetration is still low – early adopters of the technology would come to rely on information from infrastructure because it stands alone and does not need high numbers of connected road users. Several novel solutions such as infrastructure sensors and computations (e.g., camera, radar) could also be adopted to compensate during the early days of C-ITS deployment (low penetration situations) and enhance the safety in critical locations such as intersections and road crossings.

4.5. Deployment Challenges and Technological Gap

There are several challenges associated with deployment of C-ITS technologies especially during the early days of deployment when fewer connected road users are found on the roadways. One of the biggest challenges is the penetration rate (the implication of this challenge is more severe with direct communication solutions because in the case of Uu, the traditional cellular connectivity, if available, could be leveraged to provide mitigations). The penetration rate or percentage of equipped road users with these technologies could adversely impact the effectiveness of such safety systems, mainly due to lack of connectivity options available for road users to inform each other about their status. This will negatively impact the perception of rider/driver/users about the system, hence lowering trust in the technologies.

Interoperability is another technical challenge as all the road users need to understand each other and implement harmonised protocols to be able to access the over-the-air information. This challenge highlights the importance of technical standards for these applications and use cases as the cooperative nature of the technology demands such harmonisation in the implementation. It is essential that motorcycle manufacturers and car manufacturers work together on creating such technological standards and make sure that the protocols cover all technical needs of the use cases and safety applications.

Another technical challenge is the interface between a motorcycle and handheld devices, especially for pedestrian safety. Today, handheld devices in the market do not support direct communication between the device and other equipped road users. This could result in delayed realisation of pedestrian safety use cases via direct interface. Uu-based communications can be leveraged to satisfy many pedestrian related use cases in the absence of direct interface.

Dedicated interference-free frequencies for C-ITS is another technical challenge. All use cases mentioned depend on interference-free communication in critical moments leading to a potential safety-compromised situation. It is important to maintain the quality of service in those moments as every successful transmission and reception of the information could potentially save lives. Network overload and congestion increase interference and reduce the effectiveness of the safety technology. To accommodate all these use cases and road users, the system needs to have access to additional frequencies beyond a dedicated channel for V2X safety. This highlights the importance of continued conversation and consultation with respected regulators to ensure proper airways for V2X communications.

5. Crash Statistics

This section is dedicated to crash analysis. The detailed study and data analysis provided in this chapter was conducted by CMC.

To pursue the goal improving motorcycle rider safety and comfort, CMC has studied the most frequent PTW accident scenarios mainly in the GIDAS database in which PTWs become the victim of accidents (Figure 9). Out of those accident scenarios, Crossing traffic and Left turn scenarios in which PTWs become the victim are found to add up to 24.1% of the total of PTW accidents. CMC performed a study for Crossing traffic and Left turn accident scenarios, using the GIDAS database and GIDAS-PCM (Pre-Crash-Matrix) as well as a study on Italian and French two-wheeler accidents.

For other accident scenarios in which the PTW becomes the victim, i.e., Longitudinal traffic and Lane change scenarios, these will be the subject of future study. The reason why Left turn is selected prior to other scenarios is that the Left turn accidents are likely to become serious or fatal injury compared to other scenarios.

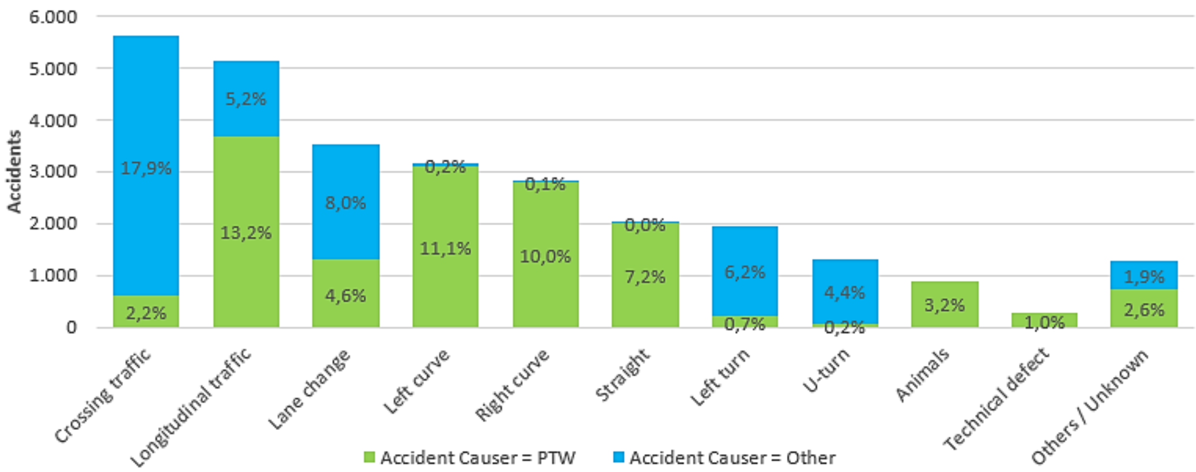


Figure 9: Accident causation in the PTW scenarios

5.1. Scenario Selection Criteria

Within the selected accident types, more precise accident types are observed, as shown in Figure 10 and Figure 11, for Crossing traffic accidents and Left turn accidents, respectively. The decision on which use case to first concentrate on was decided according to the frequency of the specific use case, i.e. accident type 302 for Crossing traffic which counts for 38% (n=2,014) of all Crossing traffic accident types and accident type 211 for Left turn which counts for 91.5% (n=1,568) of all the Left turn traffic accident types.

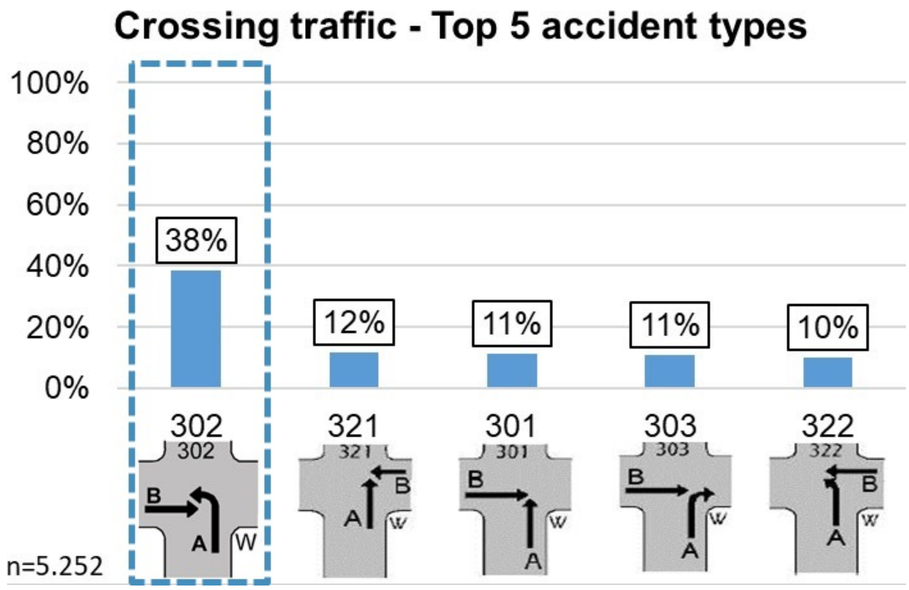


Figure 10: Selection of Crossing traffic accident type

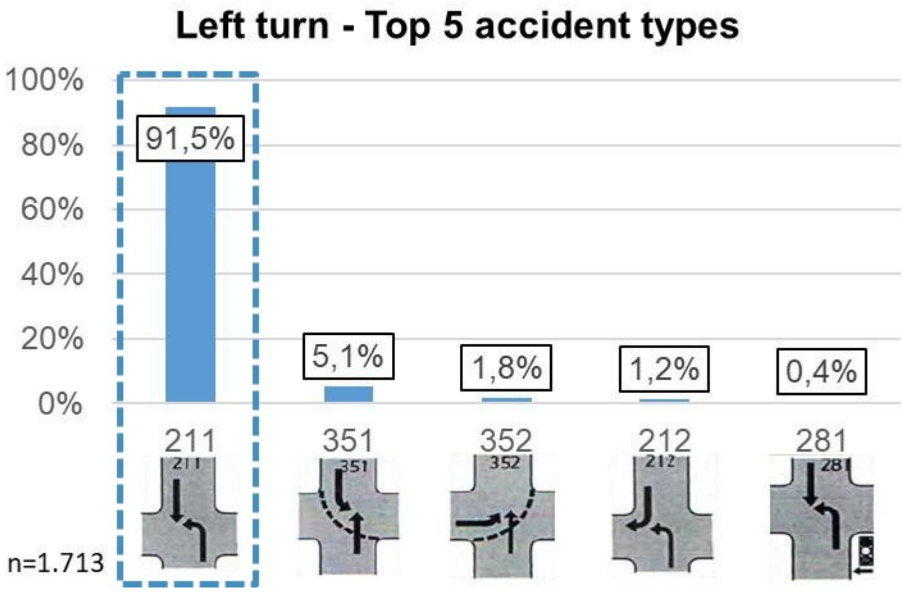


Figure 11: Selection of Left turn accident type

5.2. Cross Traffic Scenario

The Crossing traffic accident type 302 describes a conflict between a left turning road user (Participant A) who is obligated to wait ("W" in the figure), and a road user (Participant B) entitled to the right of way (Figure 12). It does not matter whether the waiting Participant A is obliged to wait by traffic signs (e.g., STOP sign, GIVE WAY sign). The accident type 302 may occur at junctions and crossings of roads, fields or cycle paths, railway crossings as well as property exits or in parking lots.

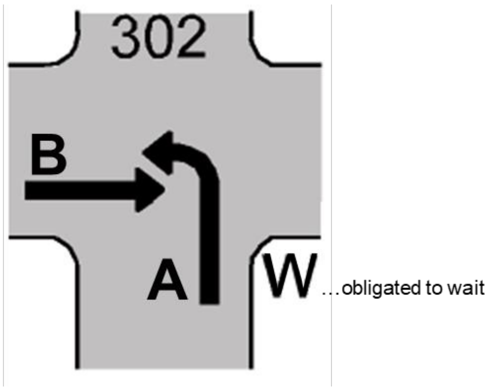


Figure 12: Crossing traffic accident type 302

Findings from the analysis results

- More than 90% of these accidents occur at junctions, crossings or property exits.
- Accidents are caused by M1/N1 vehicles (cars and trucks) in more than 95% of cases and Participant B is a PTW in more than 90% of accidents.
- The speed at collision of Participant A is 5-18km/h, while that of Participant B is 26-47km/h (75%).
- In more than 30% of accidents, there was a View obstruction from Participant A's perspective.
- Weather condition is not a major factor for the accidents.
- The last two manoeuvres before collision indicate that Participant A did not decelerate before collision, but instead, was accelerating in more than 50% of the accidents.
- TTC can be calculated at 4.5 seconds before collision (50%).

5.2.1. Details

a) Location of the accident

The majority of PTW accidents for crossing traffic occurred on urban roads which accounts for 67.3% of overall 302 type (Figure 13). This could be understood from the fact that in an urban area, more traffic participants exist, and more crossing roads exist, all making it more a frequent situation.

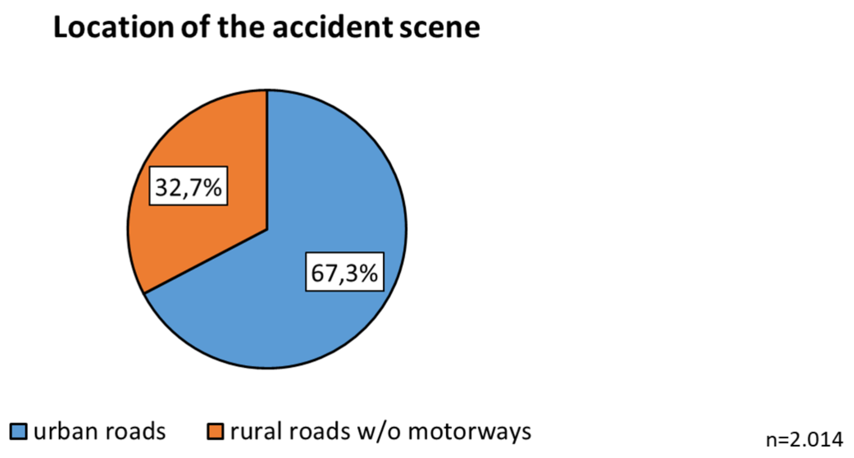


Figure 13: Location of the accident (302)

b) Accident scene

The majority of PTW accidents for Crossing traffic occurred at junctions – 53.2% of overall 302 type (Figure 14). The second most frequent accident scenario (29.5%) is at crossings. Also, accidents where vehicles exit a property account for 16.1%. It is commonly understood that PTWs, being small in size, are often misjudged by car drivers regarding their speed and distance. In the frame of the MAIDS (Motorcycle In-depth Accident Study) project, in-depth analyses of 921 accidents from five sampling areas across Europe involving PTWs were conducted (1). Focusing on the other vehicle involved, traffic-scan error was present and caused accidents in 62.9% of the analysed data. In a further 18.4% of cases, an attention failure including distraction and stress was observed. Therefore, it can be concluded that car drivers find it challenging to properly time their entry into these junctions and crossings.

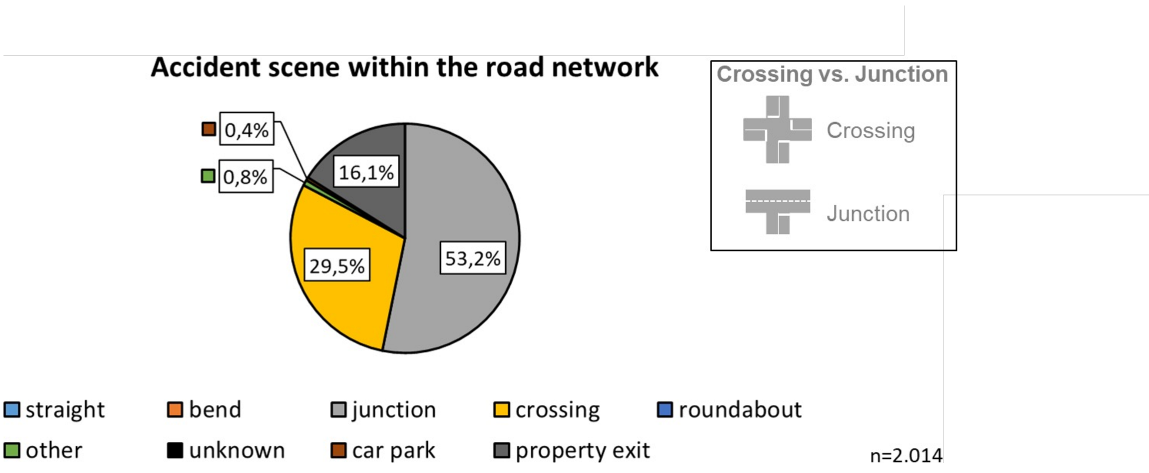


Figure 14: Accident scene (302)

c) Kind of traffic regulation

Right-of-way was cited as the predominant – 73.3% of overall 302 type accidents – traffic regulation at the accident site involving PTWs (Figure 15). Again, the PTW's size is often misjudged and even if Participant A is respecting the right-of-way, Participant A may mistime his/her entry into the junction/crossing.

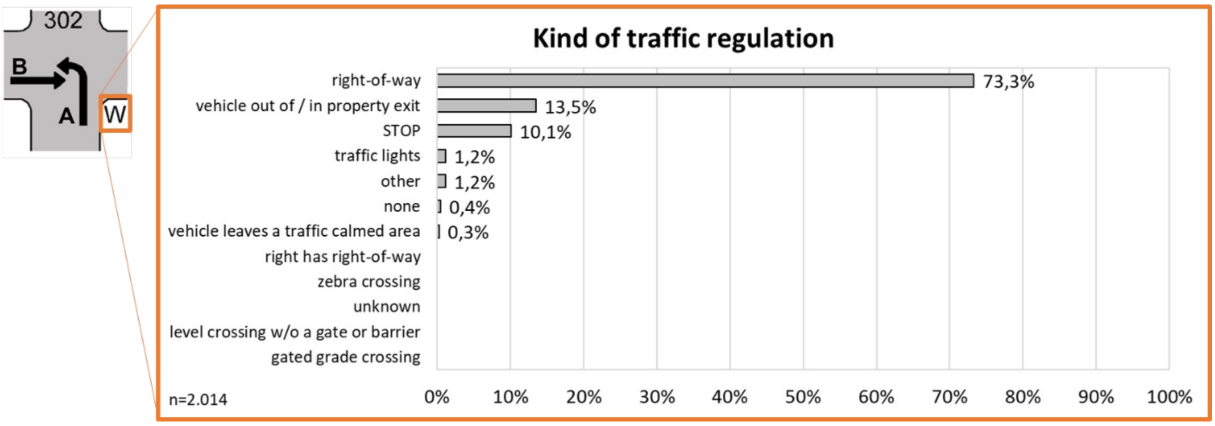


Figure 15: Kind of traffic regulation (302)

d) Kind of road user

Traffic participants in the Crossing traffic accident type 302 involving a PTW are shown in Figure 16. From the figure, it can be seen that in most cases, Participant A is an M1/N1 vehicle and for Participant B, a motorcycle.

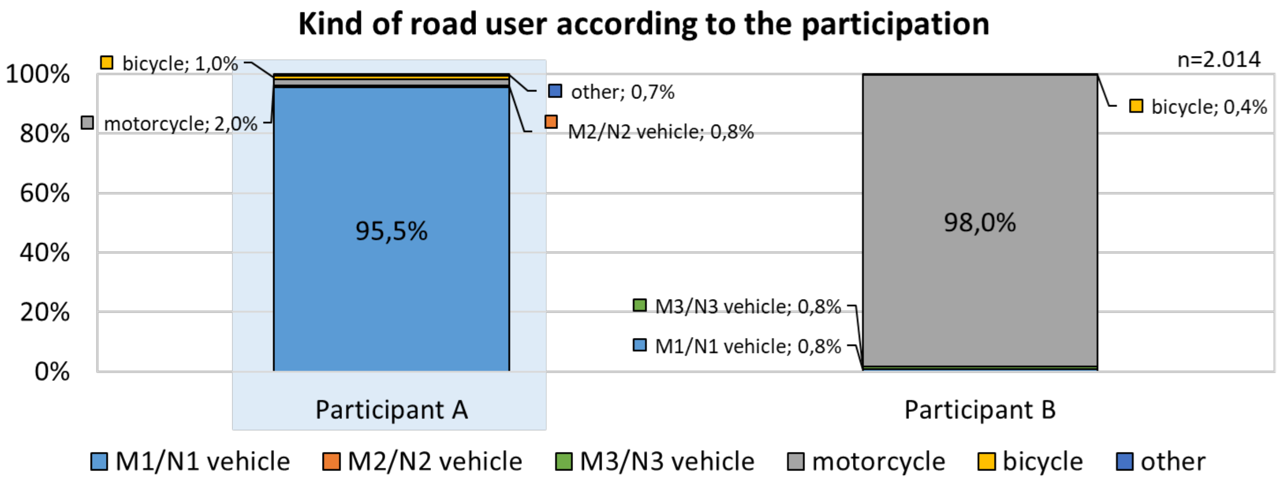


Figure 16: Kind of road user (302)

e) Main accident causer

The main accident causer in Crossing traffic accidents is shown in Figure 17. It is clear from the figure that the predominant cause is Participant A. Figure 17 and Figure 18 indicate that there is a strong need to address car driving behaviour in order to mitigate PTW accidents in Crossing traffic accident situations.

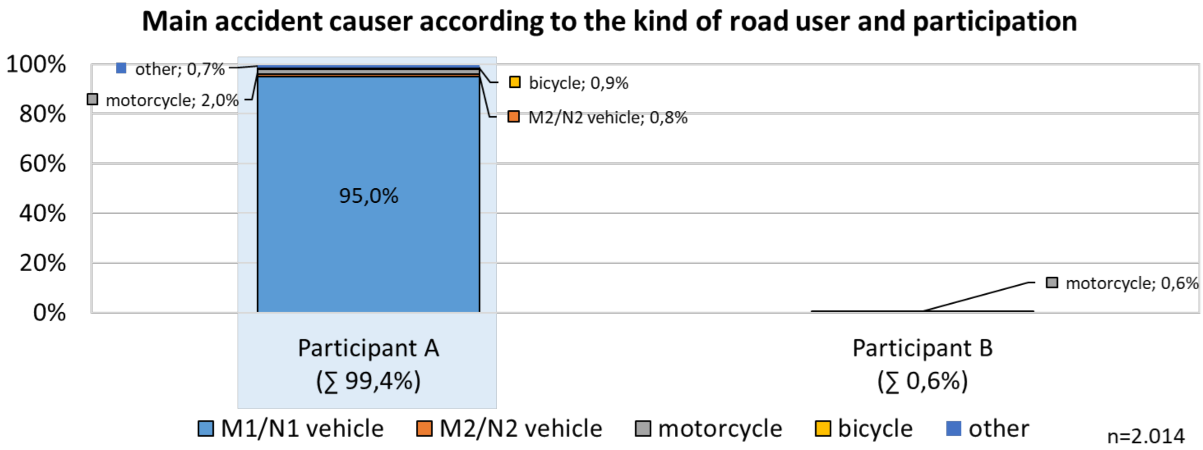


Figure 17: Main accident causer (302)

f) Main accident causation

The causation of the accidents is studied and shown in Figure 18 and Figure 19. From the figures, it is understood that the main reason for the accident was failure of Participant A to respect priority and for Participant B, it was the speed. Please remind that in 99.4% of cases, Participant A was the main accident causer and only in 0.6% of cases, Participant B was the main accident causer.

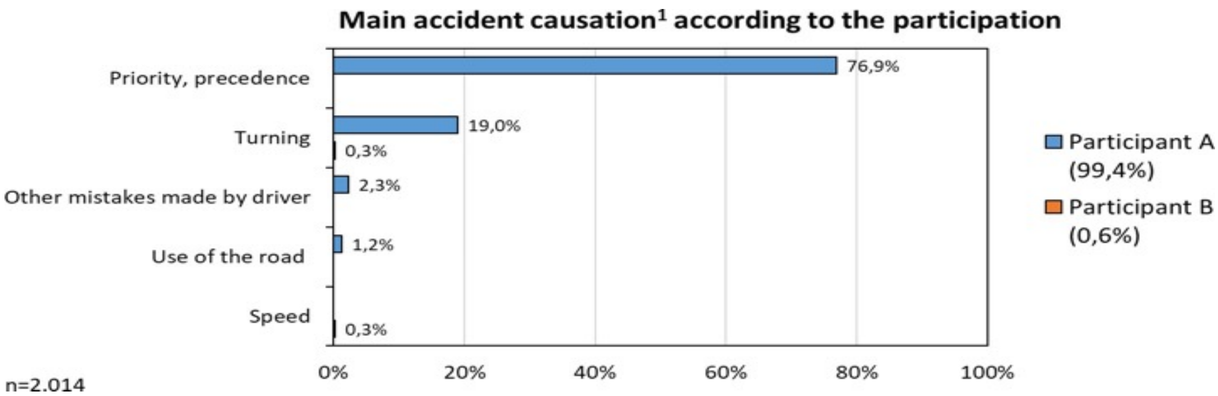


Figure 18: Main accident causation (302)

The police and also the technical investigation units in GIDAS have to assign one main accident causation in each accident (per participant).

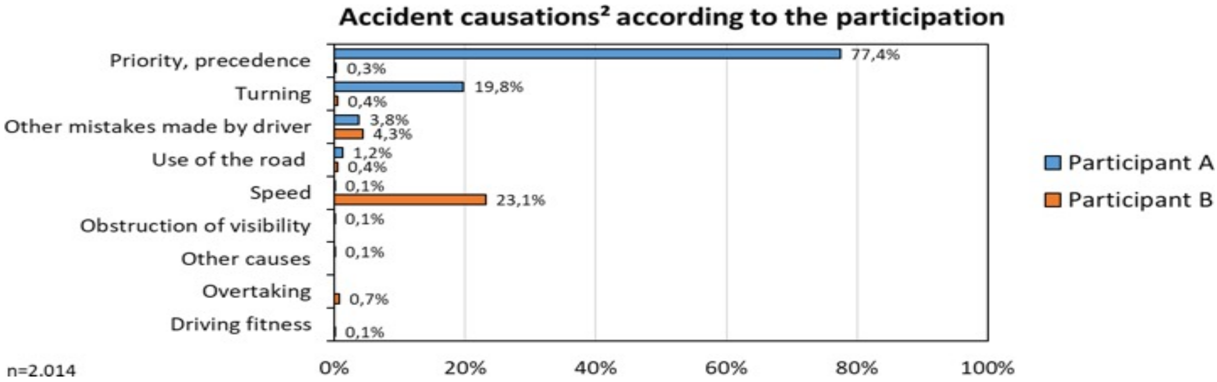


Figure 19: Accident causations (302)

The police and the technical investigation units in GIDAS can assign up to three accident causations for each accident participant. Consequently, one accident can have several accident causes depending on the participant, and so the sum of the accident causations is ≥100%.

g) Types of speed limitation

What or who provides/determines the speed limit for each participant is shown in Figure 20. Both for Participant A and B, the speed limit is mostly determined by local traffic rules, and secondly by traffic signs.

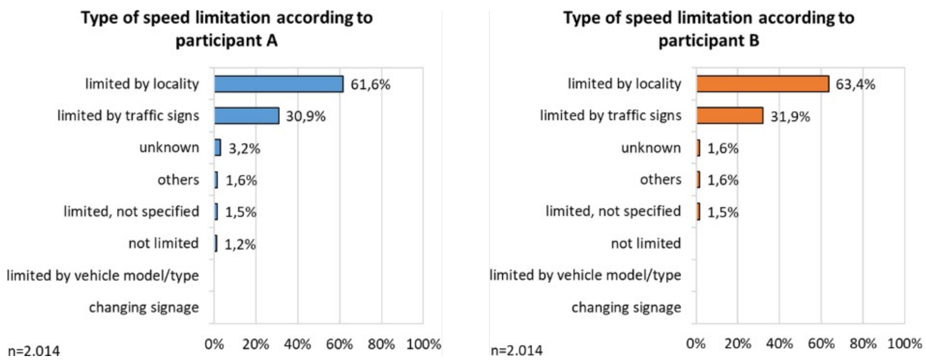


Figure 20: Types of speed limitation for the participants (302)

h) Maximum permitted speed

The maximum permitted speed at the accident site is shown in Figure 21. Two-thirds of accidents take place on urban roads, which is why it is reasonable to assume that the most frequent maximum permitted speed is 50km/h. However, as Participant B has the right of way, a higher maximum permitted speed can be observed with Participant B.

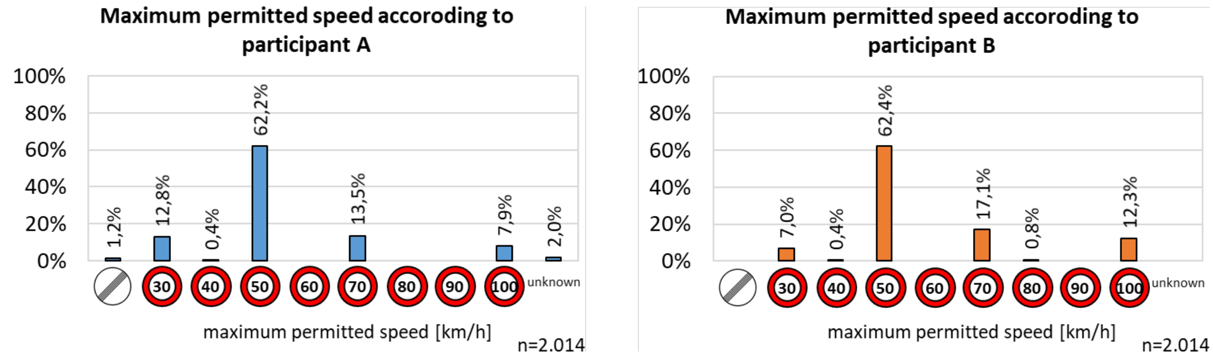


Figure 21: Maximum permitted speed (302)

Speed limit and distribution

Figure 22 shows the percentage of participants exceeding the applicable speed limit. Comparing participants A and B, it can be observed that Participant B is more often seen to have exceeded the speed limit. This could be understood from the Crossing traffic accident type that Participant A starts its action by waiting and then turns while Participant B is going straight/passing through.

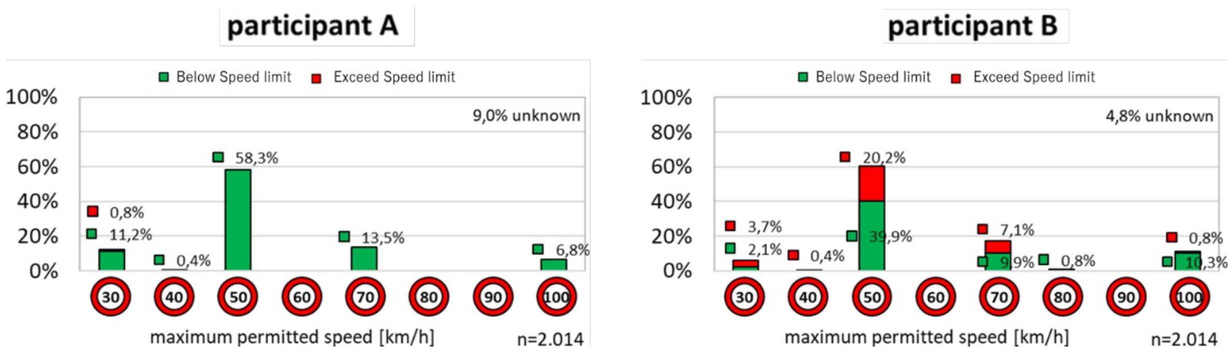


Figure 22: Exceeding Speed limit (302)

Figure 23 shows the distribution of how much Participant B exceeded the allowable speed for each given speed limit before reaching the point of incident. Though Participant B in the Crossing traffic accident scenario has the right of way, in some cases, exceeding the speed limit could be one of the influencing factors for Participant B.

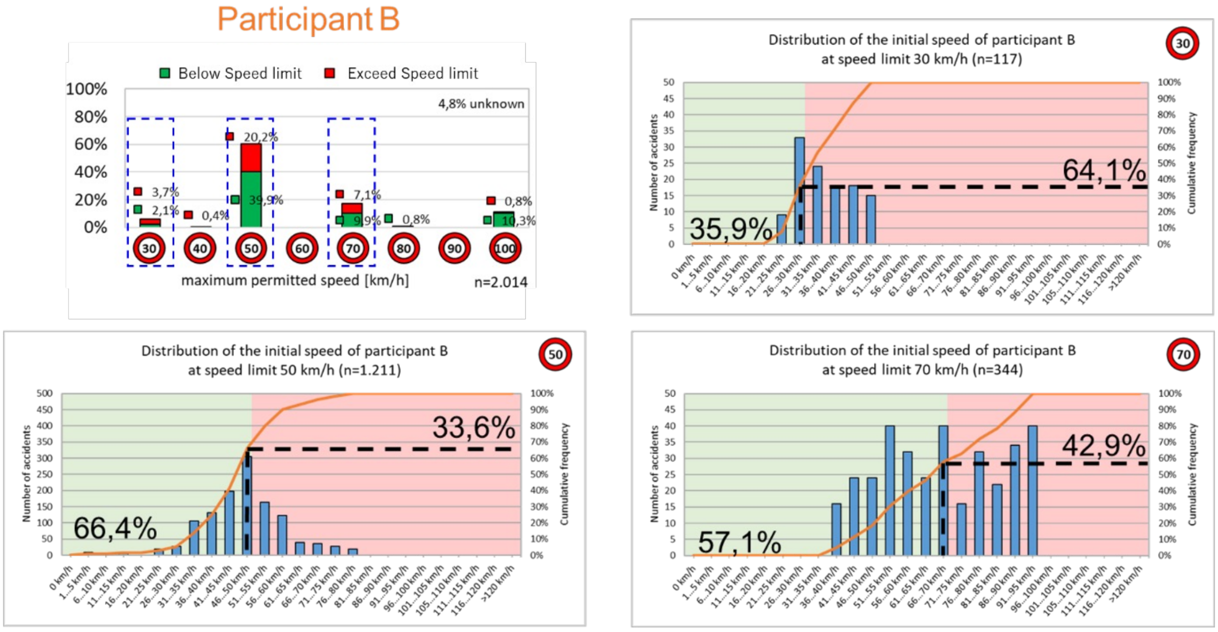


Figure 23: Speed distribution by Participant B (302)

j) Speed before the accident and at the time of collision

Figure 24 shows the initial speed of each participant. It is clear from the figure that Participant B going straight has higher average speed than Participant A who is waiting to start the turning process.

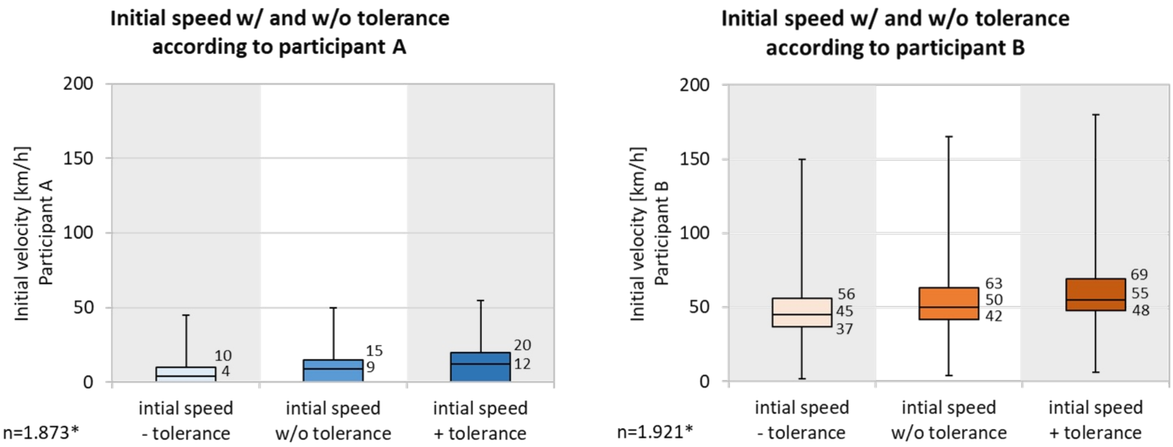


Figure 24: Initial speed of participants (302)

Figure 25 shows the collision speed of each participant. Comparing the initial speed of Participant A in Figure 24 and the collision speed in Figure 25, Participant A is found to slowly start and collide in a few km/h higher speed. This could indicate that Participant A was waiting for a chance to start the process but missed its timing and collided.

Looking at Participant B, comparing the initial speed in Figure 24 and the collision speed in Figure 25, it is seen that it starts from 50km/h initially and decelerates to 38 km/h for the median scenario which could be understood that Participant B has recognised Participant A blocking its way and has decelerated.

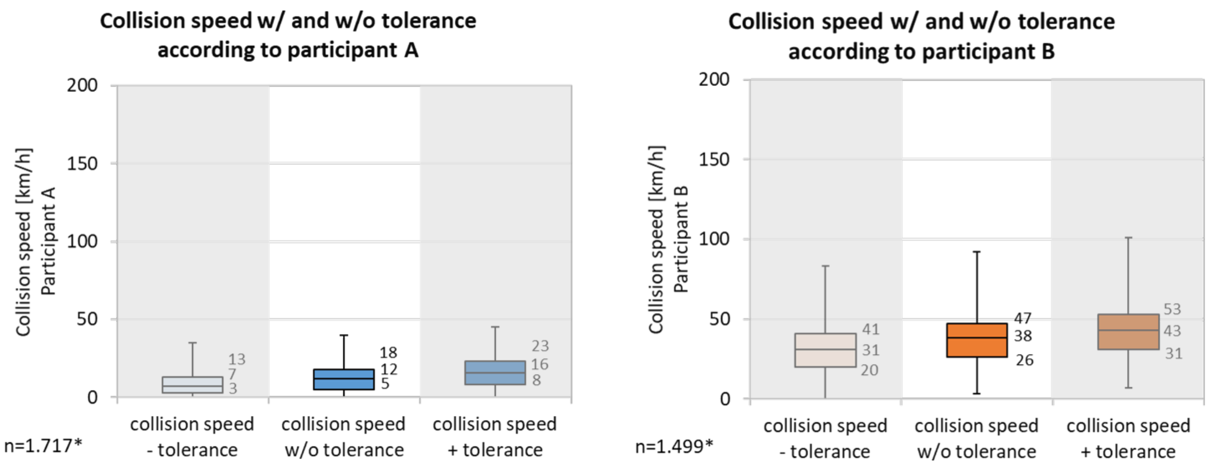


Figure 25: Collision speed of participants (302)

k) View obstruction

Figure 26 and Figure 27 show the existence of View obstructions and the types of obstruction respectively. It can be seen that around 70% of the cases had no View obstructions and the rest had a permanent obstruction, e.g., buildings. Note that moving and parked cars as examples of non-permanent obstruction.

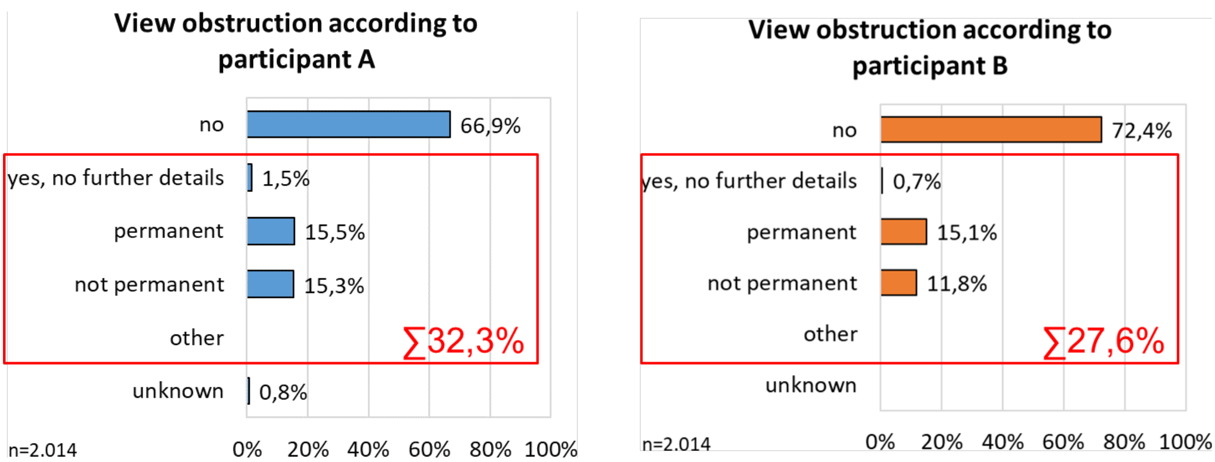


Figure 26: View obstructions (302)

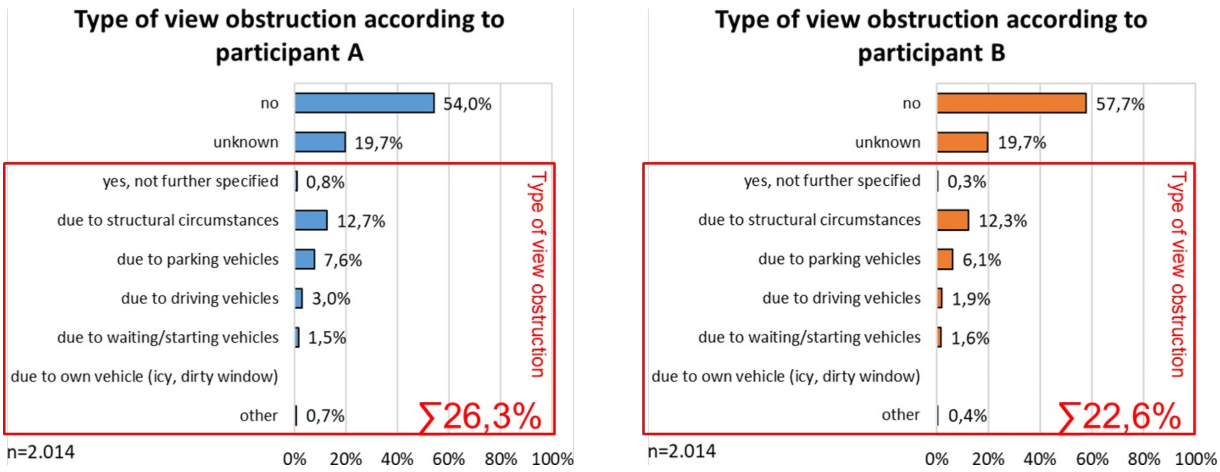


Figure 27: Type of View obstruction (302)

l) Used lane when encountering an accident

Figure 28 shows which lane the participants took when encountering an accident. The majority of this Crossing traffic accident scenario participants were driving along a single lane road.

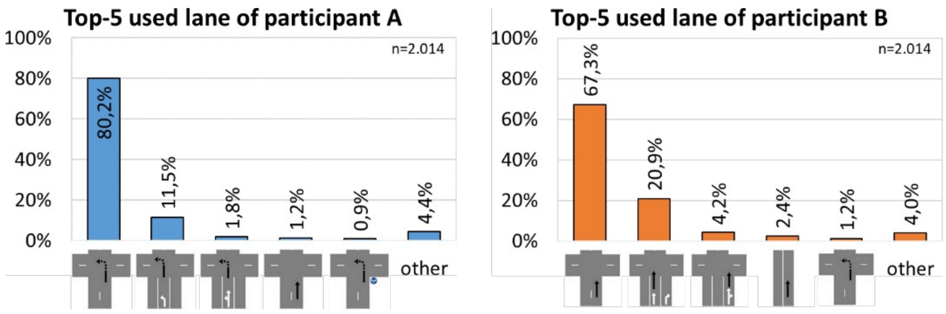


Figure 28: Used lane at an accident (302)

m) Road surface

Figure 29 shows which kind of road surface it was when encountering an accident. The majority of Crossing traffic accident scenario participants were driving on a conventional asphalt road. For Participant A, 12.6% indicated it was a paving/cobble stone road they were driving along before entering the main road.

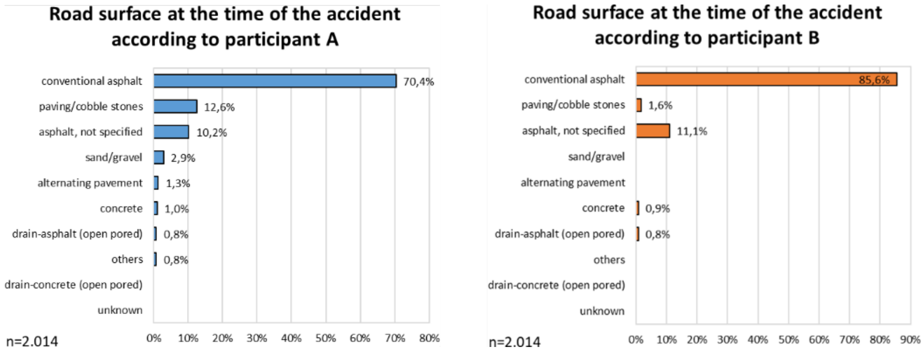


Figure 29: Road surface (302)

n) Precipitation at the time of the accident

Figure 30 shows precipitation at the time of the accident. From the figure, it can be observed that in most accidents it was not raining.

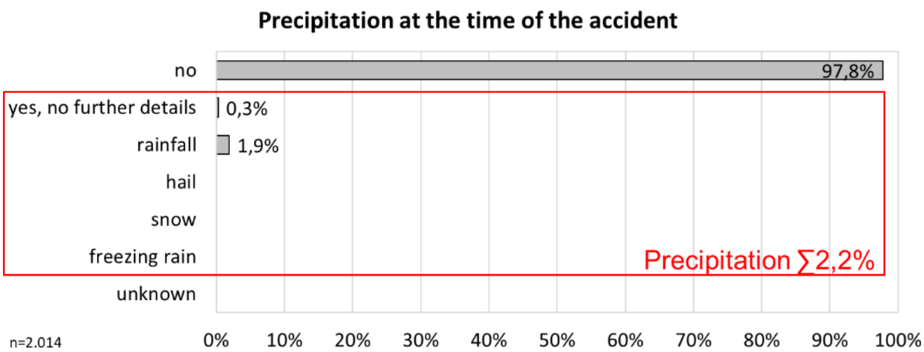


Figure 30: Precipitation (302)

o) Road condition

Figure 31 shows the road condition at the time of the accident. From the figure, it can be observed that in most accidents it was on a dry road surface which would allow full brake performance.

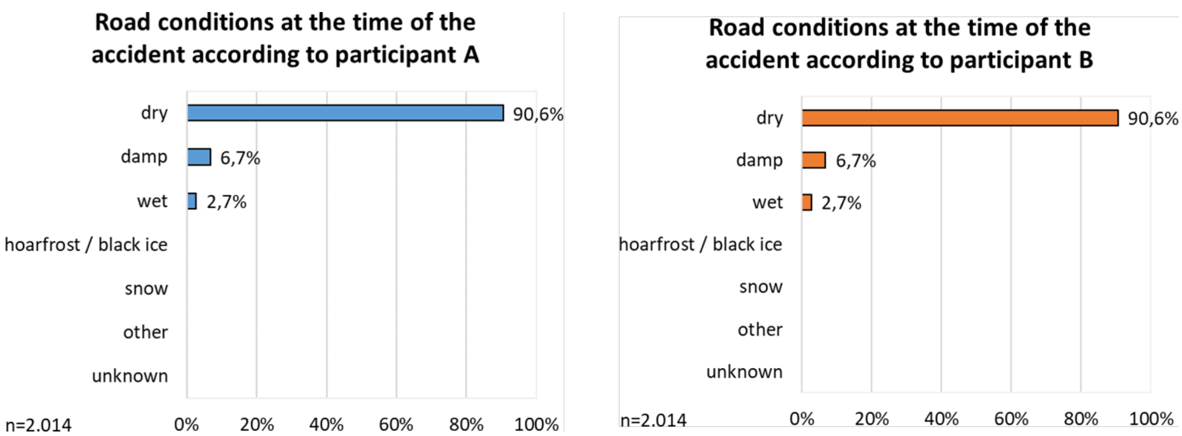


Figure 31: Road condition (302)

p) Cloudiness at the time of the accident

Figure 32 shows cloudiness at the time of the accident. Every fifth accident showed no clouds or only a few clouds in more than 40% of accidents.

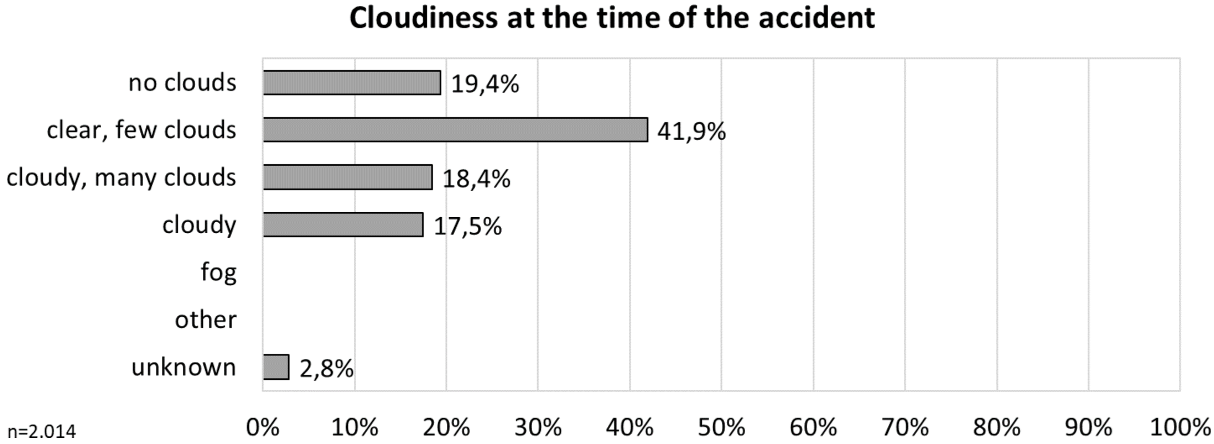


Figure 32: Cloudiness (302)

q) Interview result: visibility/audibility limitation

Figure 33 shows the participant interview results about visibility and audibility limitations. As can be seen in the figure, Participant A reported more often a limitation in visibility or audibility than Participant B. This may indicate more difficulty for Participant A in judging the manoeuvre.

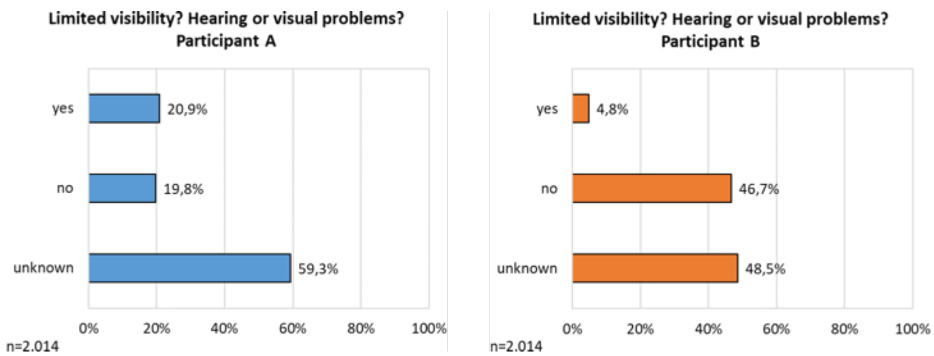


Figure 33: Interview – visibility/audibility limitation (302)

r) Interview result: overlooked/distracted, etc.

Figure 34 shows the participant interview results considering whether they overlooked important information or if they were distracted. As from the figure, Participant A reported being more distracted compared to Participant B. Figure 35 shows further insight into the influencing factors behind this result, whether stress, fatigue etc. was a factor, and over 70% said there was no influence. In most cases, Participant A's level of distraction could be attributed to simple human error.

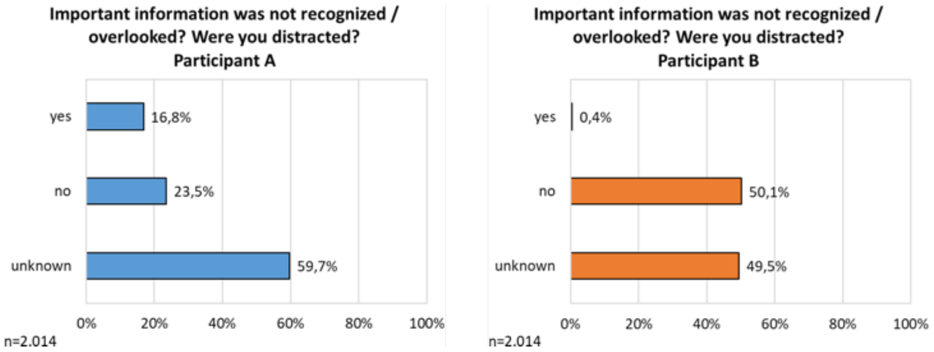


Figure 34: Interview – overlooked/distracted (302)

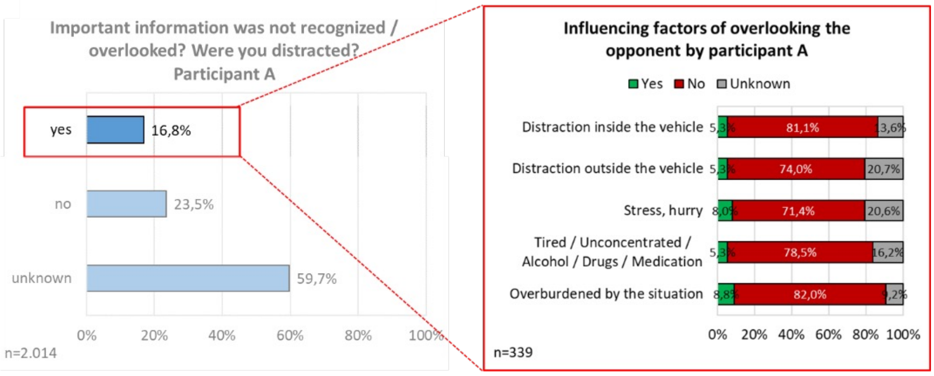


Figure 35: Interview – Influencing factors for distraction (302)

s) Interview result: misjudgement

Figure 36 shows the participant interview results on whether they misjudged the situation or not. For Participant A, out of those who answered 'yes' or 'no', (so taking out the unknown cases), 78% (=31.3/(8.8+31.3)x100) of the participants reported they had not misjudged the situation. For Participant B, this rate was higher, at 92% (=46.7/(4.1+46.7)x100). It was reported that most of the participants B believed they were innocent and had assessed the situation correctly.

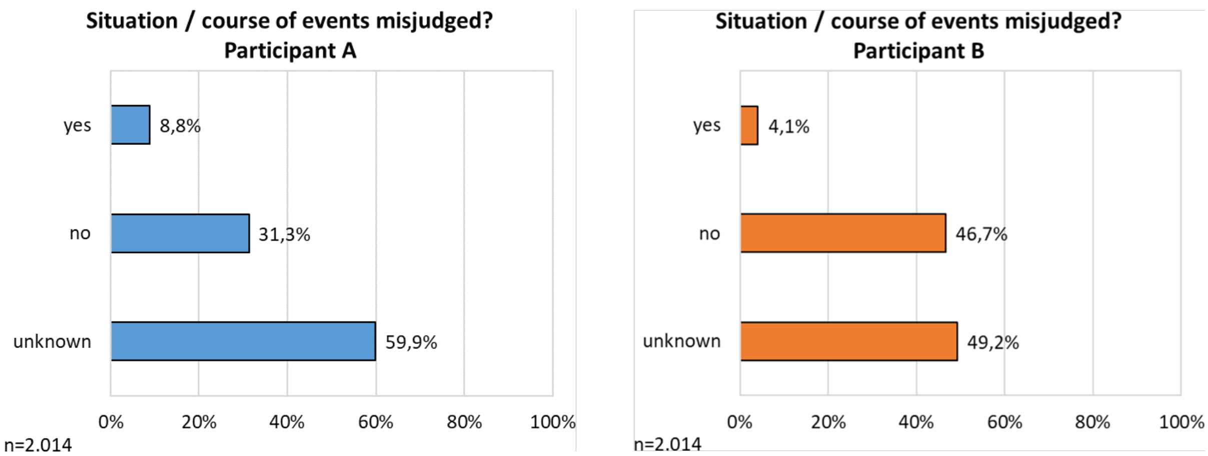


Figure 36: Interview – Misjudgement (302)

t) Interview result: accident-avoidance possibility by other action

Figure 37 shows the participant interview results whether the accident would have been possible to be avoided by other reaction/action. Comparing the number of participants answering ‘yes’ to ‘no’, for both Participant A and B, the ratio of ‘no’ is much higher, meaning that the accident was not possible to be avoided through other actions taken.

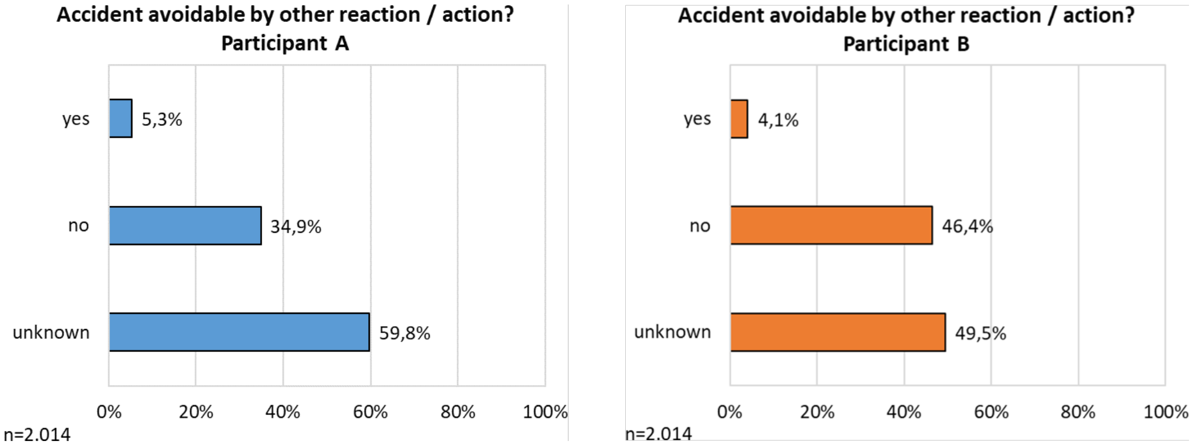


Figure 37: Interview – Accident avoidance possibility (302)

u) Interview result: mistakes in executing the avoidance action

Figure 38 shows the participant interview results about difficulties/mistakes in taking the planned action. Comparing the number of participants answering ‘yes’ to ‘no’, for both Participant A and B, the ratio of ‘no’ is much higher, meaning that the planned action was not difficult or mistakenly executed. If comparing the ‘yes’ ratio of Participant A to Participant B, the latter showed a slightly higher number, which means that the planned action, e.g., braking or steering, was slightly more difficult or mistakenly executed.

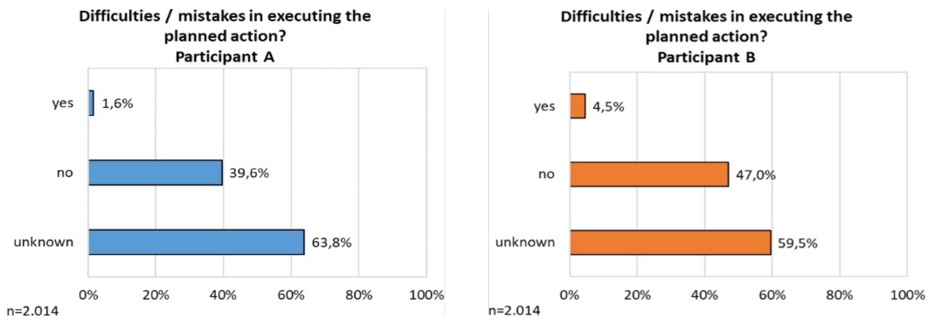


Figure 38: Interview – Mistakes in avoidance action (302)

v) Interview result: influence from vehicle technology

Figure 39 shows the participant interview results about influence of the vehicle technology. This query is asking whether the participants had difficulty in operating a certain function provided by the vehicle or were distracted by the function on/in the vehicle. The ratio of participants answering ‘no’ for both Participant A and B are much higher than those answering 'yes', meaning that the vehicle technology had little influence on the accident.

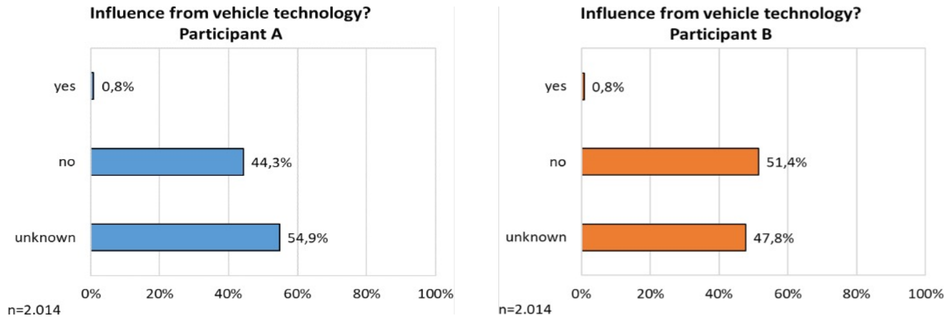


Figure 39: Interview – Influence from vehicle technology (302)

w) Interview result: influence of road condition

Figure 40 shows the participant interview results about the influence of the road condition. The ratio of participants answering 'no' for both Participant A and B are much higher than those answering 'yes', meaning that there was little influence of road conditions such as a slippery road leading to an accident.

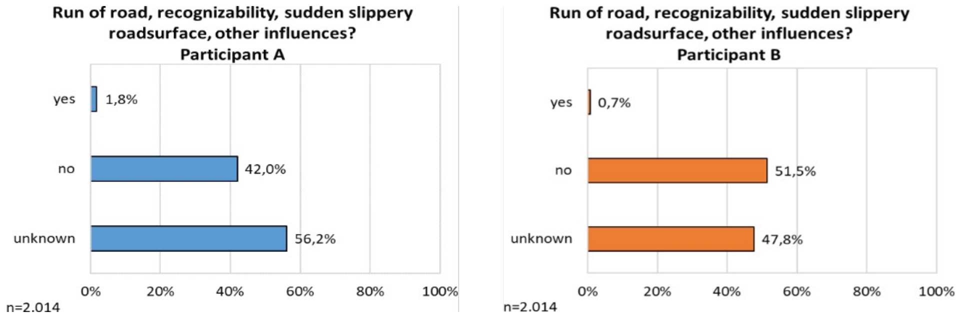


Figure 40: Interview – Influence of road condition (302)

5.3. Module Data Analysis from GDAS PCM

The database for the study of Module 2 is not the factual GIDAS database but the simulation database GIDAS-PCM, which contains more detailed information for each time step and each participant (e.g., trajectories and manoeuvres of the participants). An overview of both databases is shown in Figure 41.

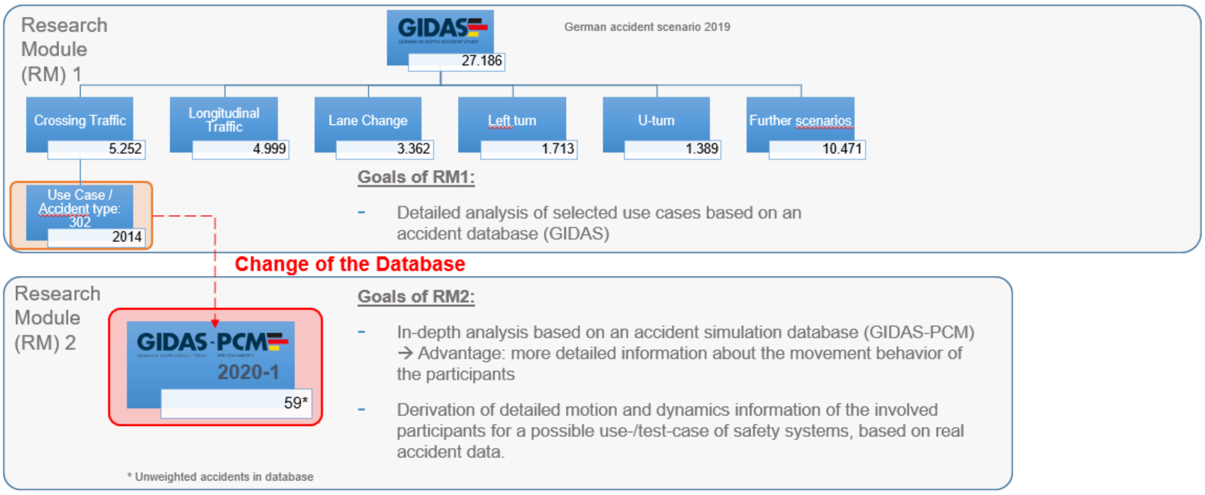


Figure 41: Overview of the database used for Module 2 study (302)

As seen in previous figures, the Crossing traffic accident account for 17.9% of accidents in which a PTW is the victim. As seen in Figure 42, GIDAS-PCM data shows that the PTW is always Participant B in the case of accident type 302, and Participant A is a passenger car.

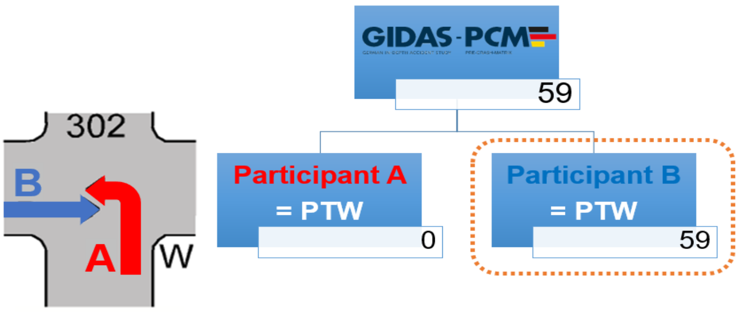


Figure 42: Assignment of the participants (302)

a) Trajectory of the traffic participants

For 59 accidents in GIDAS-PCM for Crossing traffic accident 302, the collision point for Participant B was aligned to one point and each participant's trajectories were arranged to its position accordingly. Figure 43 shows its results, and, from this data, the median value is derived and is shown in Figure 44.

- Combination overview trajectories & median values for the trajectories

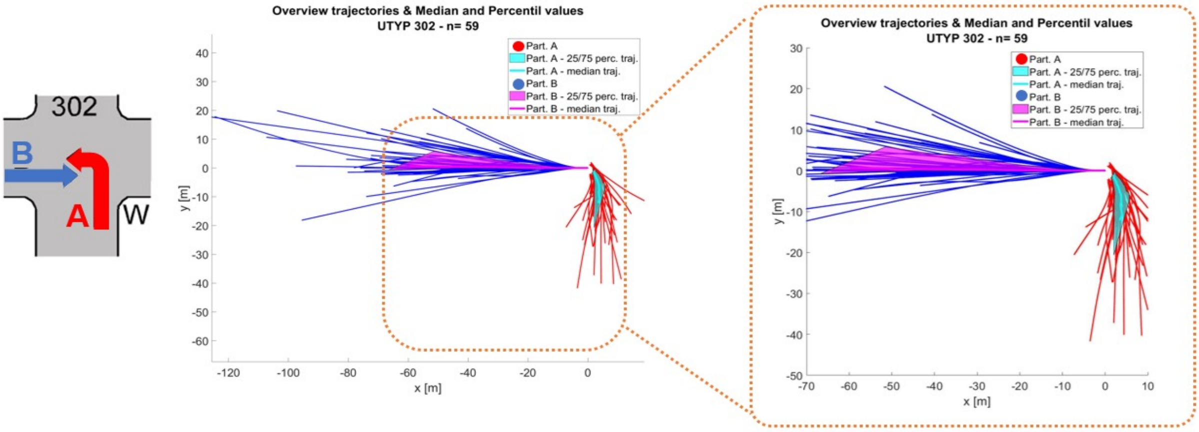


Figure 43: Trajectories of crossing traffic accident (302)

(The trajectories do not cross each other because they display the centre of gravity trajectory.)

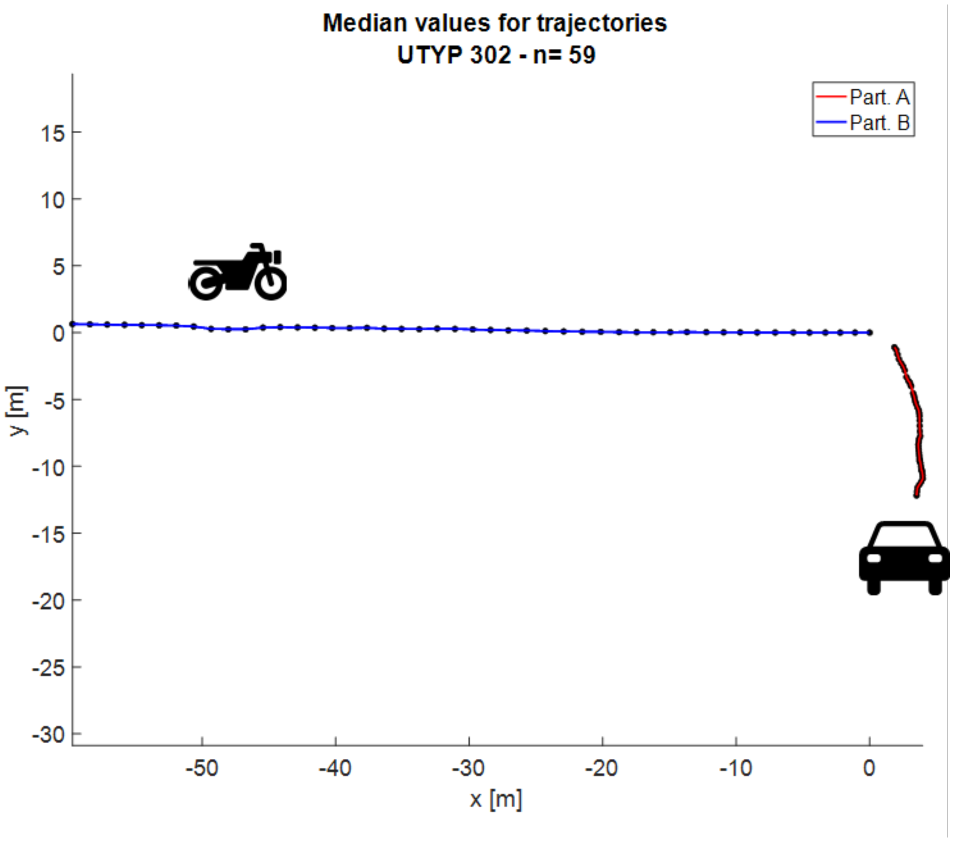


Figure 44: Median values for trajectories (302)

b) Manoeuvres

To understand what actions the participants were performing at each time point, the dynamics data of the participants were analysed and mapped into a manoeuvre catalogue. The manoeuvre catalogue is shown in Table 3 below. For example, MID (Manoeuvre IDentifier) 1 would mean moving straight ahead at a constant speed.

The criteria for evaluating whether the vehicle is in moving forward/backward, straight/left/right, accelerating/decelerating/standing still is shown in Table 4.

Table 3: Manoeuvre catalogue

MID	Lateral	Longitudinal	Movement	MID	Lateral	Longitudinal	Movement	MID	Lateral	Longitudinal	Movement
1	Straight	Forward	Constant	8	Left	Forward	Constant	14	Right	Forward	Constant
2			Acceleration	9			Acceleration	15			Acceleration
3			Deceleration	10			Deceleration	16			Deceleration
4		Backward	Constant	11		Backward	Constant	17		Backward	Constant
5			Acceleration	12			Acceleration	18			Acceleration
6			Deceleration	13			Deceleration	19			Deceleration
7	-	-	Standstill								

Table 4: Limits for the variables of the manoeuvre catalogue based on GIDAS-PCM

- VX - Longitudinal speed — VY - Lateral speed
- AX - Longitudinal acceleration — AY - Lateral acceleration

Variable	Type	
Longitudinal	Forward	Backward
Limit	$VX > 0.1\,m/s$ *OR* $\lvert VX\rvert \le 0.1\,m/s$ & $AX \ge 0.5\,m/s^2$	$VX < -0.1\,m/s$ *OR* $\lvert VX\rvert \le 0.1\,m/s$ & $AX \le -0.5\,m/s^2$

Variable	Type		
Lateral	Straight	Left	Right
Limit	$\lvert AY\rvert < 0.5\,m/s^2$	$AY \ge 0.5\,m/s^2$	$AY \le -0.5\,m/s^2$

Variable	Type			
Movement	Constant	Acceleration	Deceleration	Standstill
Limit	$\lvert AX\rvert < 0.5\,m/s^2$ *AND* $\lvert VX\rvert > 0.1\,m/s$	$AX \ge 0.5\,m/s^2$	$AX \le -0.5\,m/s^2$	$\lvert AX\rvert \le 0.1\,m/s^2$ *AND* $\lvert VX\rvert \le 0.1\,m/s$

Figure 45 shows the top five entries of the last two MIDs before Participant A has a collision. The most frequent manoeuvre was MID 2 followed by MID 9, which counts for 17%. In this manoeuvre, before starting MID 2, i.e., straight ahead (forward) acceleration, the vehicle was at a standstill meaning that it was seeking for a chance to start its vehicle. The second and third most frequent manoeuvres were MID 1 followed by MID 8, accounting for a total of 27%. In these manoeuvres, Participant A was at a constant speed from the beginning till the collision, meaning that it disregarded the obligation to wait.

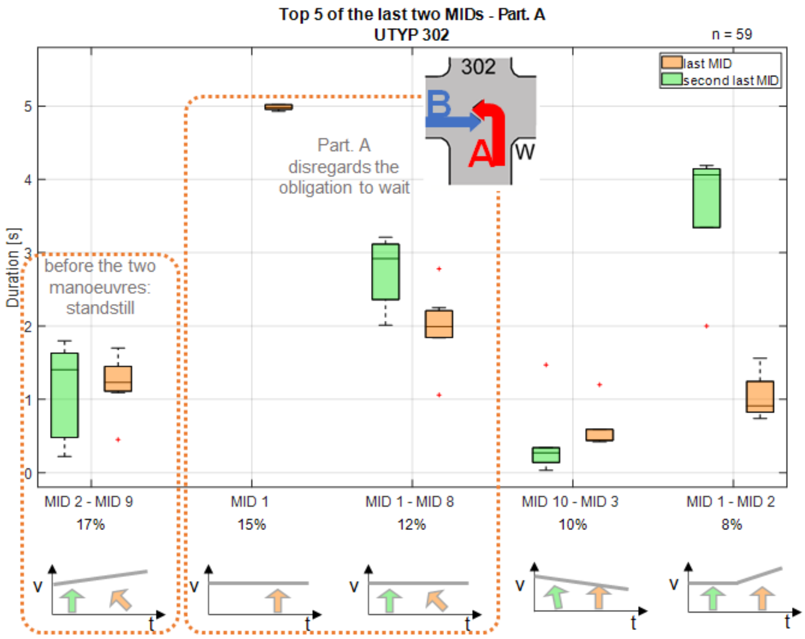


Figure 45: Top five of the last two MIDs for Participant A (302)

Figure 46 shows the top five of the last two MIDs before a collision for Participant B. As the Participant B is moving straight through a crossing, the vehicle is at a constant speed in the beginning, performs MID 1 followed by MID 3 (39% of total), and MID 8 followed by MID 10 (17%) before the rider recognises/observes Participant A at a certain point and starts to decelerate. MID 1 only or MID 1 before a collision would mean that Participant B did not have time to react to Participant A moving towards him/her.

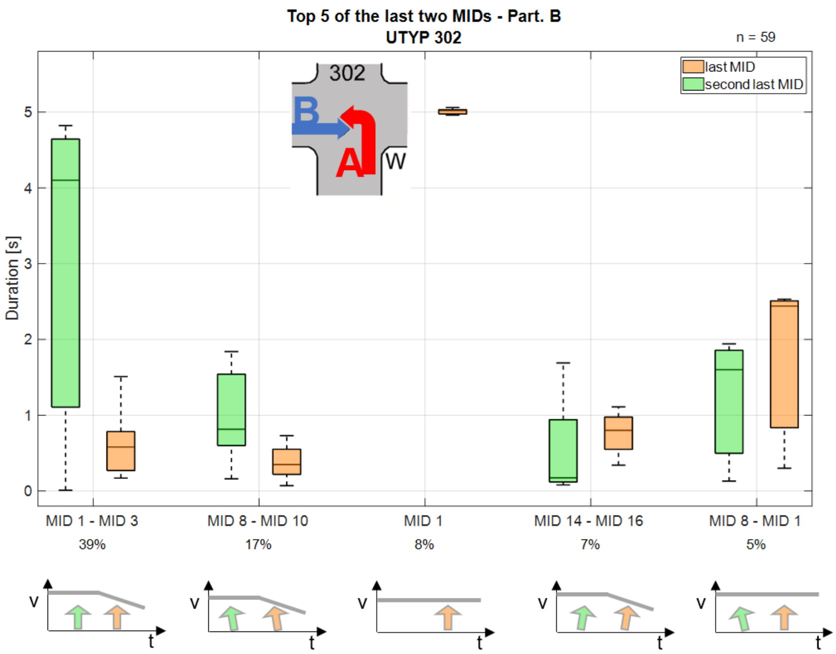
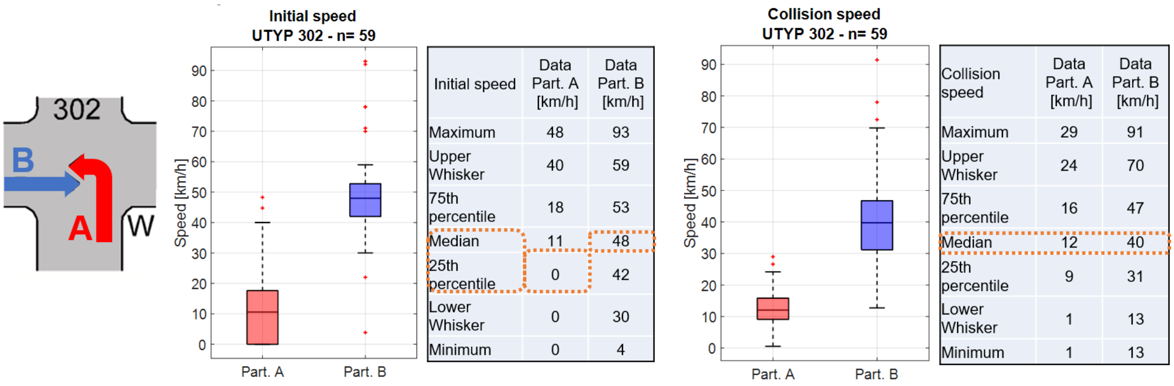


Figure 46: Top five of the last two MIDs for Participant B (302)

c) Speeds

The initial speed and collision speed of each participant is shown in Figure 47. Participant A starts from 11km/h initially and collision speed is 12km/h for the median scenario. Considering from manoeuvre analysis in 0, as Participant A most frequently starts from standstill, the initial speed of 0km/h is applied instead of 11km/h for the median scenario. Looking at Participant B, it starts from 48km/h initially and decelerates to 40km/h for the median scenario.



Initial speed	Data Part. A [km/h]	Data Part. B [km/h]
Maximum	48	93
Upper Whisker	40	59
75th percentile	18	53
Median	11	48
25th percentile	0	42
Lower Whisker	0	30
Minimum	0	4

Collision speed	Data Part. A [km/h]	Data Part. B [km/h]
Maximum	29	91
Upper Whisker	24	70
75th percentile	16	47
Median	12	40
25th percentile	9	31
Lower Whisker	1	13
Minimum	1	13

Figure 47: Initial and collision speed of participants (302)

Figure 48 shows the median values of trajectories with speed information indicated. All the data mentioned so far is entered together in order to better understand the whole picture of the median scenario for Crossing traffic accident 302.

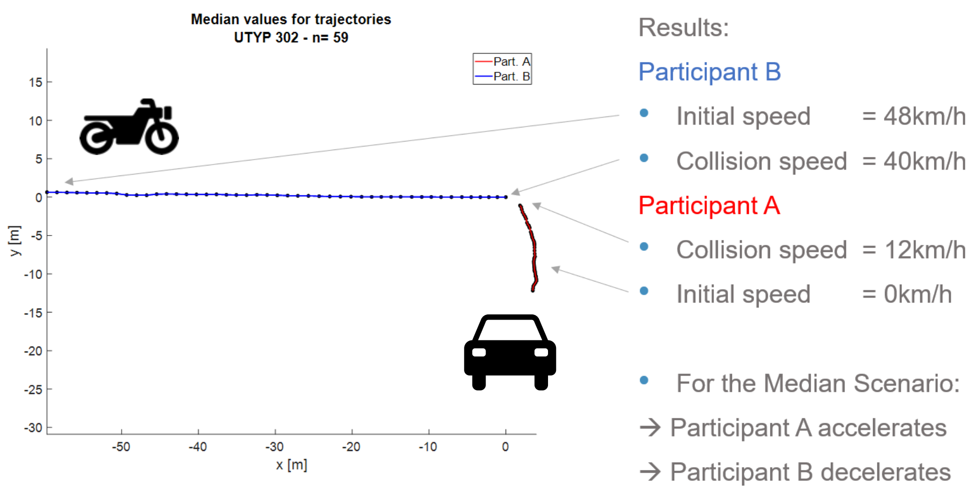
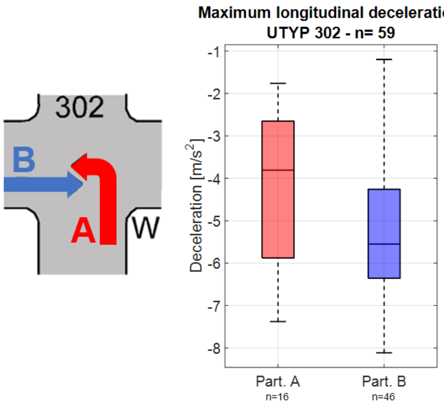


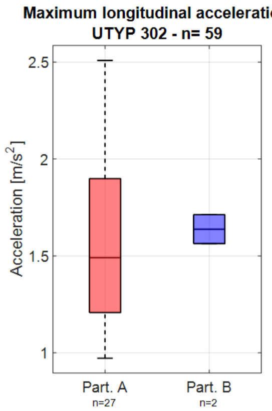
Figure 48: Results of median values for trajectories and speeds (302)

d) Decelerations/Accelerations

Figure 49 shows the analysis results of each participant's maximum deceleration and acceleration value. For the median scenario, Participant A accelerates with 1.5m/s2 from standstill and Participant B decelerate with -5.6m/s2 before the collision.



Deceleration	Data Part. A [m/s²]	Data Part. B [m/s²]
Maximum	-1,8	-1,2
Upper Whisker	-1,8	-1,2
75th percentile	-2,7	-4,3
Median	-3,8	-5,6
25th percentile	-5,9	-6,4
Lower Whisker	-7,4	-8,1
Minimum	-7,4	-8,1



Acceleration	Data Part. A [m/s²]	Data Part. B [m/s²]
Maximum	2,5	1,7
Upper Whisker	2,5	1,7
75th percentile	1,9	1,7
Median	1,5	1,6
25th percentile	1,2	1,6
Lower Whisker	1	1,6
Minimum	1	1,6

Figure 49: Deceleration/Acceleration analysis results (302)

Figure 50 shows the overview median scenario of Crossing traffic accident 302 with all the information so far derived.

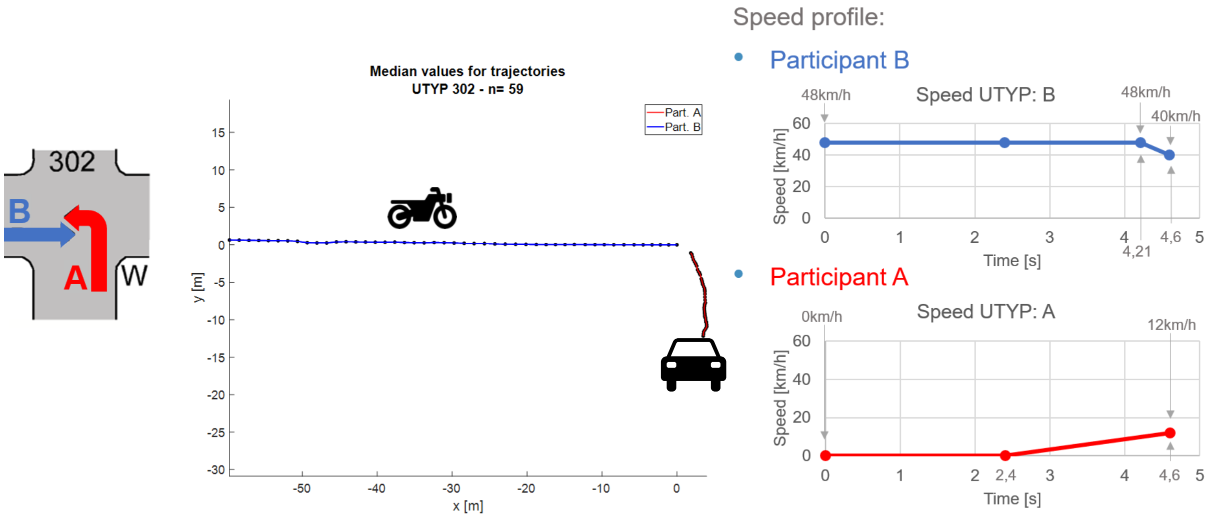


Figure 50: Overview of median scenario of crossing traffic accident 302 with trajectory, speed and deceleration/ acceleration information

e) TTC model

Time To Collision (TTC) is an important safety indicator providing time for the vehicle operator to recognise the danger ahead and make room for reaction time. Figure 51 shows the basic TTC calculation model used in this analysis. A tube for each traffic participant is extended as a straight motion with the current speed values and determines whether the two participants enter the critical conflict zone at the same time. If so, TTC is provided as a division of distance by relative speed.

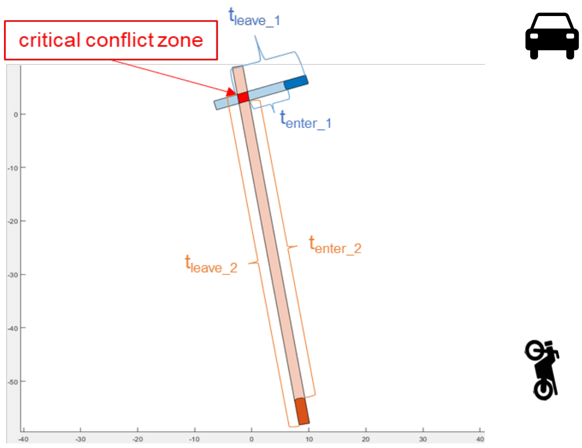


Figure 51: TTC calculation model

Figure 52 shows the TTC calculation result as a heat map for the Crossing traffic accident 302 type. The graph shows a relatively linear rise from the point of collision and high density in severely critical areas. However, 62% of the cases were able to be with TTC range > 2.6s in uncritical range (2).

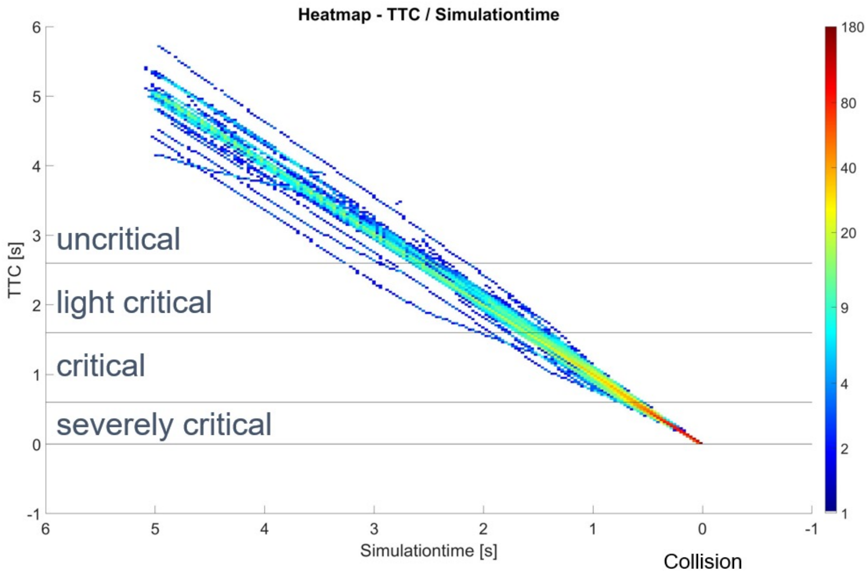


Figure 52: TTC calculation result for Crossing traffic accident 302

Figure 53 shows cumulative case numbers of TTC and where it crosses the 50% line. The figure indicates that in 50% of the cases of the Crossing traffic accident type 302 cases, the vehicle operator is informed 4.5 seconds before the collision.

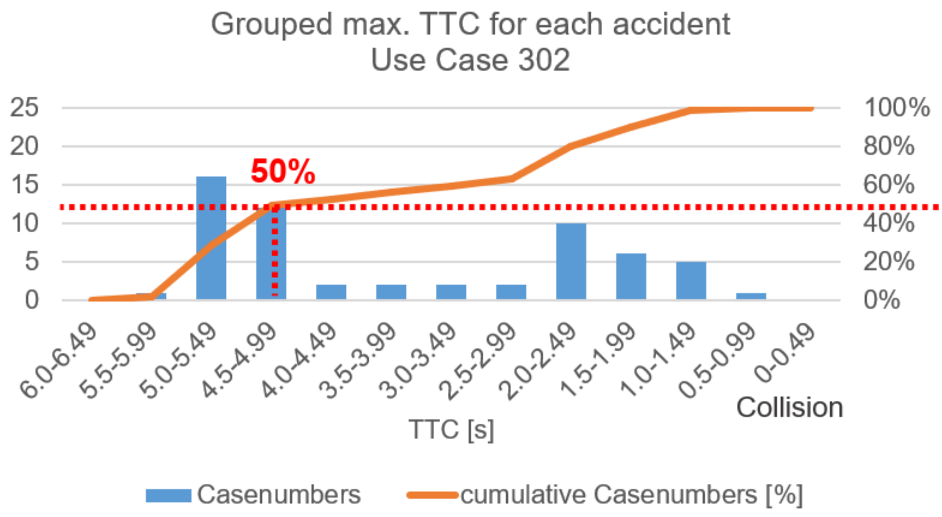


Figure 53: Cumulative case numbers of TTC for each accident (302)

5.4. Left Turn Assist

The Left turn accident type 211 is caused by a conflict between a left turning road user (Participant A) and a road user (Participant B) coming from the opposite direction (Figure 54). Accident type 211 may occur at junctions and crossings of roads, fields or cycle paths as well as access roads, e.g., to a property exit or a parking lot.

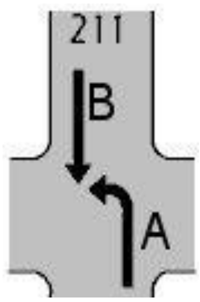


Figure 54: Left turn accident type 211

Findings from the analysis results

- More than 90% of these accidents occur at junctions, crossings or property exits.
- Accidents are caused by M1/N1 vehicles in more than 90% of cases and Participant B is a PTW in more than 90% of the accidents.
- The speed at collision of Participant A is 12-22km/h, while that of Participant B is 27-51km/h (75th percentile).
- There was a View obstruction from Participant A's perspective in around 17%

of accidents.

- Weather condition is not a major factor for the accidents.
- The last two manoeuvres before collision indicate that Participant A did not decelerate before collision in more than 40% of accidents.
- TTC can be calculated at 1.5s before collision. (50%tile).

5.4.1. Details

a) Location of the accident

The majority of PTW accidents for Left turn accidents occurred on urban roads which accounts for 79% of the overall 211 type (Figure 55). This could be understood from the fact that there is much more traffic in urban areas and thus more left turning occasions.

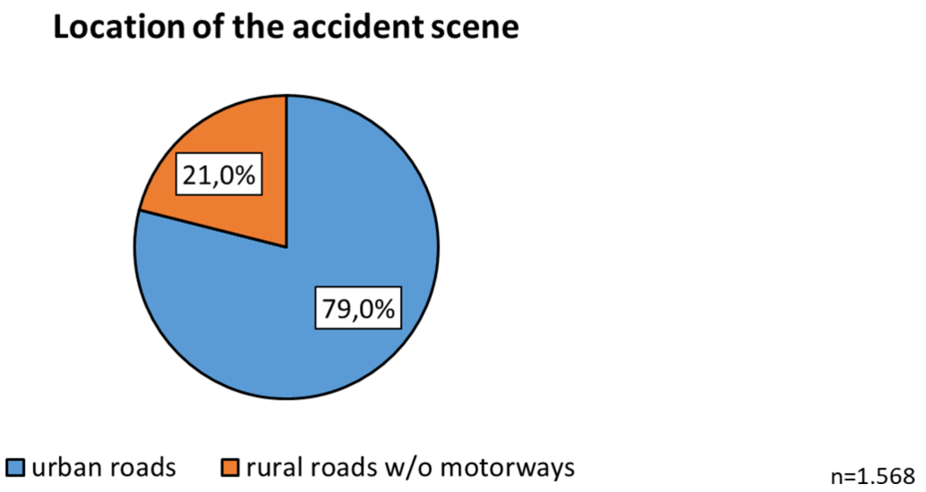


Figure 55: Location of the accident (211)

b) Accident scene

The majority of PTW accidents for left turn occurred at crossings, which accounts for 42.9% of overall 211 type. The next most frequent setting is at junctions (35.9%) and exiting properties (20.4%). The fact that PTWs are smaller and can be obscured by a vehicle in front can make it difficult for car drivers to judge their speed and distance in order to properly time a left turn manoeuvre.

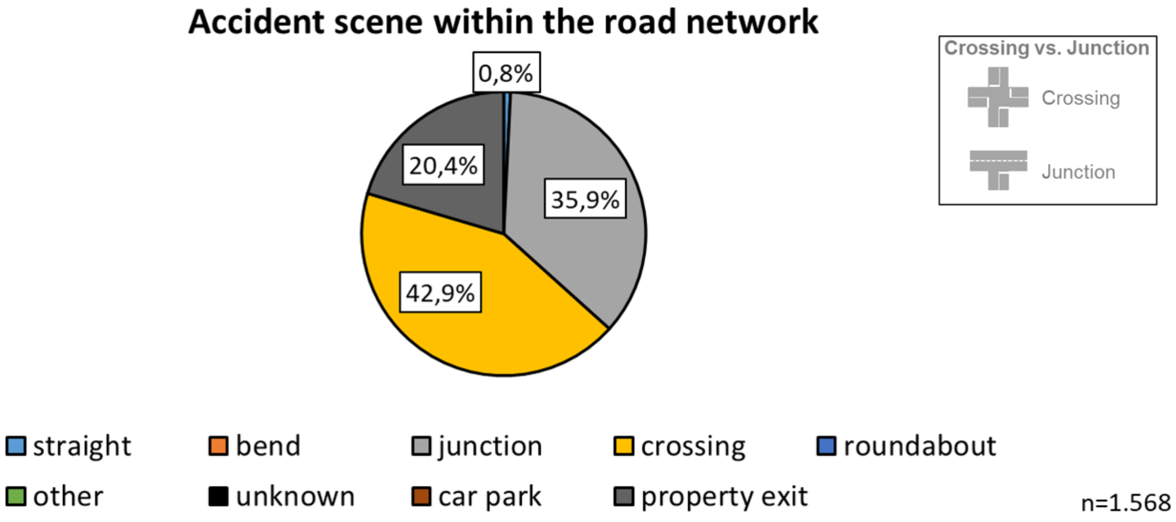


Figure 56: Accident scene (211)

c) Kind of traffic regulation

Right-of-way was cited as the predominant traffic regulation at the accident site involving PTWs, which accounts for 50.8% of overall 211 type (Figure 57). As mentioned in 4.1.2, the size of PTWs can lead to misjudgement, and even if Participant A is respecting the right of way, his/her timing of the turn could still be problematic.

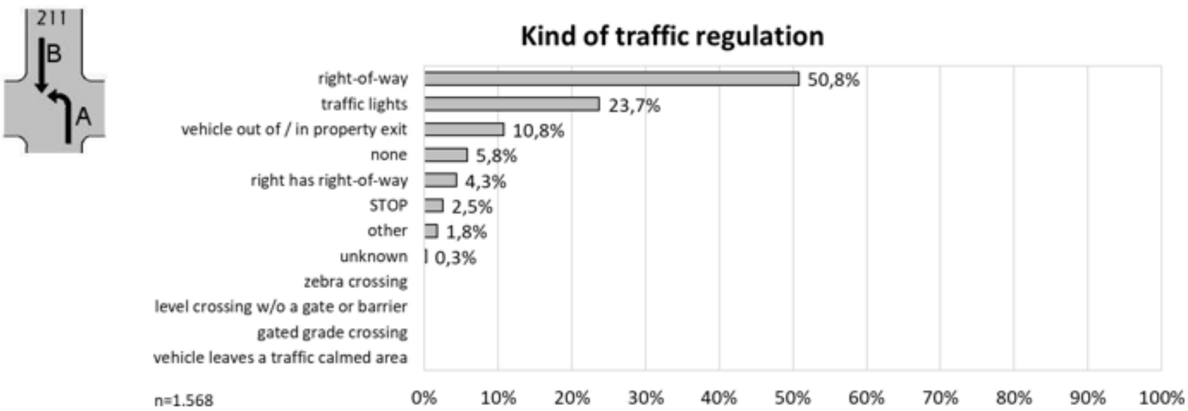


Figure 57: Kind of traffic regulation (211)

d) Kind of road user

Traffic participants in Left turn accident type 211 involving a PTW are shown in Figure 58. From the figure, it can be seen that in most cases, Participant A consists of M1/N1 vehicles (passenger cars/light commercial vehicles) and for Participant B, motorcycles.

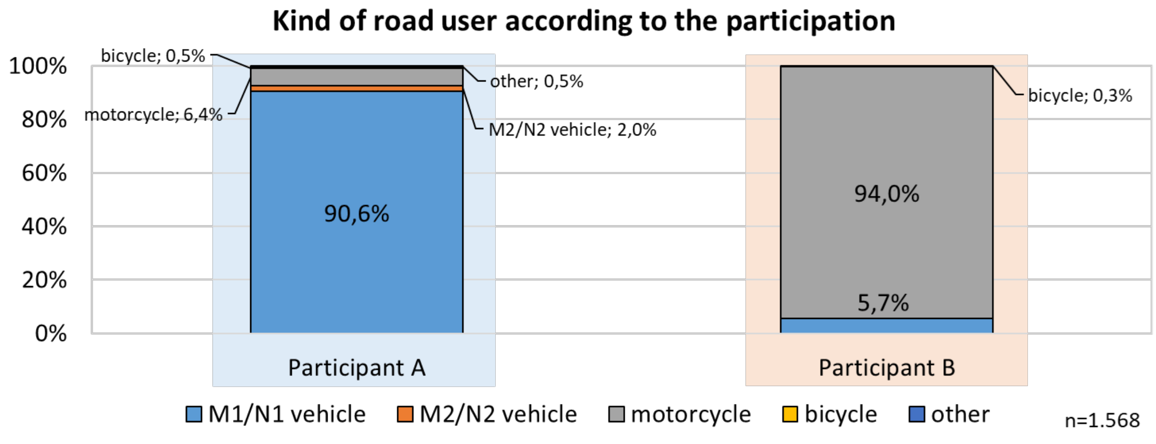


Figure 58: Kind of road user (211)

e) Main accident causer

The main accident causer in Left turn accidents is shown in Figure 59. It is clear from the figure that the main cause is Participant A and in a small percentage of cases Participant B. Previously shown figures indicate that there is a strong need to address car driving behaviour to mitigate PTW accidents in left turn situations.

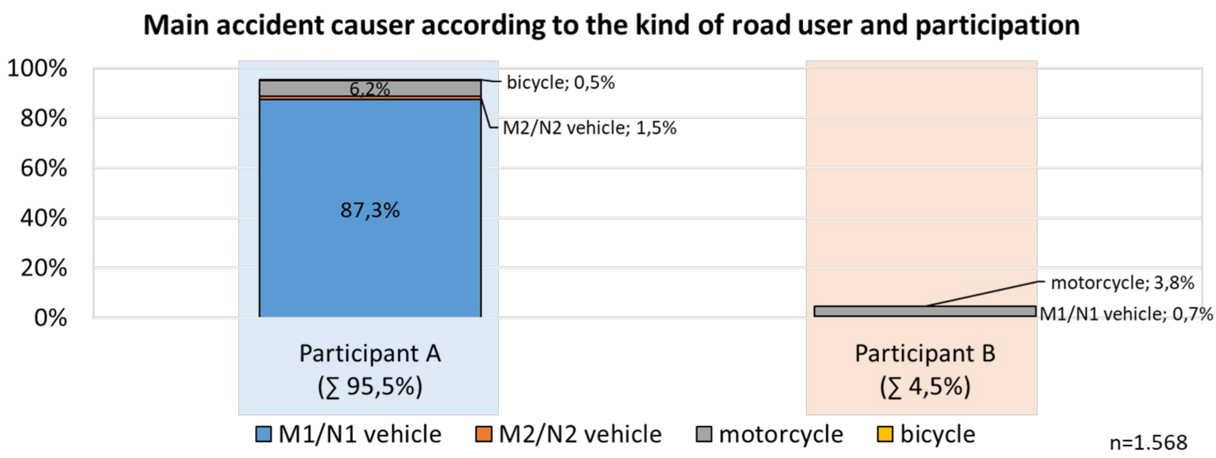


Figure 59: Main accident causer (211)

f) Main accident causation: misobeyed priority/turning, etc.

The causation of the accidents is studied and shown in Figure 60 and Figure 61. From the figures, it is understood that the main reason for the accident was the failure of Participant A to respect priority and for Participant B, it was the speed.

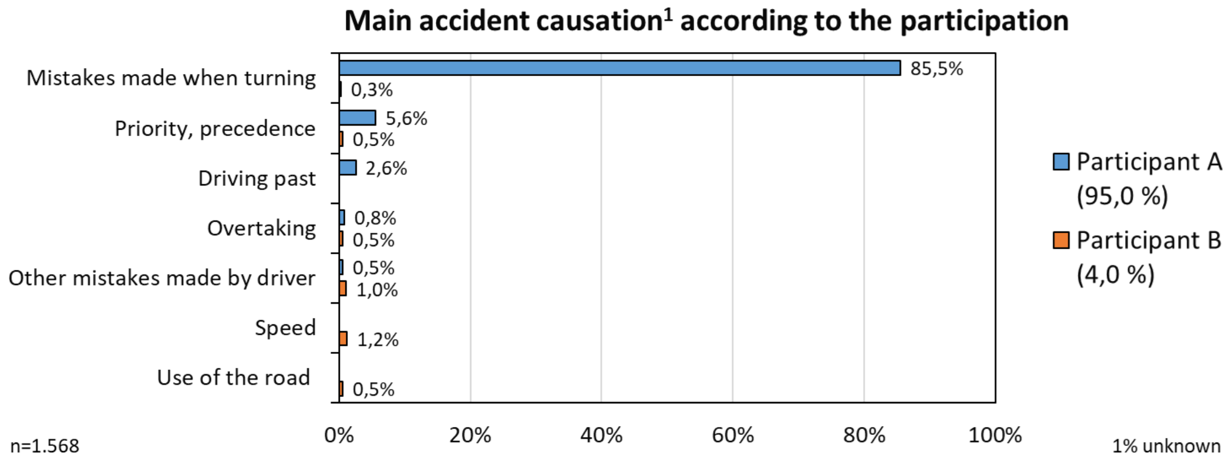


Figure 60: Main accident causation (211)

The police and also the technical investigation units in GIDAS have to assign a main accident causer with one main accident causation in each accident.

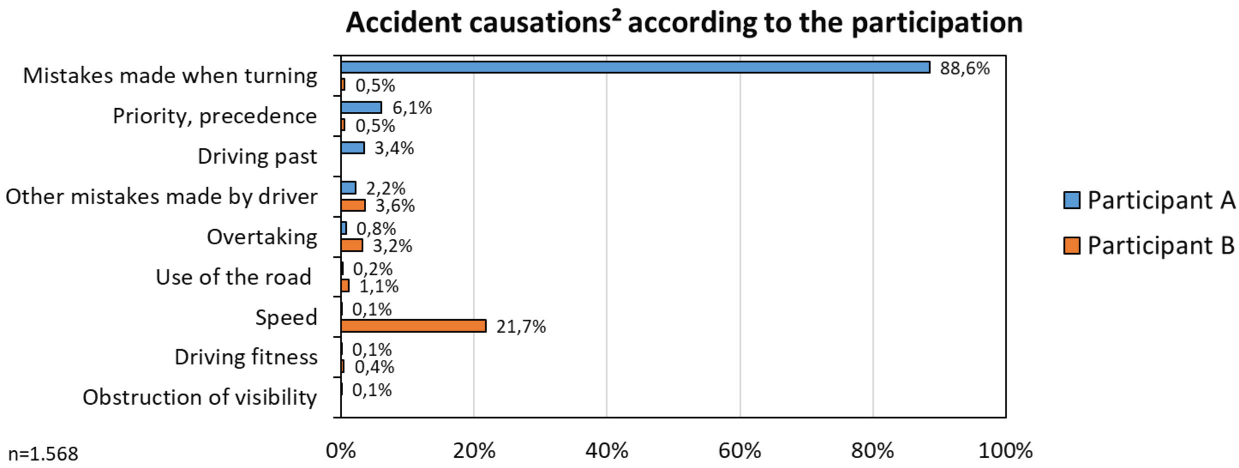


Figure 61: Accident causations (211)

The police and the technical investigation units in GIDAS can assign up to three accident causations for each accident participant. Consequently, one accident can have several accident causes depending on the Participant And so the sum of the accident causations is ≥100%.

g) Types of speed limitation: local limit/traffic sign, etc.

What or who provides the speed limit to each participant is shown in Figure 62. Both for Participant A and B, the speed limit is mostly provided by local traffic rules and secondly by traffic signs.

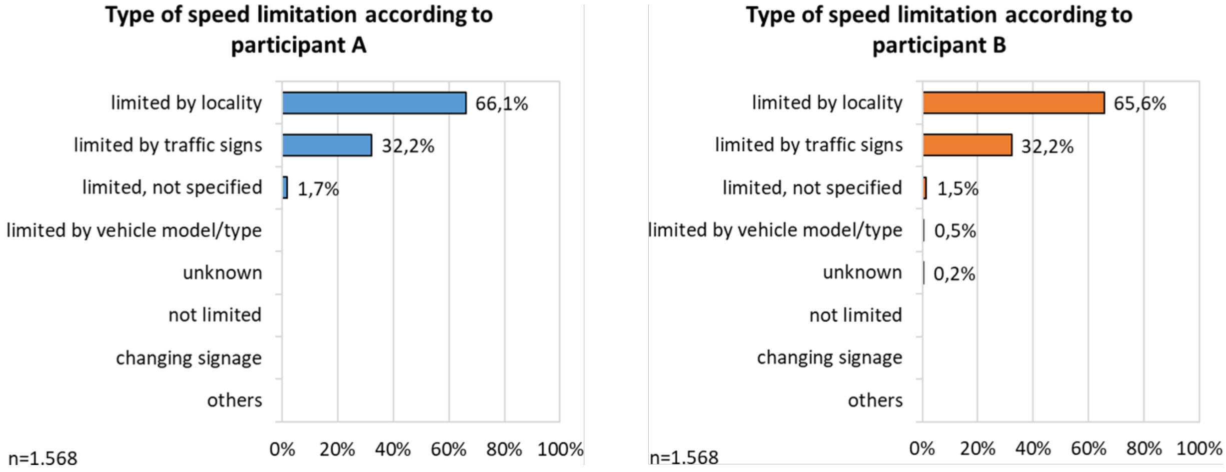


Figure 62: Types of speed limitation for the participants (211)

h) Maximum permitted speed

Maximum permitted speed at the accident site is shown in Figure 63. As previously shown, around 80% of accidents took place on urban roads, so it is reasonable to say that the most frequent maximum permitted speed is 50km/h. There cannot be seen a significant difference between maximum permitted speed for Participant A and B.

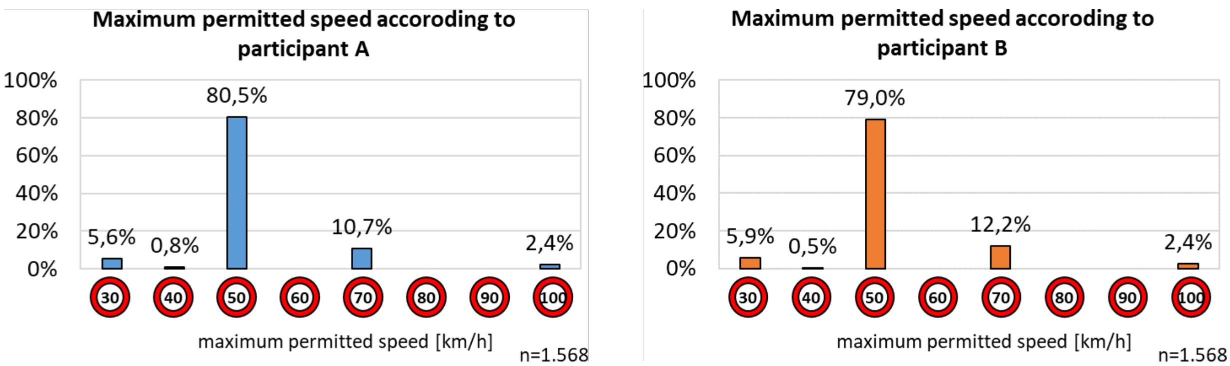


Figure 63: Maximum permitted speed (211)

i) Speed limit and distribution

Figure 64 shows the percentage of participants exceeding the applicable speed limit. Comparing participants A and B, it can be observed that Participant B is more often seen to have exceeded the speed limit. From the Left turn accident type, it could be understood that Participant A is in the turning process and slowing down so would not be exceeding the speed limit, whereas Participant B is passing straight through.

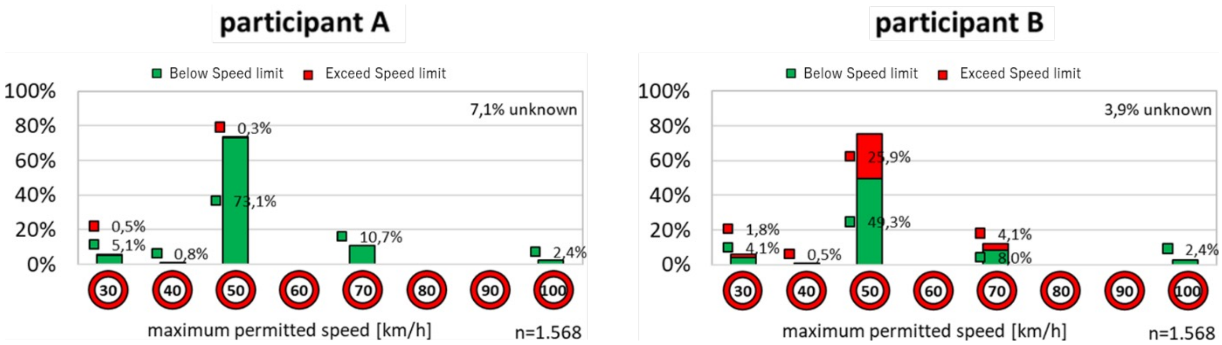


Figure 64: Exceeding speed limit (211)

Figure 65 shows the distribution of how much Participant B exceeded the allowable speed for each given limit before reaching the point of incident. Though Participant B in the Left turn accident scenario has the right of way, in some cases exceeding the speed limit could be one of the mitigating factors for Participant B.

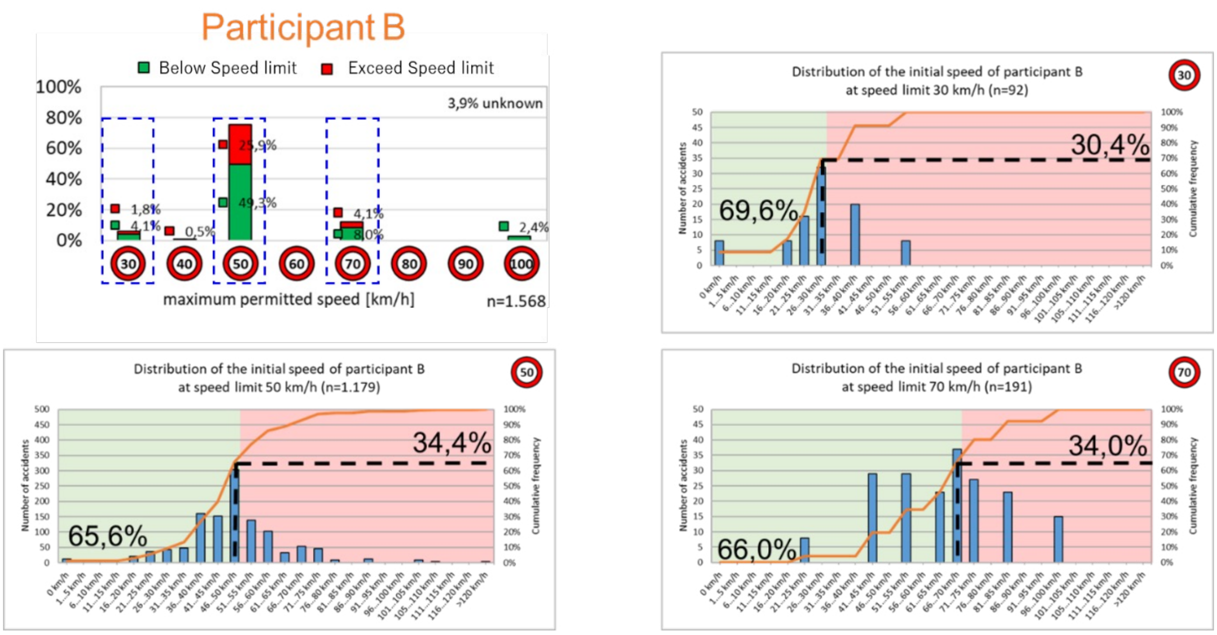


Figure 65: Speed distribution by Participant B (211)

j) Speed before the accident and at the time of collision

Figure 66 shows the initial speed of each participant. It is clear from the figure that Participant B going straight has a higher average speed than Participant A who is in the turning process.

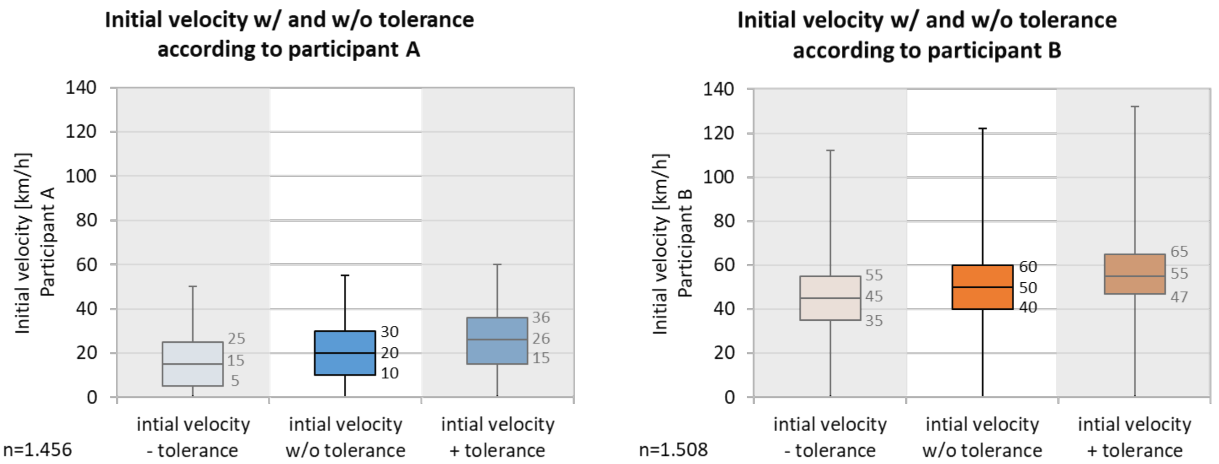


Figure 66: Initial speed of participants (211)

Figure 67 shows the colliding speed of each participant. Comparing the initial speed of Participant A, Participant A is approaching the turning point and slowing down, while Participant B seems to collide without significant speed reduction, which may be due to braking problems or poor reaction time given the situation.

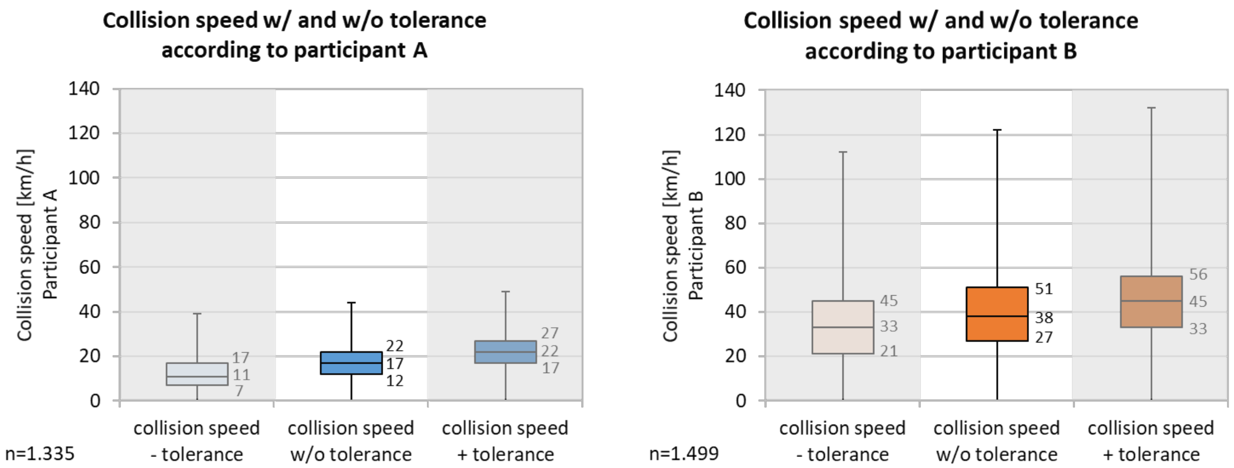


Figure 67: Collision speed of participants (211)

k) View obstruction

Figure 68 and Figure 69 show the existence of View obstructions and the types of obstruction respectively. It can be seen that around 80% of the cases had no obstructions to the drivers' view, and the rest showed a non-permanent obstruction, e.g., moving and parked cars.

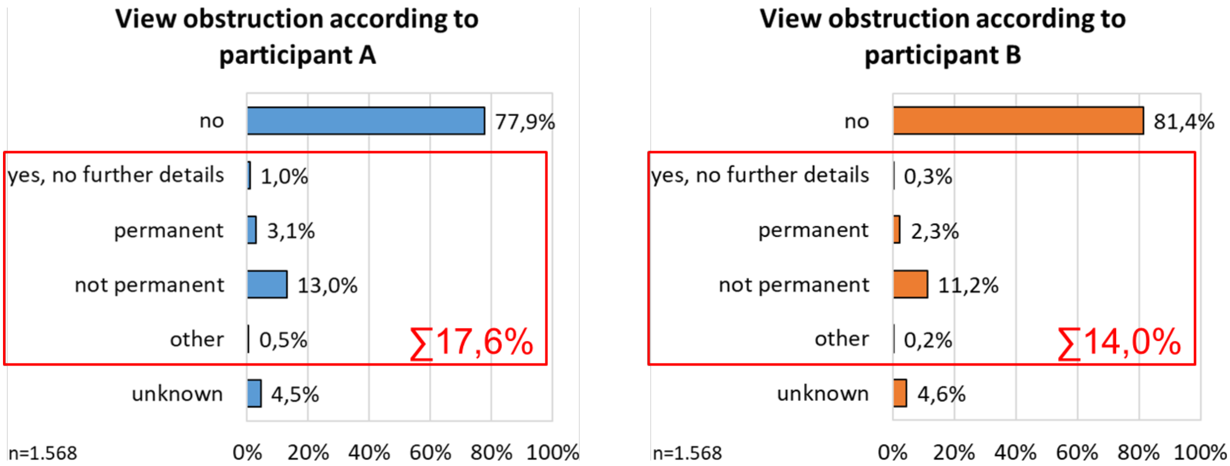


Figure 68: View obstructions (211)

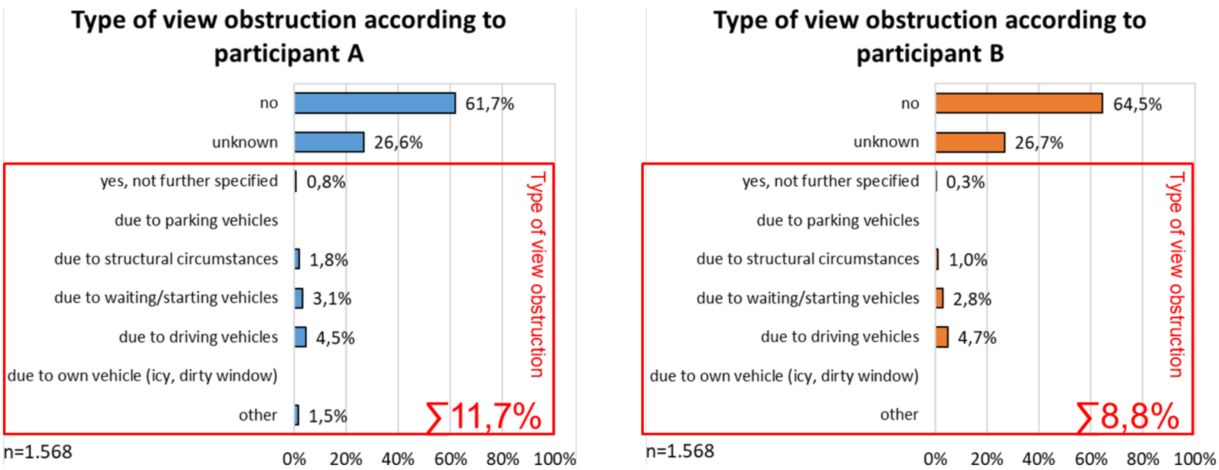


Figure 69: Type of View obstruction (211)

l) Used lane when encountering an accident

Figure 70 and Figure 71 show which lane the participants took when encountering an accident. For Participant A, the majority of left turns were taken from a single lane road or a double lane road with dedicated left turning lane. For Participant B, the majority was with a single lane, followed by a dedicated lane to go straight or a straight + turning right lane.

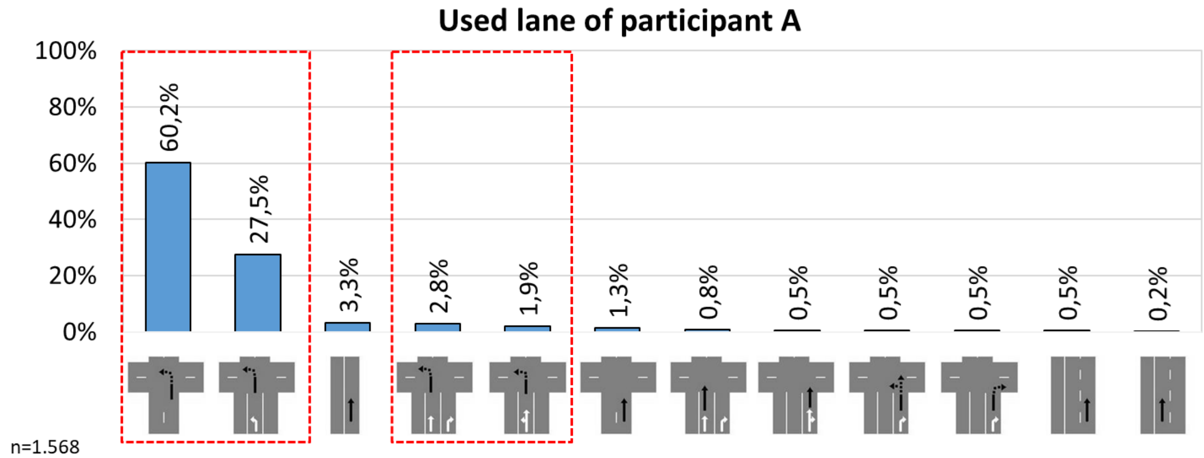


Figure 70: Used lane at an accident, Participant A (211)

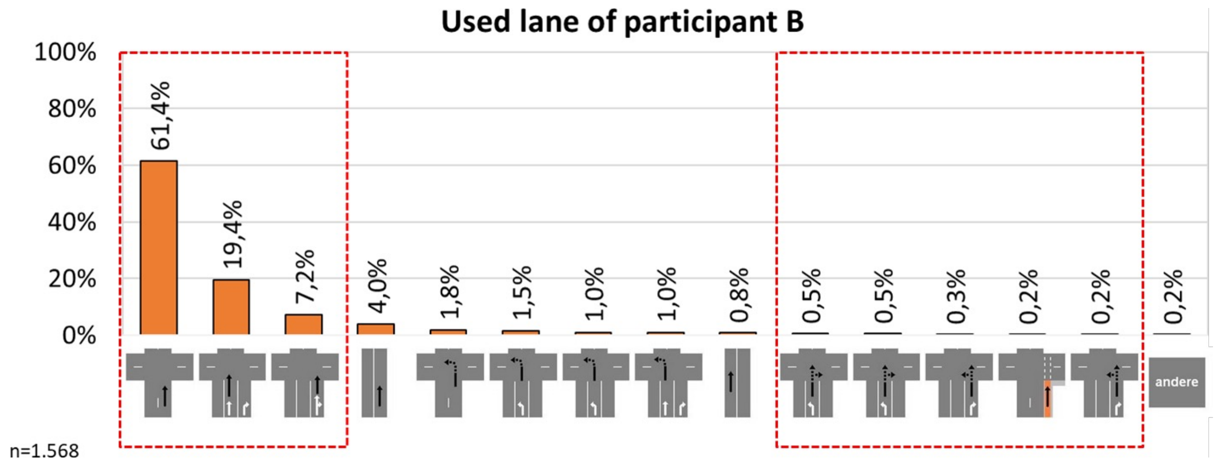


Figure 71: Used lane at an accident, Participant B (211)

m) Road surface

Figure 72 shows which kind of road surface it was when encountering an accident. The majority of Left turn accident scenario participants were driving on a conventional asphalt road.

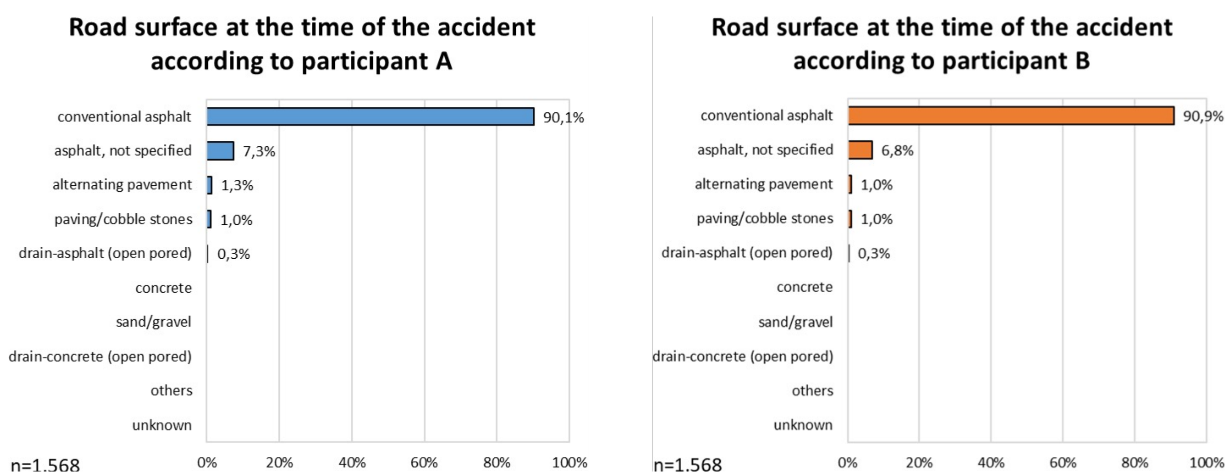


Figure 72: Road surface (211)

n) Precipitation at the time of the accident

Figure 73 shows precipitation at the time of the accident. From the figure, it can be observed that in most accidents it was not raining.

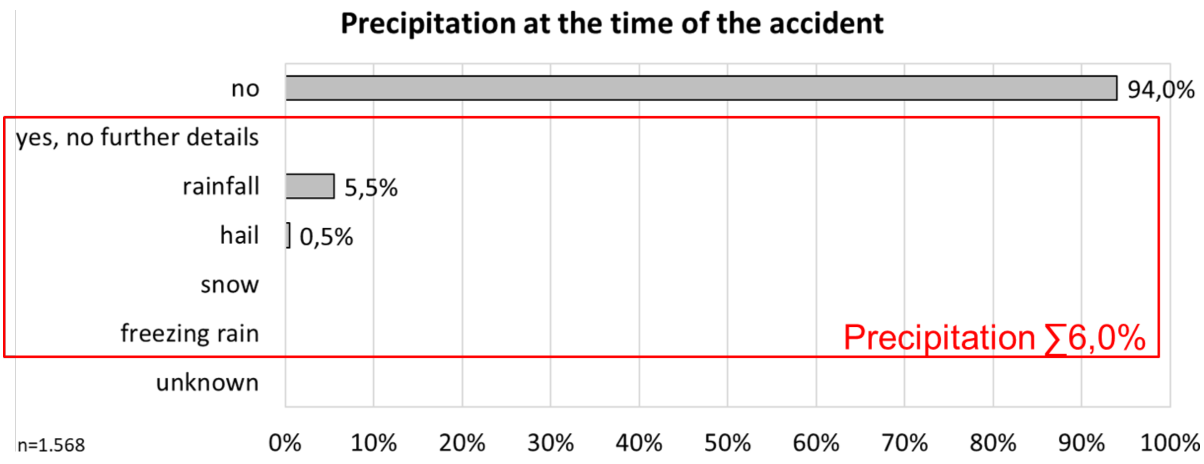


Figure 73: Precipitation (211)

o) Road condition: dry/wet/snow, etc.

Figure 74 shows the road condition at the time of the accident. From this figure and also from Figure 73, indicating that in most cases there was no precipitation, it is found that most accidents occurred on a dry road surface.

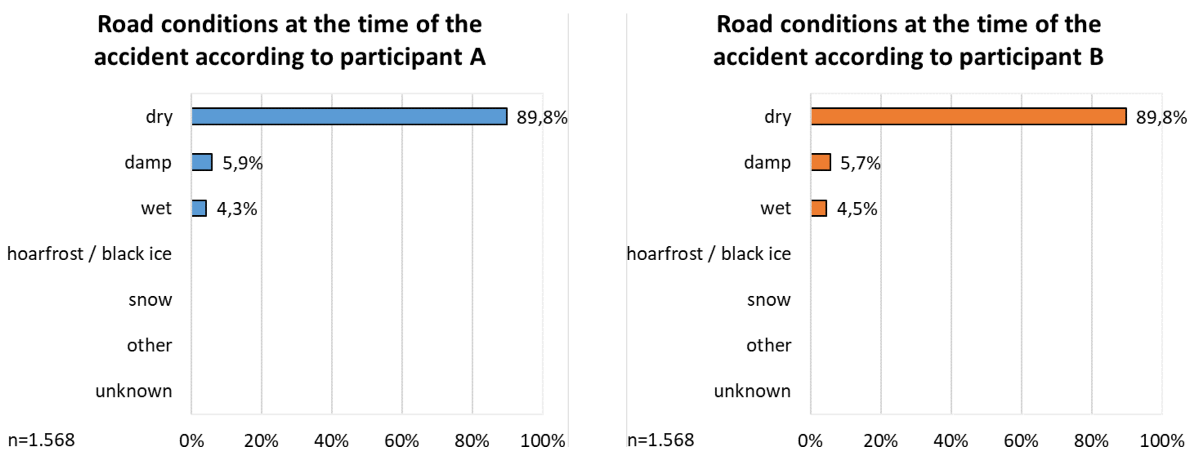


Figure 74: Road condition (211)

p) Cloudiness at the time of the accident

Figure 75 shows cloudiness at the time of the accident. Less than one in four accidents (35%) showed the presence of no clouds or very few clouds.

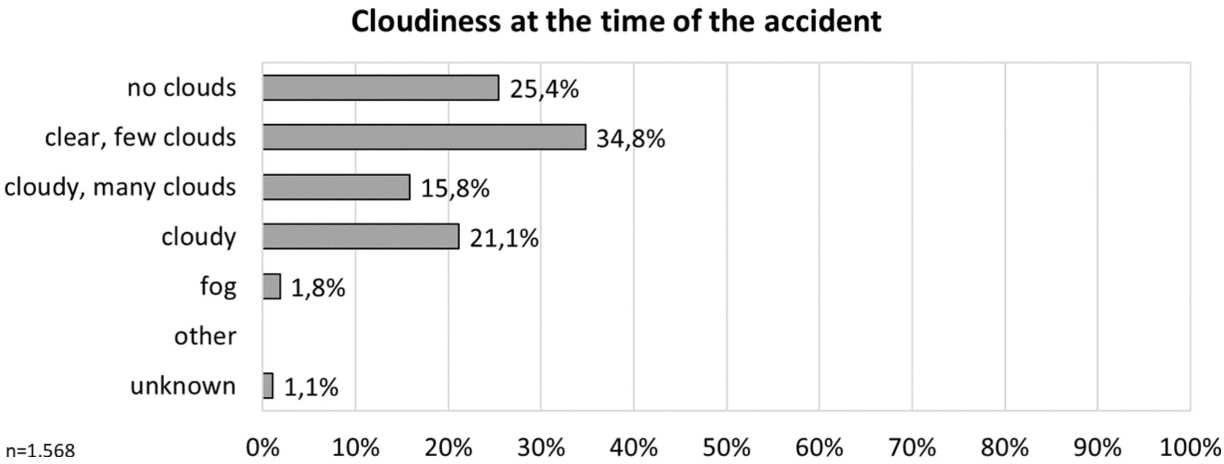


Figure 75: Cloudiness (211)

q) Interview result: visibility/audibility limitation

Figure 76 shows the participant interview results concerning visibility and audibility limitations. As the figure shows, Participant A reported more limited visibility or audibility than Participant B. This may indicate Participant A faced more challenges judging the manoeuvre.

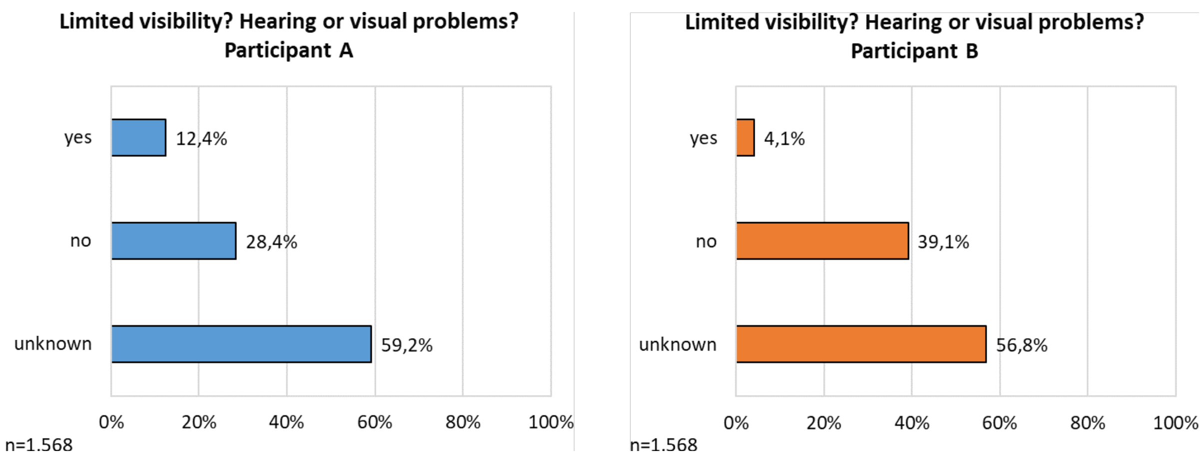


Figure 76: Interview – visibility limitation (211)

r) Interview result: overlooked / distracted, etc.

Figure 77 shows the participant interview results on whether they overlooked important information or if they were distracted. As from the figure, Participant A reports more overlooking or distraction compared to Participant B. Figure 78 shows further insight into the influencing factors of Participant A who answered that they were distracted. For the factors asked, such as stress, fatigue etc., over 70% of participants A answered that there was no influence, indicating that in most cases, human error was to blame.

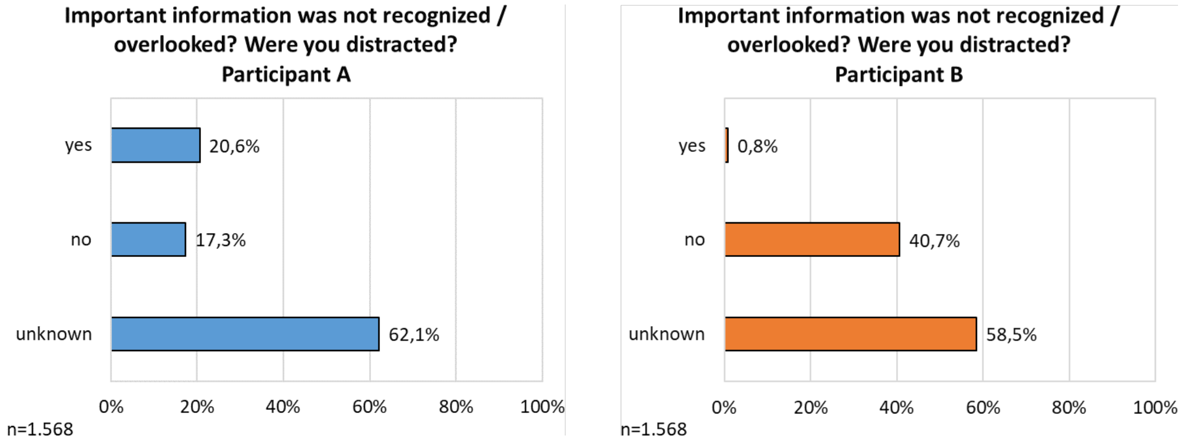


Figure 77: Interview – overlooked/distracted (211)

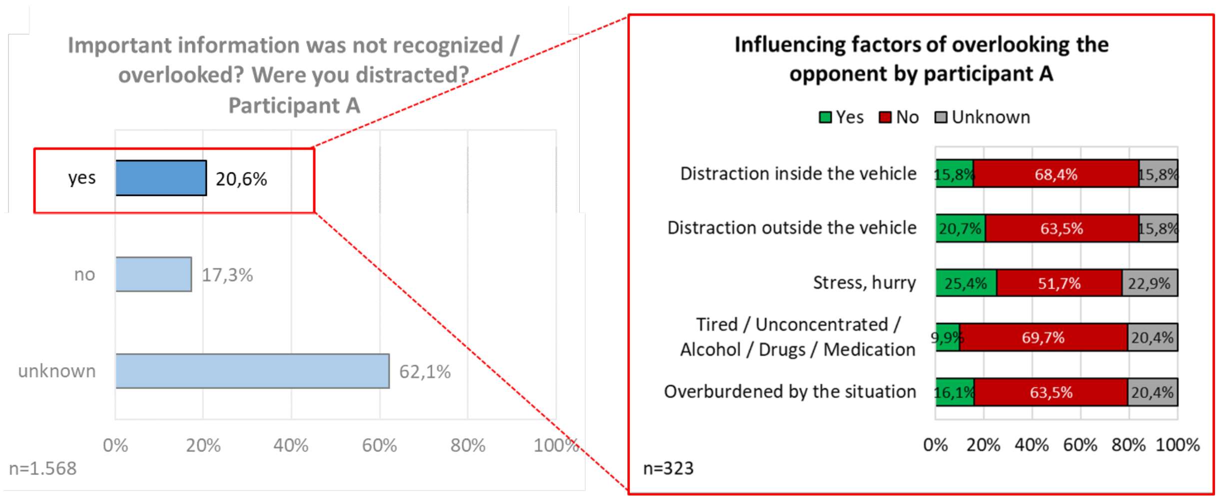


Figure 78: Interview – Influencing factor for overlooking (211)

s) Interview result: misjudgement

Figure 79 shows the participant interview results whether they misjudged the situation or not. For Participant A, out of those who answered ‘yes’ or ‘no’, (so taking out the unknown cases), 70% (= 24.8/(10.4+24.8)x100) of the participants reported they had not misjudged the situation. For Participant B, this rate is higher, at 93% (= 38.4/(2.8+38.4)x100). It was reported that most of the participants B felt they had assessed the situation correctly.

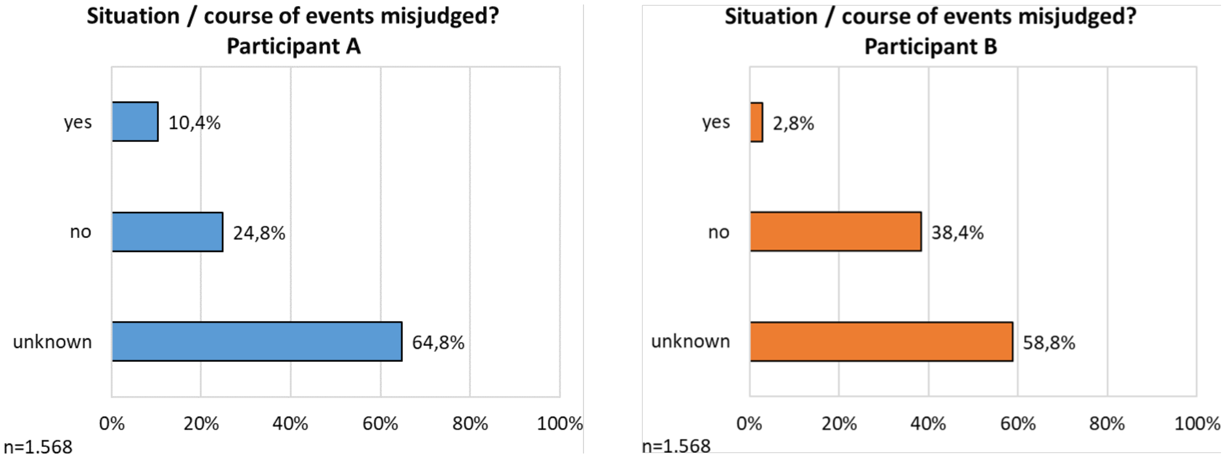


Figure 79: Interview – Misjudgement (211)

t) Interview result: accident-avoidance possibility by other action

Figure 80 shows the participant interview results on whether the accident was possible to be avoided by other reaction/action. Comparing the number of participants answering ‘yes’ to ‘no’, for both Participant A and B, the ratio of ‘no’ is much higher, meaning it was impossible to avoid the accident by taking other actions.

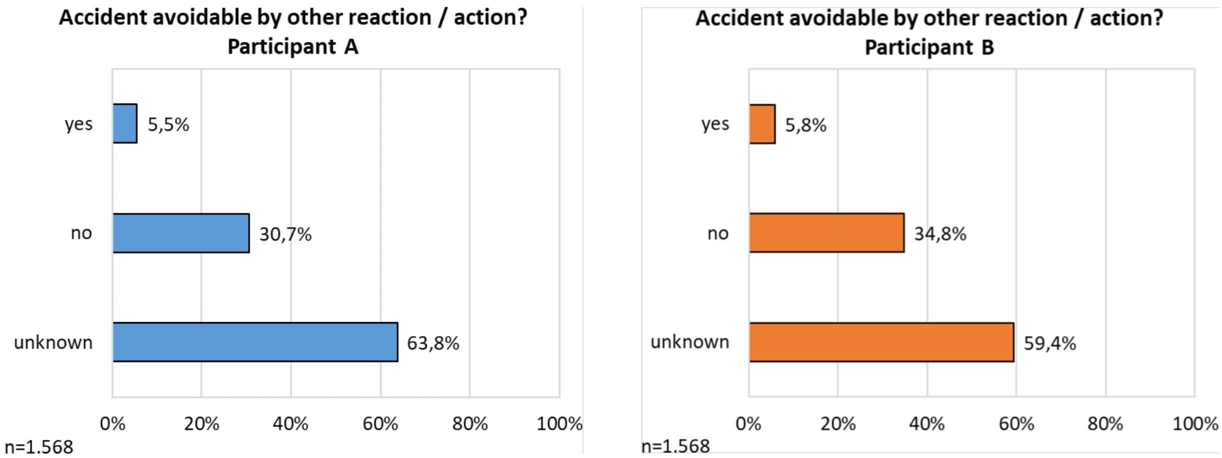


Figure 80: Interview – Accident avoidance possibility (211)

u) Interview result: mistakes in executing the avoidance action

Figure 81 shows the participant interview results about difficulties/mistakes in taking the planned action. Comparing the number of participants answering ‘yes’ to ‘no’, for both Participant A and B, the ratio of ‘no’ is much higher, meaning that the planned action was not difficult to execute or a mistake. If comparing the ‘yes’ ratio of Participant A to Participant B, the latter reported a slightly higher number, which means that the planned action, e.g., braking, steering or swerving away, was slightly more often difficult or mistakenly executed.

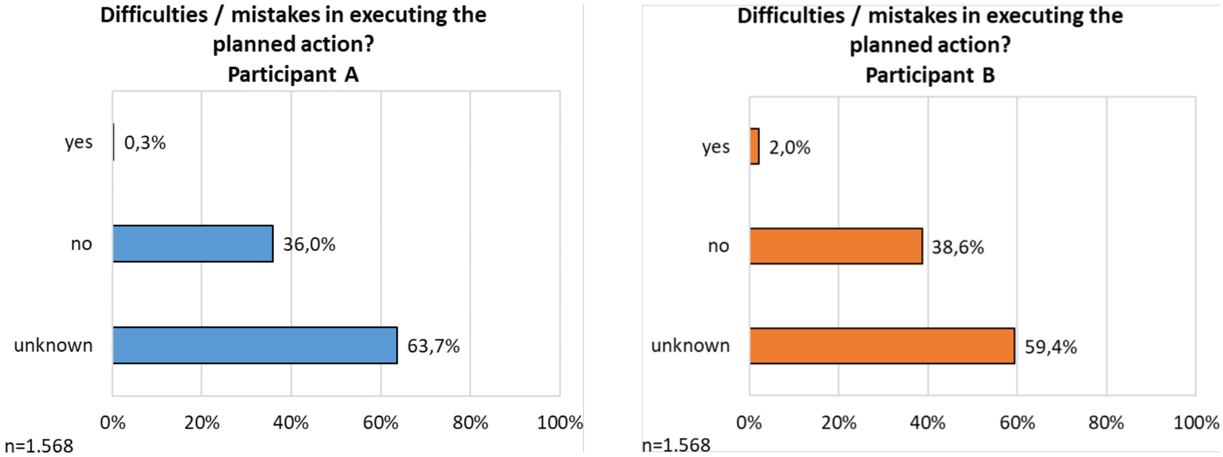


Figure 81: Interview – Mistakes in avoidance action (211)

v) Interview result: influence from vehicle technology

Figure 82 shows the participant interview results about the influence of vehicle technology. This is asking whether the participants had difficulty in operating a certain function provided by the vehicle or were distracted by the function on or in the vehicle. There were no participants A nor participants B answering 'yes' to this query.

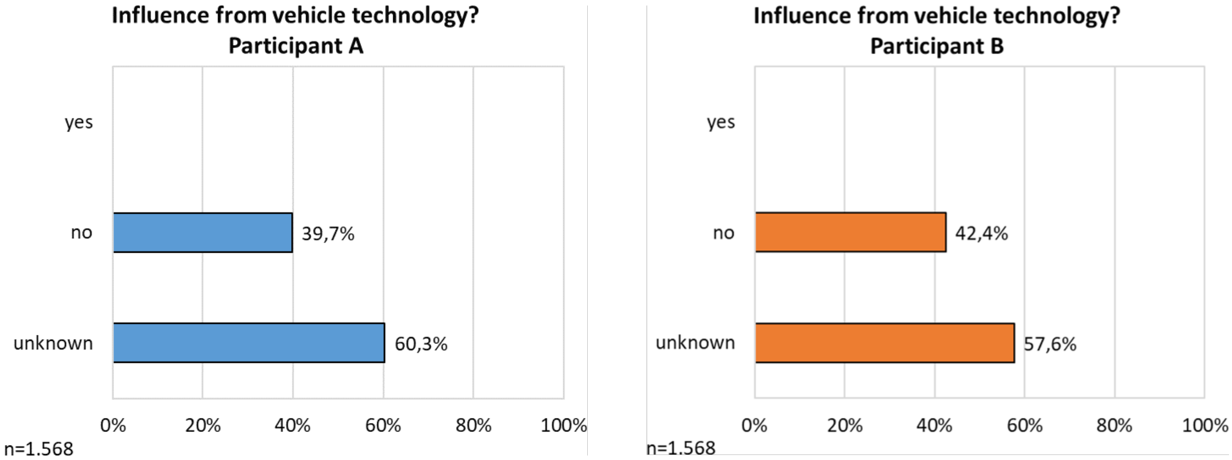


Figure 82: Interview – Influence from vehicle technology (211)

w) Interview result: influence of road condition

Figure 83 shows the participant interview results about the influence of the road conditions. The ratio of participants answering 'no' for both Participant A and B groups is much higher than those answering 'yes', meaning that there was little influence of road conditions, such as a slippery surface, leading to an accident.

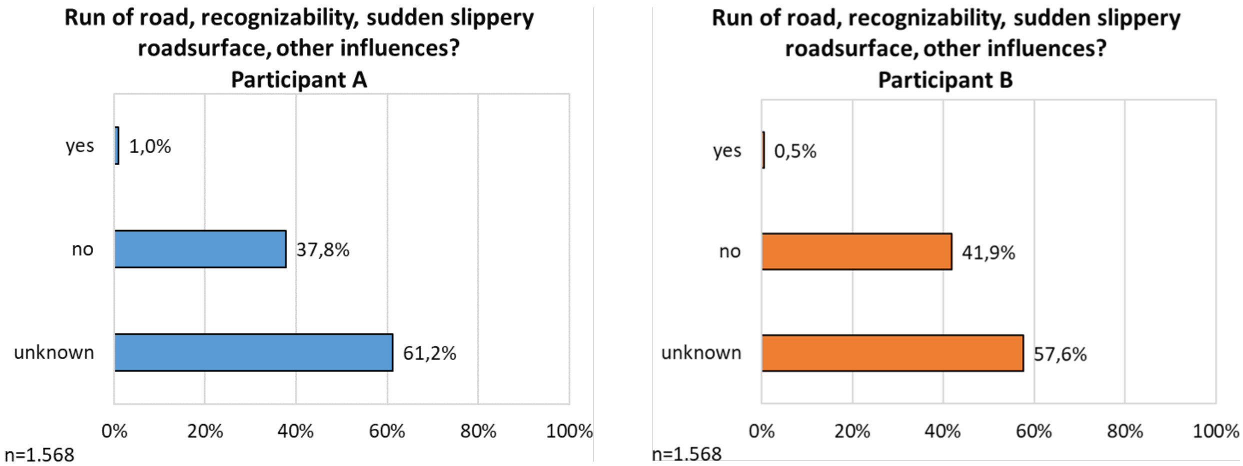


Figure 83: Interview – Influence of road condition (211)

x. Conclusions on both accident scenarios

The GIDAS database for the study of Module 2 varies from the simulation database GIDAS-PCM used in the previous case. It contains more detailed information for each time step and each participant (e.g., trajectories and manoeuvres of the participants). An overview of both databases is shown in Figure 84.

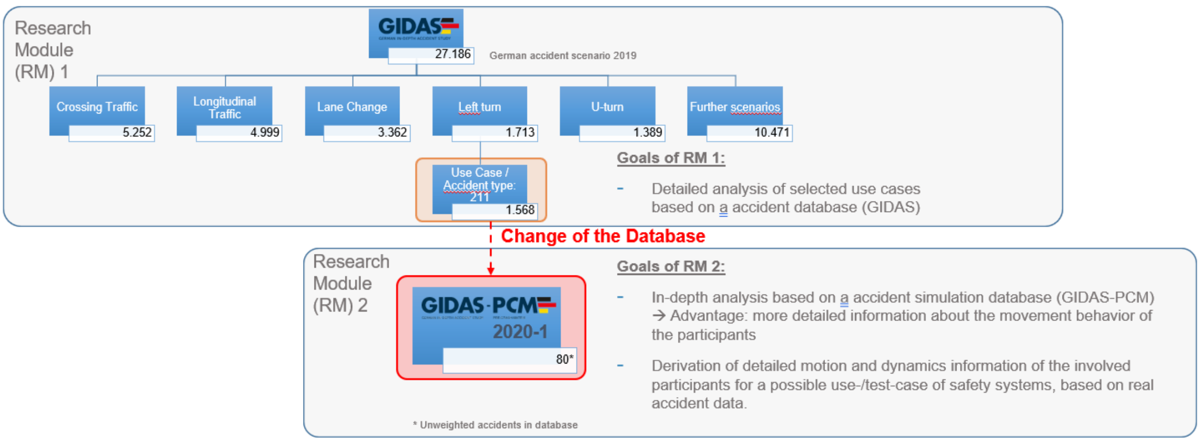


Figure 84: Overview of database used for Module 2 study (211)

For Left turn accident type 211, analysis is performed for 6.2% of the cases, in which PTW is the victim (i.e., Participant B) and Participant A is a passenger car, as shown in Figure 85.

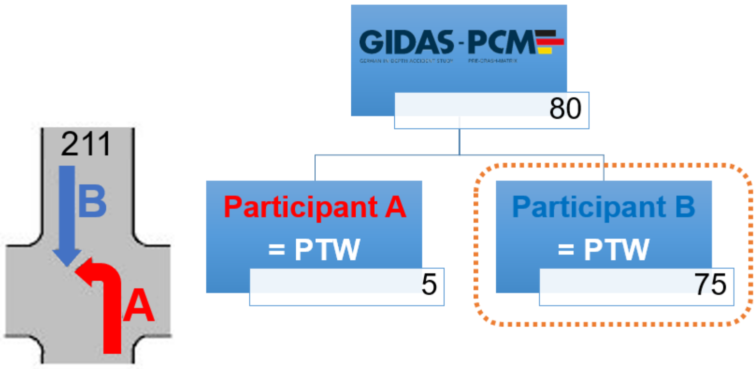


Figure 85: Assignment of the participants (211)

For 75 accidents in GIDAS-PCM for Left turn accident 211, the collision point for Participant B was aligned to one point and all participants' trajectories were arranged to its position accordingly. Figure 86 shows the results, and, from this data, the median value is derived and shown in Figure 87.

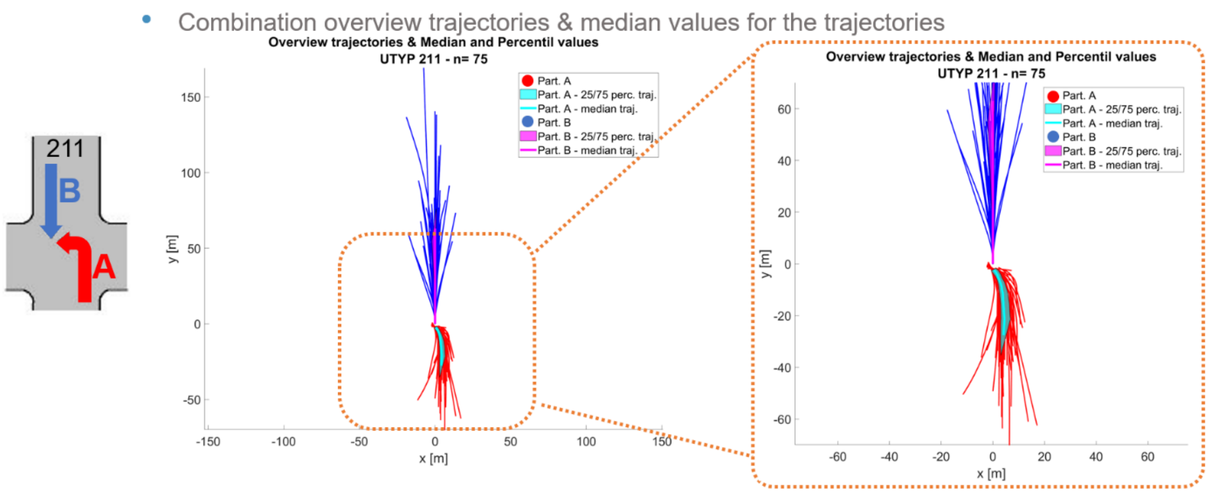


Figure 86: Trajectories of Left turn accident (211)

(The trajectories do not cross each other because they display the centre of gravity trajectory.)

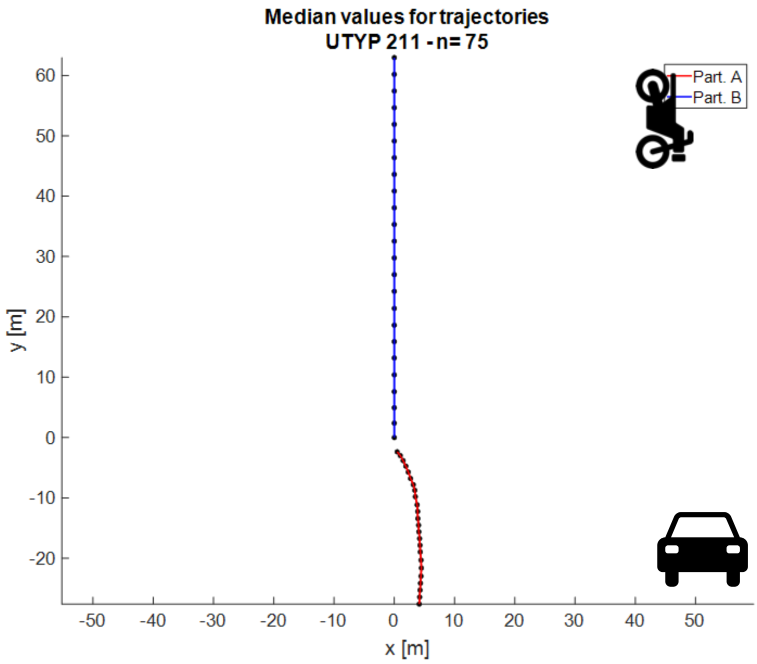


Figure 87: Median values for trajectories (211)

To understand what actions the participants were performing at each point in time, the dynamics data of the participants were analysed and mapped into a manoeuvre catalogue and the criteria of the vehicle's movement were commonly used for Left turn accident 211 types as well. Figure 88 shows the top five of the last two MIDs before a Participant A collision.

The most frequent manoeuvre was MID 1 followed by MID 8 (39% of the total). In this manoeuvre, Participant A constantly moves towards the left turning point and makes the turn at a constant speed, which could mean Participant A either did not register the oncoming Participant B or did so too late to take avoidance action.

The next most frequent manoeuvres were MID 8 followed by MID 10, and MID 10 followed by MID 3, which together made up 25% of the total. In these manoeuvres, Participant A slows down at the left turning point, i.e., the vehicle operator registered the oncoming Participant B, but then misjudged the timing of the turn, which led to a collision.

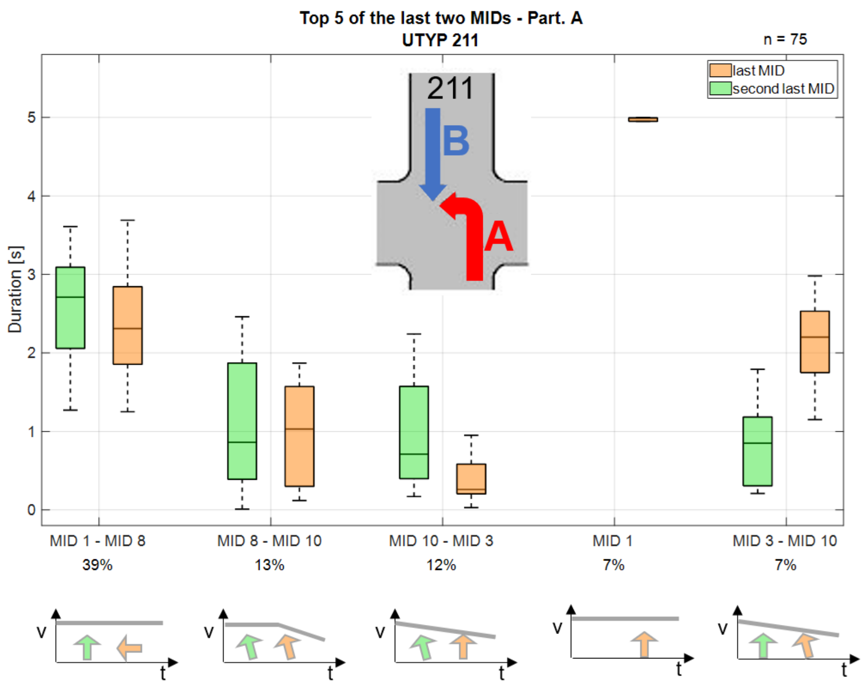


Figure 88: Top five of the last two MIDs for Participant A (211)

Figure 89 shows the top five of the last two MIDs before a collision for Participant B. As Participant B is going straight through, the vehicle is at a constant speed at the beginning, and as observed in the MID 1 followed by MID 3 scenario, which accounts for 51% of incidents, the rider recognises Participant A at a certain point and starts to decelerate. MID 1 only or MID 1 before a collision would mean that Participant B did not have time to react to Participant A or realised too late. MID 14 followed by MID 16 and MID 8 followed by MID 10 show some avoidance response; a change of direction either right or left while slowing down.

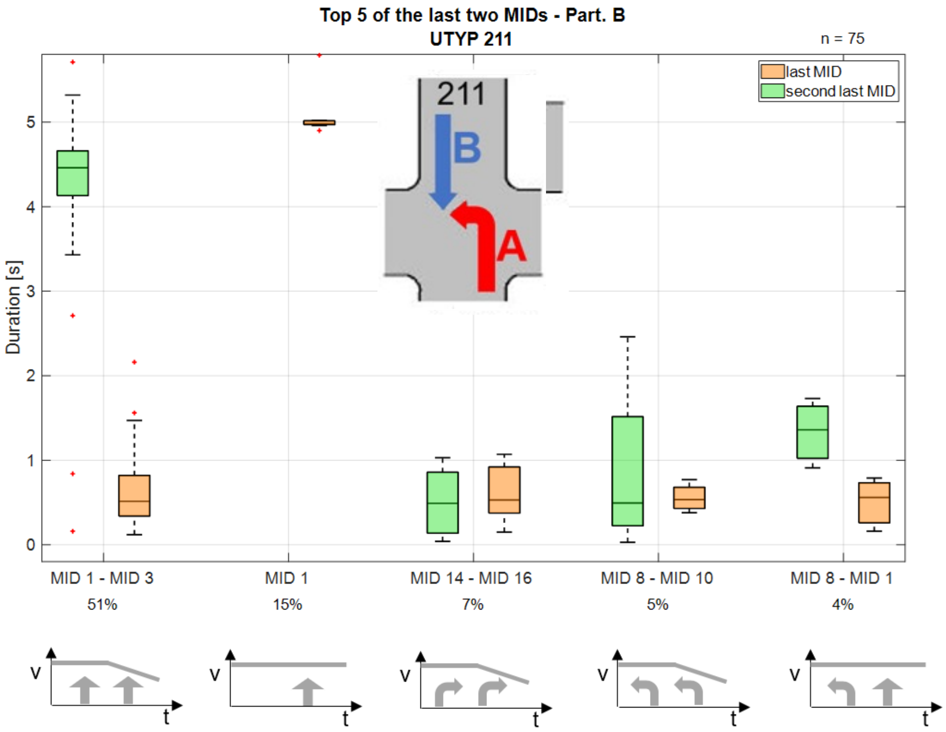
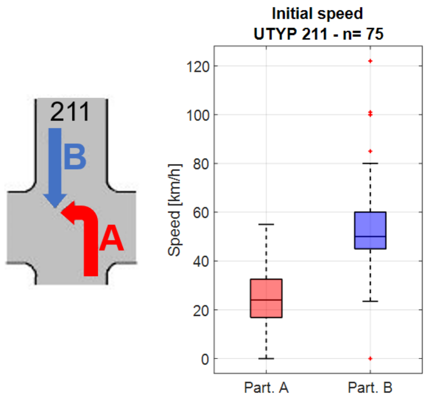
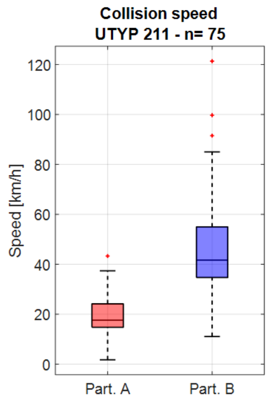


Figure 89: Top five of the last two MIDs for Participant B (211)

The initial speed and collision speed of each participant is shown in Figure 90. As a median value, Participant A is at 24km/h and Participant B is at 50km/h. Collision speed for Participant A as the median value is constant at 18km/h and for Participant B with some slowing down at 42km/h.



Initial speed	Data Part. A [km/h]	Data Part. B [km/h]
Maximum	55	122
Upper Whisker	55	80
75th percentile	33	60
Median	24	50
25th percentile	17	45
Lower Whisker	0	23
Minimum	0	0



Collision speed	Data Part. A [km/h]	Data Part. B [km/h]
Maximum	43	121
Upper Whisker	37	85
75th percentile	24	55
Median	18	42
25th percentile	15	35
Lower Whisker	2	11
Minimum	2	11

Figure 90: Initial and collision speed of participants (211)

Figure 91 shows the median values of trajectories with speed information indicated. All the data mentioned so far was entered together in order to better understand the whole median scenario for Left turn accident 211.

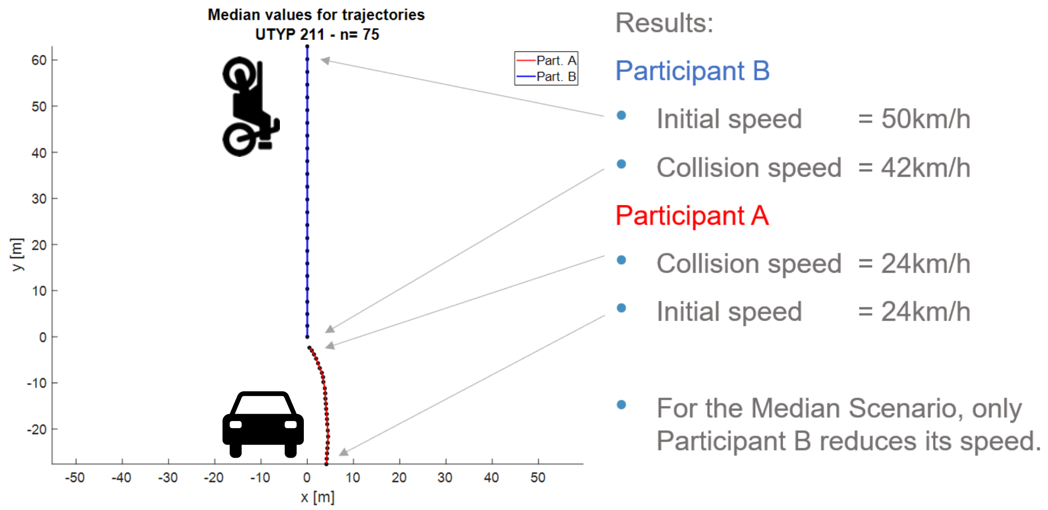
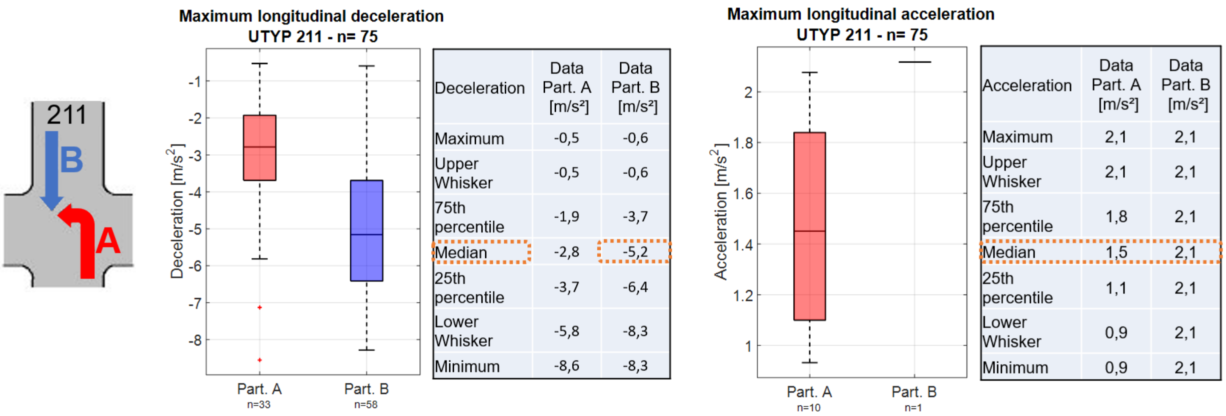


Figure 91: Results of median values for trajectories and speeds (211)

Figure 92 shows the results of each participant's maximum deceleration and acceleration value. For the median scenario, Participant A decelerated by -2.8m/s2, and Participant B decelerated by -5.6m/s2 before the collision.



Deceleration	Data Part. A [m/s²]	Data Part. B [m/s²]
Maximum	-0,5	-0,6
Upper Whisker	-0,5	-0,6
75th percentile	-1,9	-3,7
Median	-2,8	-5,2
25th percentile	-3,7	-6,4
Lower Whisker	-5,8	-8,3
Minimum	-8,6	-8,3

Acceleration	Data Part. A [m/s²]	Data Part. B [m/s²]
Maximum	2,1	2,1
Upper Whisker	2,1	2,1
75th percentile	1,8	2,1
Median	1,5	2,1
25th percentile	1,1	2,1
Lower Whisker	0,9	2,1
Minimum	0,9	2,1

Figure 92: Deceleration/Acceleration analysis results (211)

Figure 93 shows the median scenario overview of Left turn accidents type 211 with all the information so far derived.

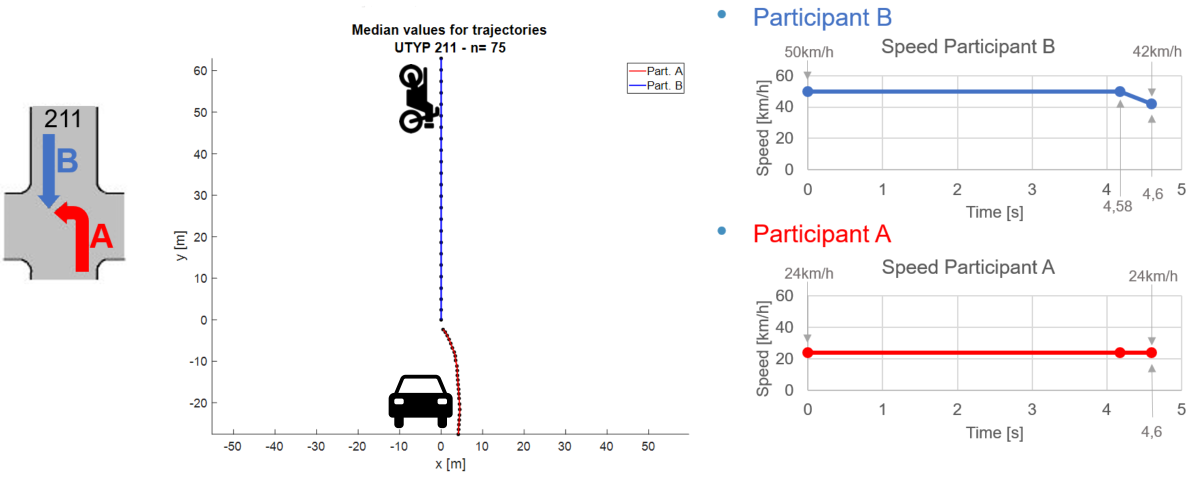


Figure 93: Overview of median scenario of Left turn accident 211 with trajectory, speed and deceleration/ acceleration information

Time To Collision (TTC) is an important safety indicator of the time for the vehicle operator to recognise the danger ahead and allow for reaction time. Figure 94 shows the basic TTC calculation model used in this analysis. A tube for each traffic participant is extended as a linear/straight motion with the current speed values and determines whether the two participants enter the critical conflict zone at the same time. If so, TTC is provided as a division of distance by relative speed.

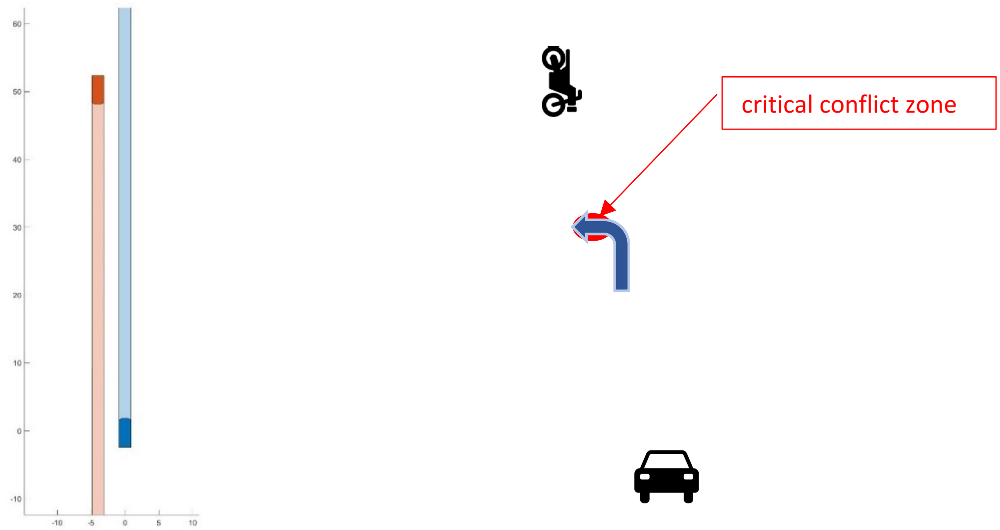


Figure 94: TTC calculation model

Figure 95 shows the TTC calculation result in a heat map for Left turn type 211 accidents. The graph shows a relatively linear rise from the point of collision and high density in severely critical areas. However, in the area TTC > 1.6s, it becomes low density which indicates that it is difficult to provide TTC before 1.6s. This is due to the fact that with Left turn accidents, before Participant A starts its action to turn left, it is going in parallel with Participant B and the extended tube never crosses, resulting in no conflict zone.

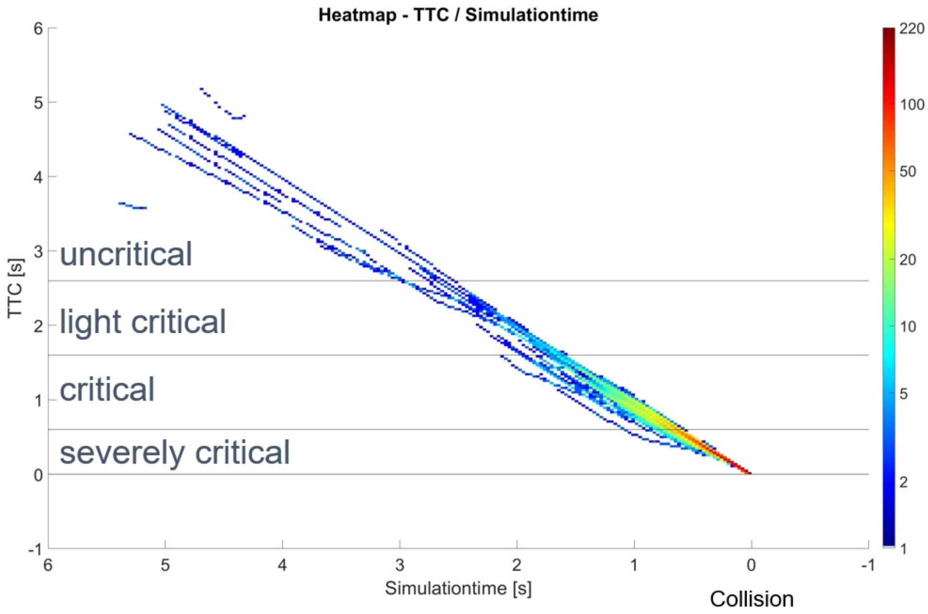


Figure 95: TTC calculation result for Left turn accident 211

Figure 96 shows cumulative case numbers of TTC and where they cross the 50% line, i.e., half of the vehicle operators can only be informed 1.5s seconds before the collision.

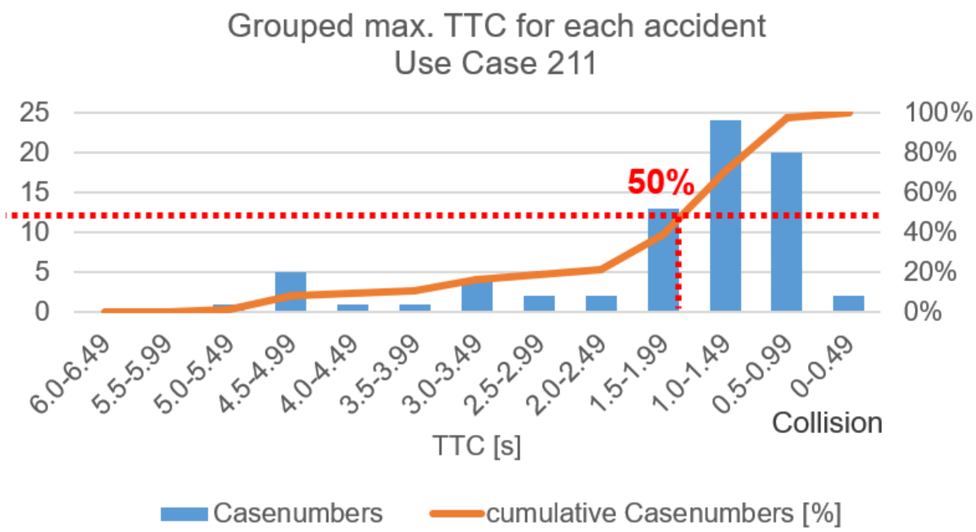


Figure 96: Cumulative case numbers of TTC for each accident (211)

CMC analysed Crossing traffic accident type 302 and Left turn accident type 211 in detail based on the GIDAS database and GIDAS-PCM. These databases provide insights into a great number of aspects of each reported accident, for example road conditions, speed, visibility, trajectories, actions of the participants etc. In analysis Module 1, a total of 23 potential influencing or mitigating factors were investigated and reported, including the ones that eventually did not appear to make any significant contribution to the accident. In analysis Module 2, an additional give investigation was conducted to understand the accident situation more clearly.

From the analysis, an important outcome is that no explicit View obstruction existed in the majority of cases, and yet Participant A (mainly cars/trucks) failed to observe Participant B (mainly PTWs) or misjudged, mistimed or incorrectly responded to the situation, leading to a collision. This implies the need for technology support to inform Participant A about the oncoming Participant B.

In addition, the study of TTC shows that the earliest possibility to notify a vehicle driver/ rider is 4.5s (Median) before the collision in Crossing traffic accident type 302 cases, while it is 1.5s (Median) in Left turn accident type 211 cases, as shown in Figure 97.

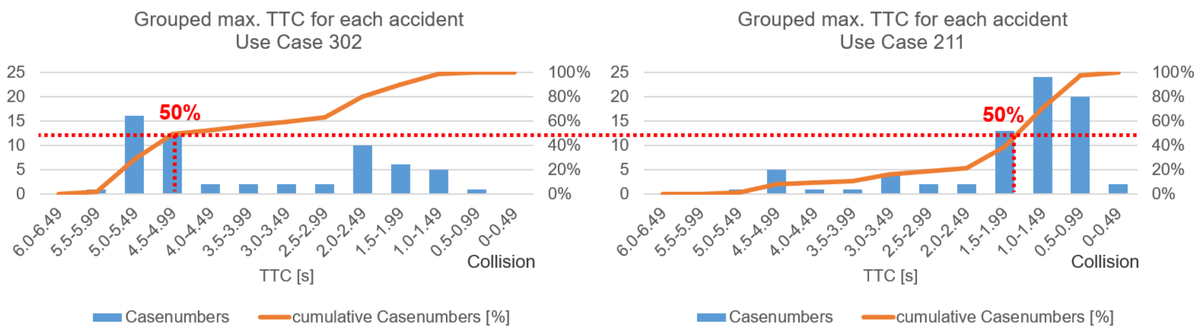


Figure 97: Comparison of cumulative TTC case numbers for 302 and 211

A further challenge remains concerning the appropriate timing to inform the vehicle operator of the danger ahead. To provide notifications with a sufficient time margin before a collision, a different TTC calculation method, which detects the risk earlier, needs to be applied. This time margin, however, should be optimised to avoid excessive false positives and does not simply mean 'the longer the better'.

5.5. Reaction Time and Time to Collision

5.5.1. Background and Motivation

As a result of the sophisticated accident analysis conducted within CMC Next, TTC values for specific accident types are available. For instance, in accident type 302 (cross traffic), a driver/ rider can be informed 4.5s prior to a potential collision, but high false positive rates remain an issue. The question is, what might be the latest possible point in time for a warning to be issued without undermining the safety benefit of the application? This fine-grained data was missing for PTWs. Consequently, as part of the user study conducted on a motorcycle riding simulator, empirical data on PTW rider reaction times can now be supplied with a view towards optimising notifications. It helps to understand whether (and indeed how well) the investigated rider notification reduces critical events. It provides information on whether and how different reaction times of PTW riders compare to passenger car drivers in a similar setup. Further, it provides a reference reaction time for OEMs to achieve with their own HMI warning concepts. This knowledge bridges the gap between results from the 'accidentology site' and use/test case definitions aimed at supporting decisions on how an application's display and alerts should appear (e.g., advisory notification, crash warning, active intervention).

5.5.2. Methods

5.5.2.1. Motorcycle simulator description

The DESMORI dynamic motorcycle riding simulator was used for the participant study (Figure 98). It is equipped with a BMW F800S mock-up mounted on a '6 degrees of freedom' hydraulic Stewart platform. The mock-up enables the rider to interact with realistic controls, such as the usual handlebar, brake lever/pedal, clutch, gear selector, etc. The manual gear shift uses a sequential six-speed gearbox. An electrical actuator produces steering torque in the handlebar of up to 80Nm. The rider steers the motorcycle through a combination of steering torque and induced roll torque situations by shifting his/her weight. The concave screen measuring 4.5m x 2.8m, which enables a 220° horizontal field of view. The two rear-mirrors are realised by 7-inch TFT-displays while the dashboard is displayed on a 10-inch TFT-touchscreen. Sound is provided via body shakers, which are attached to the riders' helmets. Moreover, a shaker that is installed below the seat delivers vibrations from the engine and simulated road roughness. A rope-towing mechanism simulates longitudinal forces to the rider torso.

Figure 98: DESMORI Dynamic motorcycle riding simulator at WIVW

5.5.2.2. Test Course

The test course had a total length of around 37km. It consists of different modules representing rural and urban roads. The order of modules was delivered in four versions to avoid sequence effects in the findings. There was one urban and one rural test scenario covered twice by every participant. The trajectories, geometry etc. were exactly the same, while the virtual environment was different to prevent riders from anticipating manoeuvres (learning from experience). Both test scenarios obscured the 'conflict partner' from the rider's view at the moment the warning was triggered (Figure

99). Additionally, there was a rural and an urban baseline scenario without warning, but otherwise completely comparable conditions. The urban test scenario came from the FT Accidentology results. It was a Cross traffic scenario (accident type 302 in the GIDAS database). The PTW was approaching a crossing and had the right of way. A passenger car that was obligated to wait came from the right-hand side and did not see the PTW rider when entering the crossing. The view was obstructed by buildings close to the road. The passenger car came to a stop covering about a third of the PTW's lane.

Figure 99: Urban (left) and rural (right) test scenario.

In the rural scenario, the obstacle was a construction site or a broken-down vehicle, respectively. These obstacles could not be seen due to trees close to the road and a right-hand bend with a slight downhill section afterwards.

5.5.2.3. Study Procedure

Figure 100 illustrates the study procedure. All participants were welcomed and received an informed consent document providing all necessary information related to the study. Following the study instruction, a rating on the acceptance of C-ITS applications on PTWs was collected. The first ride on the simulator followed to familiarise riders with the virtual vehicle. Following the successful completion of this ride, the participants received specific instructions for the test ride. It contained information on the C-ITS application (working principle, type of rider notification, etc.), trip length, traffic regulations etc.

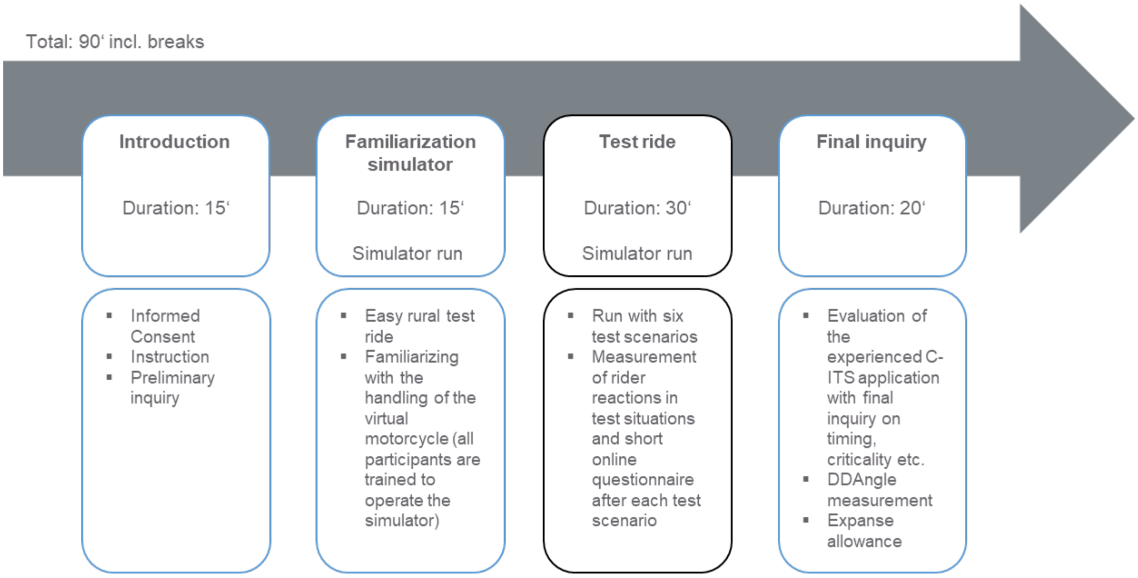


Figure 100: Schematic study procedure

After each test scenario the riders answered two questions while riding. At the end of the process a final questionnaire was conducted, and riders received an expense allowance. In order to facilitate the interpretation of the data, every participant mounted the mock-up motorcycle again and assessed whether he/she could recognise the dashboard in the peripheral field of view. Additionally, the dashboard's downward angle was measured, as illustrated in Figure 101.

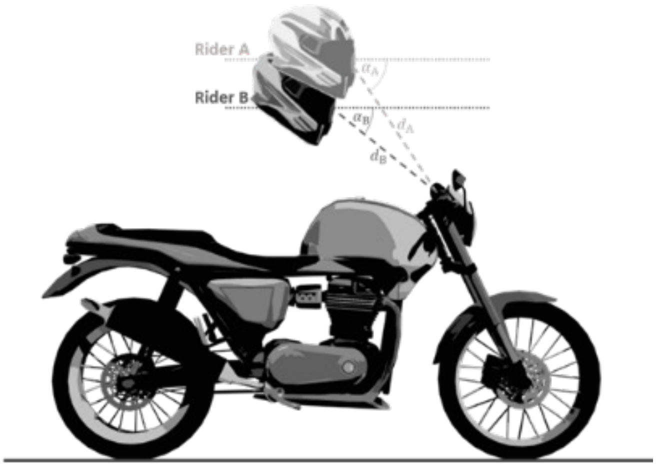


Figure 101: Schematic representation of different dashboard downward angles as a function of different rider heights

5.5.2.4. Rider Notification

The rider notification provides a purely visual warning to the rider, which is shown on the upper edge of the dashboard (see Figure 102). The 7-inch simulated dashboard has a 1920 x 1080 resolution and is mounted at an average dashboard downward angle of approximately 33°.

During the test, the alert was designed as a non-specific warning with a red rectangle (16mm x 27mm). The decision was taken to investigate an OEM-independent, generic warning.

Figure 102: Rider notification (red rectangle) in the dashboard

Further, the decision was a take a conservative approach, which means that a minimum notification would be subject to investigation. The notification was triggered with a Time-To-Arrival (TTA) = 3s prior to when the obstacle became visible. The warning was then displayed for three seconds and disappeared automatically.

5.5.2.5. Measures and Statistical Analysis

Three different types of reactions were analysed (Figure 103).

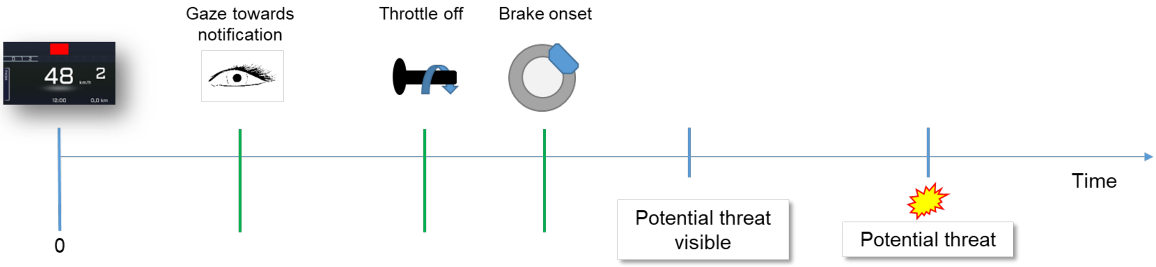


Figure 103: Schematic representation of different possibilities to calculate reaction times

The starting time t0 for any calculation is always the issuing of the visual warning in the dashboard (warning onset). The following three types of reactions are analysed:

Warning onset until gaze towards notification. The gaze behaviour, which distinguishes between 'gaze towards dashboard' and 'gaze not towards dashboard' is retrieved from the video data via manual video annotation. It is assumed that a gaze towards the dashboard while the warning is displayed goes along with the recognition of the warning, which is one of the major variables of interest.

Warning onset until throttle off. This parameter measures the time between warning onset and the release of the throttle twist grip as potentially the first intuitive reaction to reduce the speed. A throttle twist grip release is defined as complete release to the neutral throttle position.

Warning onset until brake onset. This parameter measures the time between warning onset and the start of mechanical braking (either front or rear brake or both) as a rider reaction for significant speed reduction. Brake onset is defined as an operation of any brake lever.

During the testing, depending on the evolution of each specific test scenario, throttle off and brake onset did not necessarily have to occur, if a rider judged the situation as sufficiently controllable and safe. If there was no gaze towards the dashboard, the situation was counted as a 'missed warning'. Consequently, no type of reaction towards a warning can be calculated in this case. Any rider responding later than 300ms after the warning onset was regarded as a response to the warning instead of a regular 'control gaze' towards the dashboard.

In addition to the vehicle dynamics data, subjective measures were gathered. After each test situation the riders were asked whether the C-ITS application emitted a warning. If the answer was positive, the riders were asked what their reaction was. This information helps to interpret the riding data. For instance, a rider may reply that he/she recognised the warning but decided not to brake, because there was enough space in the lane to evade the potential conflict situation/collision. The second question targeted the perceived criticality of the situation. The answers were given on a 'criticality scale', as displayed in Figure 104. Both questions were answered while riding.

Figure 104: Situation criticality scale (English version translated from Neukum et al., 2008)

A final set of questions completed the testing experience. The riders were asked to rate the recognisability of the rider notification on a 16-point verbal (categorisation) scale ranging from '0 impossible' to '15 very good'. Furthermore, the riders were asked about the perceived warning timing and their general attitude towards C-ITS-based assistance systems on/in motorcycles. The latter question was also asked at the very beginning before riders experienced the C-ITS application in the simulation. The answers were given on a 13-point verbal (categorisation) scale as shown in Figure 105. For acceptance ratings below '0', participants were asked for the underlying reasons.

Way too early/ strongly disagree			Too early/ disagree			Neither nor	Too late/ agree			Way too late/ Strongly agree		
-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6

Figure 105: 13-point verbal (categorisation) scale

The dashboard downward angle was measured in degrees by the experimenter using a goniometer, while the participant was sitting on the motorcycle simulator wearing his/her full-face helmet. Figure 106 shows an average head down angle towards the dashboard of 33° with a considerable spread between participants depending on rider height, torso length, etc. The interquartile range of 5.3° covers the range from 30.9° to 36.2°.

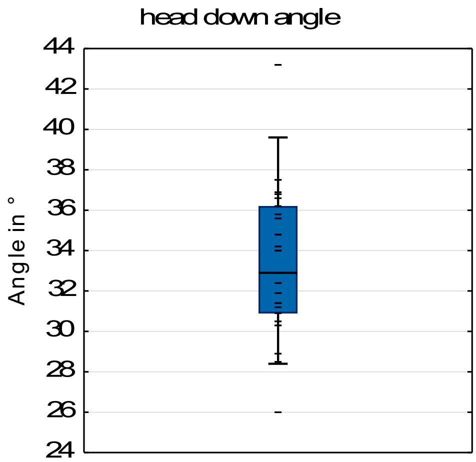


Figure 106: Measured head down angles towards the dashboard

The data analysis is based on different subgroups in the dataset:

1. Complete dataset for the estimation of the warning's effect in comparison to the baseline
2. Comparison of urban and rural test scenarios for the estimation of the riding environment's effect on riders' behaviour
3. Analysis of the trials for which the riders' reported to have seen the warning in order to analyse rider reactions that can be attributed as a reaction to the warning

Video annotation was done with *SILAB VideoAnalysis®*. Data has been pre-processed with *MatLab®* and further analysed using *Statistica® and SPSS®*. Descriptive data, such as means, distributions etc. show raw data if not elsewise stated. A base 10-logarithm was calculated for inferential statistics regarding the reaction times, to account for skewness and abnormal distribution of the raw data.

5.5.2.6. Participants Panel

A total of N = 24 riders participated in the study, while n = 3 were female. The panel represented a wide spread of different ages and levels of riding experience, as can be seen in Table 5. The study has been approved by WIVW's group in charge for ethical assessment. The strict ethical guideline as defined in the standard operating procedures based on the Guidelines for Safeguarding Good Research Practice of the German Research Foundation (DFG) as well as the Code of Professional Ethics of the German Association of Psychologists (bdp) and the German Psychological Society (DGPs) has been followed. All participants were recruited from the WIVW motorcycle rider panel, which consists of non-professional riders that had previously been trained to ride the simulator safely.

Table 5: Panel description (N = 24 with n = 3 female riders)

	Mean	Standard deviation	Minimum	Maximum
Age in years	36	12	20	60
Motorcycle mileage covered during the last 12 months in km	3,854	3,232	500	12,000
Motorcycle mileage during lifetime in km	78,500	79,900	2,000	300,000

5.5.3. Results

The analysed segments start with the warning onset and stop when the rider has passed the potentially critical situation. The presentation of the results follows the defined rider reaction variables 'gaze behaviour', 'throttle off', 'brake onset', and 'subjective measures'.

5.5.3.1. Gaze Behaviour

In both warning and baseline scenarios, riders' show (control) gazes towards the dashboard. On average, one gaze towards the dashboard takes approximately 400ms. In the baseline condition, more regular control gazes towards the dashboard can be observed in the urban area as compared to the rural setting. The number of riders with at least one gaze towards the dashboard increases with a warning being presented, as can be seen from Figure 107 left (Rural: with a warning 56% (27/48) instead of 9% (2/22) without warning; Urban: with a warning 94% (45/48) instead of 63% (15/24) without warning).

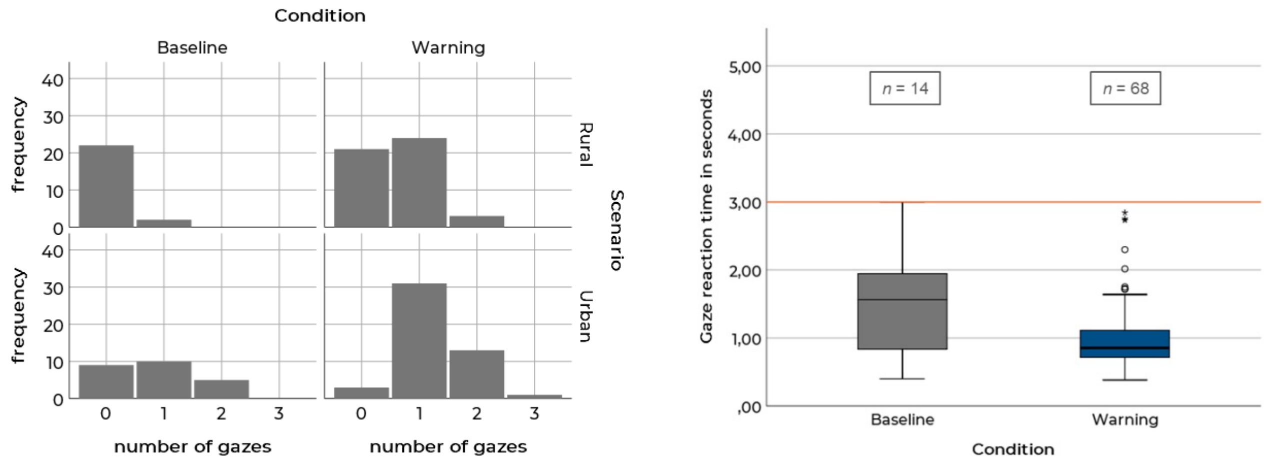


Figure 107: Distribution of gaze frequency towards the dashboard in the (hypothetical for baseline) warning period (left). Boxplot for riders' gaze reaction times after the (hypothetical) emission of a warning towards the dashboard (right). The orange horizontal line indicates the point in time when the obstacle becomes visible, and the warning disappears.

Regarding gaze reaction time (Figure 107 right), within the warning condition most riders react on a rather homogeneous level. While 50% of the participants look at the warning within 0.85s or less (Median value), 25% need more than 1.12s (75th percentile). In comparison to the baseline condition, the riders record earlier gazes towards the dashboard in the warning condition ($F(1,11) = 6.89$, $p = .024$, $\eta^2_{part} = .385$).

Figure 108 shows a more detailed analysis of the participants' gaze reaction times, taking into account the differences between the investigated rural and urban scenarios. Within the warning scenarios a difference regarding the frequency of gaze reactions towards the warning can be observed (42/48 reactions within the urban scenarios vs. 26/48 within the rural scenarios). Besides the higher number of participants who directed their gaze towards the dashboard after the warning appeared in the rural scenarios, faster reaction times can be observed on average (m_{Rural} = 1.22 sec; m_{Urban} = 0.91 sec).

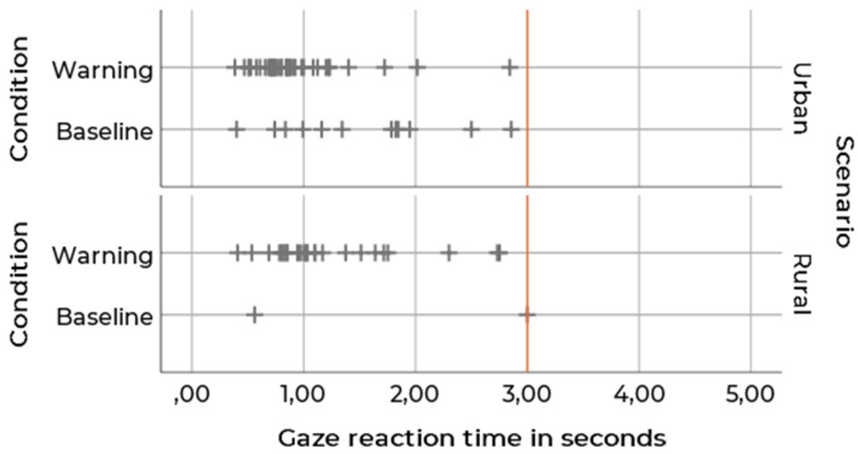


Figure 108: Riders' gaze reaction time after the warning has been emitted for rural and urban scenarios in warning and baseline condition. + indicates a single measurement, the orange vertical line indicates the point in time when the obstacle becomes visible, and the warning disappears.

5.5.3.2. Throttle Off

Regarding 'throttle off', a comparable ratio of rider reactions between the baseline and the warning condition can be observed compared to riders' gaze reactions. Again, more riders react within the warning condition ($n_{Warning}$ = 55/ 96; $n_{Baseline}$ = 10/ 48). While a majority of the riders within the warning condition shows a throttle off reaction before the obstacle becomes visible, almost all riders react after the corresponding point in time in the baseline condition (indicated by the orange vertical line in Figure 109). In the warning condition a median value (*Mdn* = 1.51 sec) for the throttle reaction time can be observed.

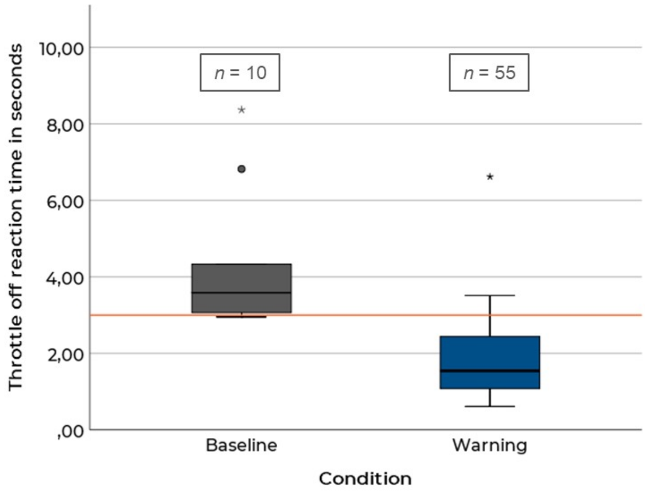


Figure 109: Boxplot for riders' throttle reaction time after the (hypothetical) emission of a warning towards the dashboard. The orange horizontal line indicates the point in time when the obstacle becomes visible and the warning disappears

Taking into account the difference between rural and the urban scenario, a higher number of reactions can be observed in the urban scenarios (n_{Urban} = 34/ 48; n_{Rural} = 21/ 48). Additionally, riders react earlier in the urban scenarios compared to the rural scenarios within the warning condition (Mdn_{Urban} = 1.27 sec; Mdn_{Rural} = 2.13 sec). The baseline throttle response is shown in Figure 110, as a comparison, to see that the warning must have been the reason to release the throttle and not the scenario itself.

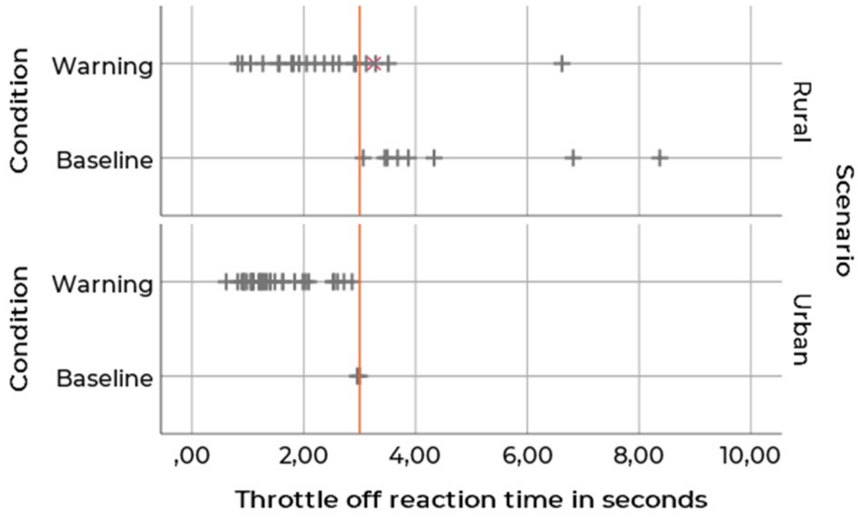


Figure 110: Riders' throttle off reaction times after the warning has been emitted for rural and urban scenarios in warning and baseline (corresponding time section) condition. + indicates a single measurement, x indicates a reaction, where the rider stated to not have seen a warning, the orange vertical line indicates the point in time when the obstacle becomes visible and the warning disappears

5.5.3.3. Brake Reaction

The measured brake reaction times are well in line with the gaze and throttle off reaction times. Figure 111 summarises the brake reaction times. Once again, the baseline values are given as a comparison to estimated effect of the warning instead of the scenario itself. While all riders in the baseline condition react after the point in time at which the obstacle becomes visible, more than 50% of the riders in the warning condition show a brake reaction initiation before the obstacle becomes visible (*Mdn* = 2.49 sec).

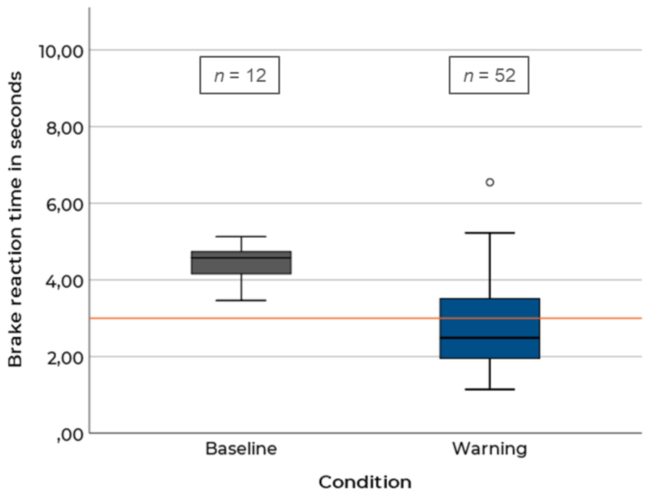


Figure 111: Boxplot for riders' throttle reaction times after the (hypothetical) emission of a warning on the dashboard. The orange horizontal line indicates the point in time when the obstacle becomes visible and the warning disappears

Figure 112 shows a more detailed analysis of riders' brake reaction times.

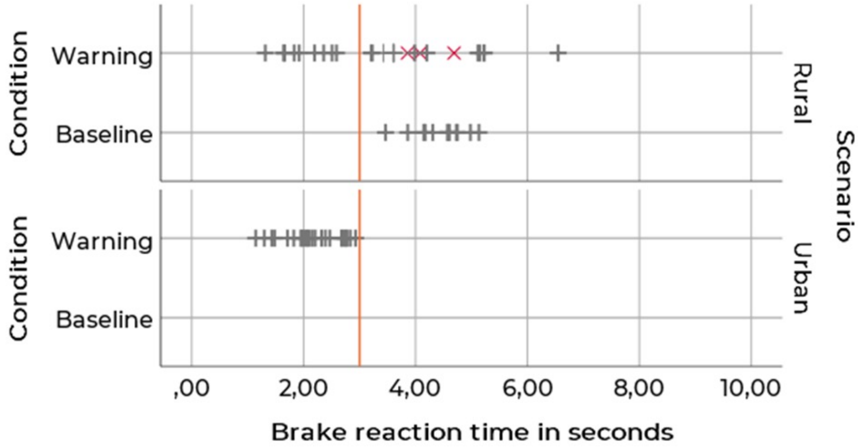


Figure 112: Riders' brake reaction time after the warning has been emitted for rural and urban scenarios in warning and baseline (corresponding time section) condition. + indicates a single measurement, x indicates a reaction, where the rider stated not to have seen a warning, the orange vertical line indicates the point in time when the obstacle becomes visible and the warning disappears

All brake reactions in the urban warning condition are observed before the obstacle becomes visible (*Max* = 2.93 sec; obstacle becoming visible at 3 sec). In contrast, less than 50% of the participants show a brake reaction before the obstacle becomes visible in the rural scenario (*Mdn* = 3.51 sec; obstacle becomes visible at 3 sec). In the baseline condition no brake reactions can be observed in the urban scenarios while there are *n* = 12 participants who react in the rural scenario (between *Min* = 3.46 sec and *Max* = 5.13 sec) as a response to the broken-down vehicle – after the point at which the warning would have been emitted.

Figure 113 shows a summarised rider reaction time plot which displays data from riders who have seen the warning, so throttle off and brake onset can be interpreted as reactions to the warning. This is especially true for reactions within the warning period of three seconds (left of the orange vertical line) as the potentially critical situation only became visible afterwards. As can be seen from the plot, rider reactions for gaze, throttle and brake start earlier in the urban scenario compared to the rural scenario (median values represented by the vertical black lines within the blue boxes displaying the interquartile range). Within the urban and rural scenarios, a shift can be observed with gaze reaction times occurring first, followed by throttle off reactions and brake reactions occurring last. In the urban scenario all participants react within the warning period or, in other words, before the obstacle becomes visible. In the rural scenario especially brake reactions, which start after the warning period, can be observed in more than 50% of the investigated cases.

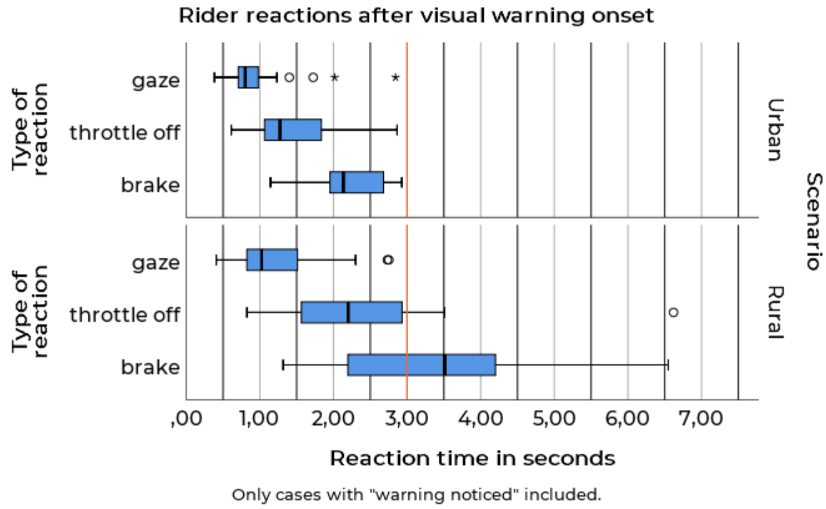


Figure 113: Summary rider reaction time boxplot containing data from participants who reported to have seen the warning. The plot shows rider reaction times for gaze, throttle and brake reactions separately for urban and rural scenarios. The orange vertical line indicates the point in time when the obstacle becomes visible and the warning disappears

5.5.3.4. Reaction Times Following the Gaze Reaction

In the following section, rider responses between the gaze reaction time and the throttle off reaction and, respectively, the gaze reaction time and brake onset reaction time will be reported (Figure 114).

The majority of riders shows a throttle off response within approximately 1s after the gaze has been directed towards the warning.

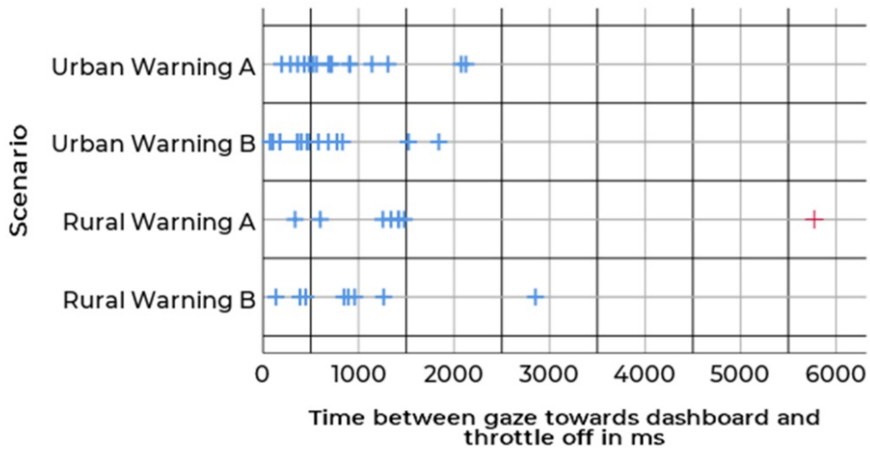


Figure 114: Rider reaction times between gaze reaction and throttle off for the individual warning scenarios

In the majority of observations, the riders react within approximately 1.5s with a brake onset after directing the gaze towards the dashboard (Figure 115).

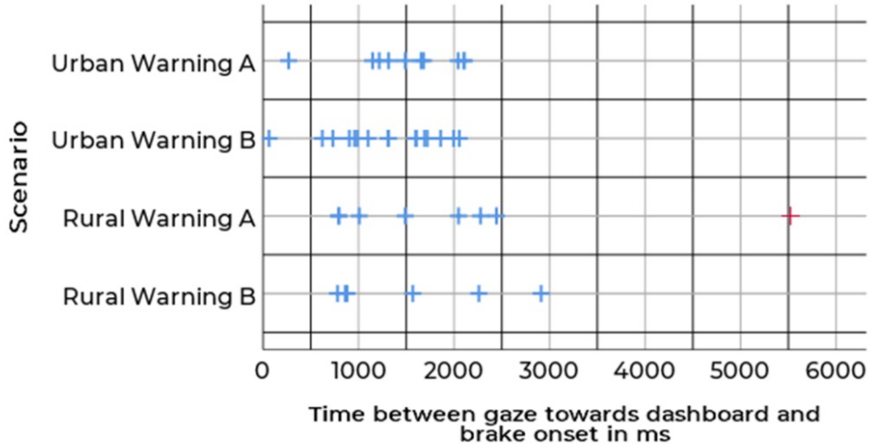


Figure 115: Rider reaction times between gaze reaction and brake onset for the individual warning scenarios

5.5.3.5. Subjective Measures

The participants were asked to rate the perceived situation criticality after each scenario. On average, the scenarios created unpleasant to dangerous situations, as intended (Figure 116). Yet, the situation itself was not subject to investigation, but it serves as a plausible reason for the riders to receive a notification. The warning decreases the perceived criticality in the more time critical crossing scenario, but not in the rural broken-down vehicle scenario (interaction effect: $F(1,23) = 45.60$, $p < .001$, $\eta^2_{part} = .66$).

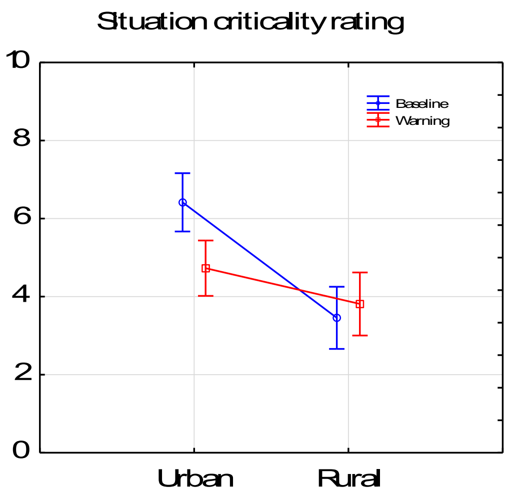


Figure 116: Situation criticality rating for baseline and warning condition for rural and urban scenarios

At the end of the study, the participants were asked to rate the perceptibility of the warning (Figure 115 left). On average, the riders rate the perceptibility of the warning as ‘medium’ (*Mdn* = 8), with a majority of the participants rating the warning in a range from ‘medium’ to ‘good’. The participants gave feedback regarding potential for improvement (Table 6), which includes visual representation of the warning (e.g., a flashing warning icon), the warning position (e.g., a higher position of the warning), warning size, and the inclusion of other modalities, especially acoustic alerts.

Table 6: Feedback and proposed improvements for the warning concept from the participants' perspective (Numbers in parentheses indicate frequency of mention)

visual representation	warning position	warning size	other modalities
Flashing icon (5)	higher warning position (5) or even head-mounted presentation of visual warnings (4)	red rectangle should be increased in size e.g., with the whole display flashing periodically (3)	Inclusion of acoustic warning (7)
Better visual perceptibility needed especially for hazardous situations (3)			Innovative solutions such as a vibrating handlebar
Warning should be specific (regarding situation criticality; red rectangle is associated with extreme criticality)			

The majority of participants rate the warning timing somewhere between ‘appropriate’ to ‘too late’ (Figure 117 right). Only few participants rate the warning as being too early.

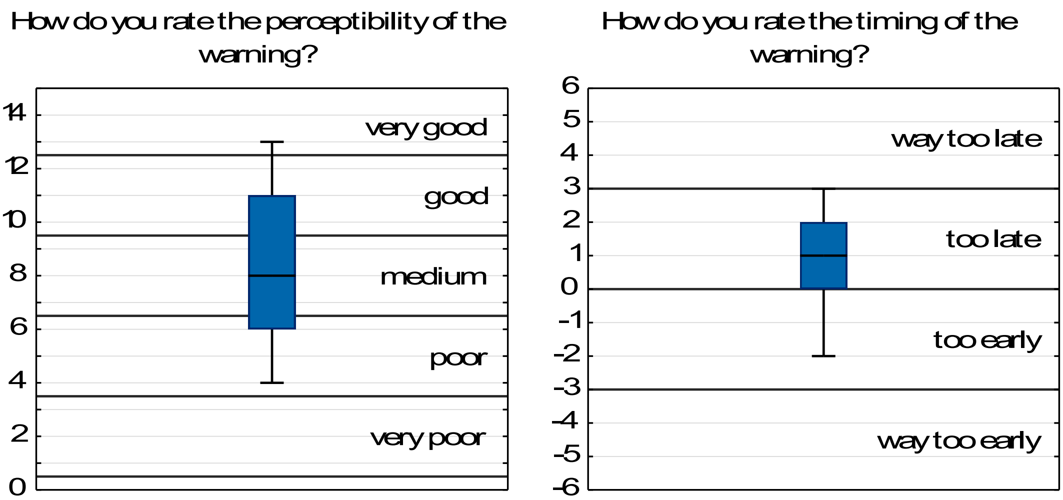


Figure 117: Rating of warning's perceptibility (left) and rating of the warning's timing (right).

The participants were asked before and after the ride to rate their attitude towards C-ITS applications for PTWs. The majority of participants stated to have a ‘favourable’ to ‘strongly favourable opinion’ towards C-ITS both before and after doing the simulation, with only few individuals reporting a ‘negative opinion’ (Figure 117 left). Figure 118 right depicts participants' individual change in attitude before and after the experiment.

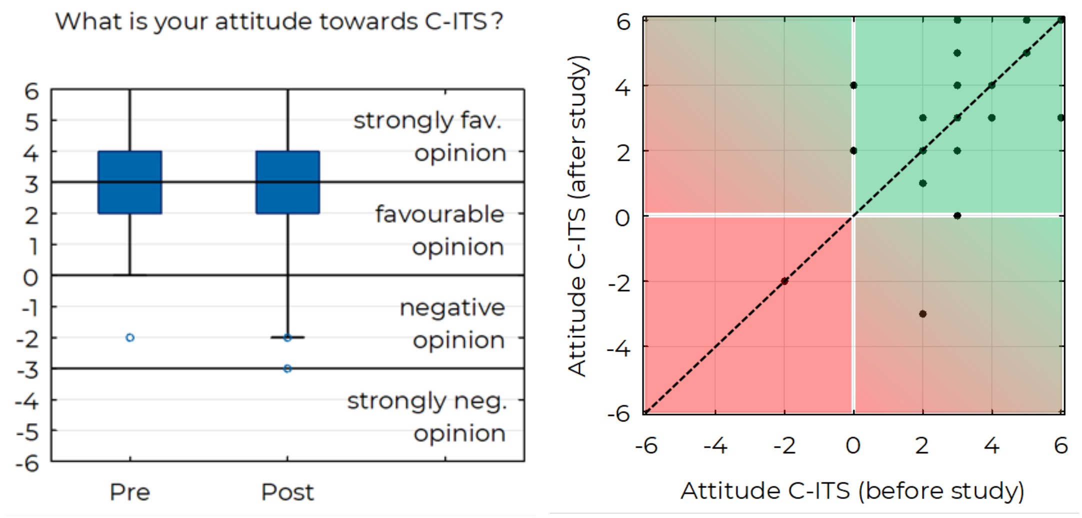


Figure 118: Attitude towards C-ITS applications on PTWs before and after the study (left) and change in attitude towards them before and after the study, per participant (right)

Data points in the upper right area represent participants who rated the system positively before and after the study, which covers the majority of values. Data points along the angle bisector (dashed line) represent participants that did not change their attitude. Values below the angle bisector indicate changes towards more negative, and above the angle bisector towards more positive evaluations after the study. The values seem evenly spread so that more experience with the system in the study did not significantly change the attitude.

5.5.4. Discussion

The present deliverable described a dynamic motorcycle simulator study, which investigated motorcycle riders' reaction times towards visual warnings. A 'conservative' rider notification in terms of a red rectangle displayed in the dashboard without auditory/sound alerts was investigated. Two scenario types were included: a cross traffic scenario in an urban environment and a broken-down vehicle (road works scenario) on a rural road. Both scenario types were experienced twice with a warning and once without a warning by every participant. To prevent 'expectancy effects', dummy scenarios were included that resembled the test scenarios in terms of road geometry, View obstruction etc., but did not include any potentially critical situation. This scenario design worked well as the participants could not identify the scripted critical scenarios while approaching. This means that no expectancy effects occurred, such as unnaturally cautious behaviour while approaching the test scenarios).

The first reaction time of interest was the time between warning onset and gaze directed towards the dashboard. Even in the baseline condition, riders have shown control gazes towards the dashboard during the hypothetical warning period. Yet, under the warning condition the number of gazes towards the dashboard was clearly increased. On the face of it, this has a high validity as riders seem to control their speed more often in the city compared to the approach phase of a rural curve. Additionally, the riders directed their gaze earlier towards the dashboard, which indicates that the warning was salient enough to catch the riders' attention. Yet, 16 out of 96 warnings were missed, which primarily occurred in the rural scenarios. This might be a result of different gaze behaviour for rural and urban scenarios. The latter providing a more vivid environment and potentially a higher perceived need to control the velocity on a more regular basis.

In summary, the purely visual warning could be noticed by a majority of riders, given an average dashboard downward angle of 33°. Yet, an improved rider notification design (e.g., warning tone, visual signals closer to the natural line of sight, etc.) was requested by the riders, which could increase the acceptance of an application and should have the potential to create less missed warnings and potentially shorten reaction times further. The investigated scenarios did not include imminent crash warnings, but advisory warnings with 3s between warning onset and a potentially critical situation becoming visible. Given the gaze reaction times, 3s is still regarded as slightly too late, on average, from the riders' point of view. With an average gaze reaction time of approximately 1s, the difference of 2s between recognising a warning and a potential threat becoming visible is experienced as slightly too late, on average.

In the baseline condition no throttle off or brake reactions were observed in the hypothetical warning period. This means that the throttle off and brake reactions observed were really a response to the warning and not the scenario itself. It is important to mention that the participants did not stay passive in potentially critical situations. When the obstacle became visible the majority took avoidance action (swerving) as braking was no longer an option (promising manoeuvre). This was especially true in the urban scenario. Yet, these reactions occurred when the potential threat became visible and was therefore not subject to investigation in this study. The difference between the rural and urban scenarios, which was already found for riders' gaze reaction times, was also observed for throttle off and brake reactions. Thus, the road type seems clearly to make a difference. The underlying reason for the different reaction times might be the scenario itself (e.g. the urban crossing scenario requires a faster reaction than the rural broken-down vehicle warning from the point in time when the critical situation becomes visible) or psychological effects such as imposed rider workload (e.g. higher level of awareness in the urban setting with more action in the periphery) as a result of the scenario.

The collected data seems to show differences to datasets on driver reaction times in the passenger car domain. For instance, guidelines such as the ISO 15623 2013 (E) suggest minimal driver reaction times of 0.4s and maximal reaction times of 1.5s or SAE J2400 names 1.18s before starting a response to a Forward Collision Warning. Passenger car simulator study results, for instance by Winkler et al. (2015), measured 0.86s, on average, as brake reaction time with a purely visual generic warning in a Heads-Up Display (HUD) in a time-critical crossing scenario with a pedestrian. Bella and Silvestri (2017) investigated a cross traffic scenario in a driving simulator with a purely visual warning in the dashboard triggered approximately with a TTC of 4s. Their average reaction, defined as time between warning onset and the moment when the driver starts to decrease speed, is 0.94s. For the crossing scenario in this study, as the fairest comparison, the mean throttle response was 1.47s and 2.18s for braking. Completely missed warnings were not really an issue in the cited passenger car research.

Obviously, simulator studies come with certain limitations, including missing environmental factors (e.g. sun glare) and a focus on relative or scenario-dependent validity regimes, thus precluding a one-to-one match with results gained in a field study. Yet, the chosen simulator study has clear advantages, which made it efficient and appropriate to follow this approach. Firstly, there was almost no information on PTW rider reaction times available, so this study presented some valuable empirical evidence in this domain. The fact that simulations offer a fully controlled environment in terms of the behaviour of other traffic participants, and repeatable critical scenarios with convenient and precise measurement of all necessary data are also clear advantages. Further, using simulations avoids certain ethical and safety constraints associated with field tests, investigating rider reaction times in potentially critical scenarios. In addition, field test results may not be 'generalisable' to the degree that simulations can be. Field testing a specific PTW – with its given ergonomics, dashboard angle, etc. – would be completely different to the setup on, say, a chopper or touring motorbike.

5.5.5. Conclusion of Subchapter

Firstly, the results of the presented user-centred simulator study successfully provide an initial estimation of motorcycle rider reaction times to a generic purely visual warning. These reaction times can be seen as a benchmark for future visual warning designs. Thus, it is an opportunity for OEMs or TIER1-suppliers to compare the reactions triggered by their rider notification solutions in a comparable setup to the generic warning design in order to assess their efficacy. Therefore, new warning designs should ideally result in lower or at least equal rider reaction times and less missed warnings as compared to the given conservative rider notification. Besides the already acceptable salience of the investigated warnings, potential improvements were identified, which should be taken into account for further developments.

Secondly, even though it is impossible to identify absolutely comparable studies from the passenger car domain, the empirical evidence suggests a need for PTW-specific reaction time analysis as more missed warnings were observed and reaction time distributions differed.

Thirdly, the distributions of rider reaction times can serve as important input to the tuning of rider behaviour models, which are required to create effectiveness estimations for (C-ITS) safety applications by means of traffic simulation.

6. Use Case Creation

The detailed study and data analysis provided in this chapter was conducted by CMC. The following use cases are based on PTW-specific accident analysis. PTWs have different characteristics compared to other road users, including their smaller size and different driving dynamics compared to other types of vehicles, which may end up in a variety of dangerous situations as described below:

- Hidden behind another participant or object
- Delay of detection by other road users such as car drivers
- Hidden in the blind spot
- Speed and distance easily misjudged
- Filtering through narrow space

The following chapters describe important use cases with conflict potential for Advanced Driver Assistance Systems (ADAS) based on onboard sensor systems such as camera or radar, and C-ITS technologies taking PTW-specific characteristics into consideration.

The basic criterion to decide whether a conflict situation will arise or not is the TTC, which defines what time is left before the conflict emerges. For the TTC calculation, a path prediction is used which assumes constant speed and trajectory for each Participant At every point in time. If these paths cross and would lead to a collision, a TTC can be calculated. For the following analyses, the GIDAS database was used and weighted to the German motorcycle accident statistics 2019.[1,2]

6.1. Cross Traffic Use Cases

Crossing traffic accident types according to the GIDAS database describe a conflict between a road user (Participant A) who is obligated to wait ("W" in Figure 4) and a road user (Participant B) entitled to the right of way.

This type of accident with PTW participation happens most often in urban areas (67%), at junctions (53%), with the traffic regulation 'right of way' (73%). In addition, this scenario may occur at junctions and crossings of roads, fields or cycle paths, railway crossings as well as property exits or parking lots. Due to right-of-way violations, the scenario ends in a collision. According to the GIDAS database, the accident type 302 is the most common within the Crossing traffic scenario, shown in *Figure 119*.

[1] GIDAS dataset from 30.06.20 weighted to Germany 2019, https://www.gidas.org/start.html

[2] The methodology for the creating of the dataset can be found in chapter 3.3 of the document "CMC Basic Specification Assessment of C-ITS application potential", https://www.cmc-info.net/assessment.html

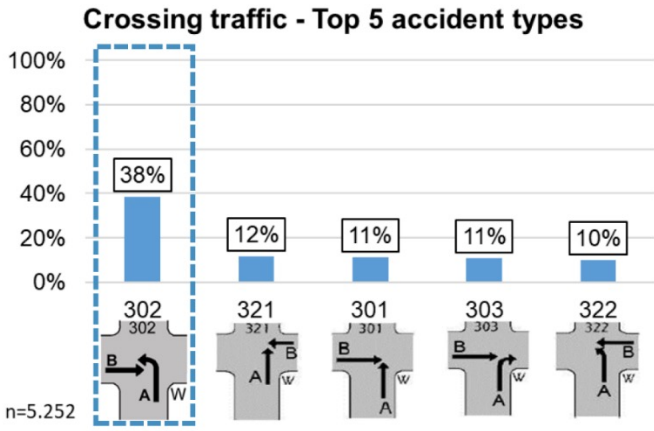


Figure 119: Selection of crossing traffic accident type3

6.1.1. Objective/Desired Behaviour

Ideally, Participant A should receive an advisory notification about the oncoming Participant B. In 62% of the analysed cases (GIDAS accident type 302), a TTC calculation earlier than TTC = 2.6 s is possible and gives Participant A time to decelerate and let Participant B pass.[4] If Participant A would start accelerating anyway, an active intervention combined with an earliest possible warning would mitigate the situation.

6.1.2. Expected Benefits

According to the GIDAS database, Crossing traffic is the most frequent scenario in which PTWs become the victim of an accident. Applications which prevent or mitigate these accident scenarios have high potential to save lives and reduce injuries.

6.2. Actors and Relations

6.2.1. ADAS Only

In our example participant A is a car which is about to enter the intersection to turn left. Participant A is obligated to wait. The car is equipped with onboard ADAS, such as camera and radar. Participant B is a PTW which is entering the intersection from the left side according to the perspective of participant A. Participant B is entitled to the right of way. The car is using active intervention such as Autonomous Emergency Braking (AEB), which will be accompanied by a warning.

6.2.2. ADAS + C-ITS

Participant A is a car which is about to enter the intersection to turn left. Participant A is obligated to wait. The car is equipped with onboard ADAS and C-ITS enabling direct

[3] Gesamtverband der Deutschen Versicherungswirtschaft e.V. (GDV), Unfallforschung der Versicherer; Unfalltypenkatalog, Leitfaden zur Bestimmung des Unfalltyps

[4] GIDAS-PCM 2020-1, https://www.vufo.de/gidas-pcm/

communication between the participants (V2X – Communication). Therefore, the car is receiving and processing the V2X messages sent by the participants. The car is using active intervention such as AEB based on onboard sensors, which will be accompanied by a warning. Participant B is a PTW which is entering the intersection from the left side according to the perspective of participant A. Participant B is entitled to the right of way. The PTW is equipped with a V2X communication unit and the PTW is sending a CAM regularly.

6.2.3. Traffic Situations

As described above, the use case focuses on a conflict which arises in perpendicular traffic. While the motivation to address this use case comes from the accident type 302, with a Left-turning Participant A, the use case also covers situations with other planned trajectories by participant A (e.g., going straight or turning right). The basic conflict remains the same. Still, the descriptions will focus on the accident type 302 situation. The following chapters explain possible situations more in detail. For accident type 302, different road type situations are explained, in order to cover the variety of real traffic crossing scenarios:

1-1: T – Junction: Participant A is waiting on a perpendicular street to the main carriageway and intends to turn left into the main carriageway. Participant B is travelling on the main carriageway heading towards the junction.

1-2: Crossing: Participant A is on a perpendicular road to Participant B, waiting to turn left onto the same road, but onto the opposite lane of Participant B. Participant B is travelling towards the crossing.

1-3: Property Exit: Participant A intends to enter the main carriageway from a property exit (which means Participant A enters the carriageway at a point which is not defined as a junction on a digital map). Participant B is travelling perpendicular to Participant A and is approaching the property exit.

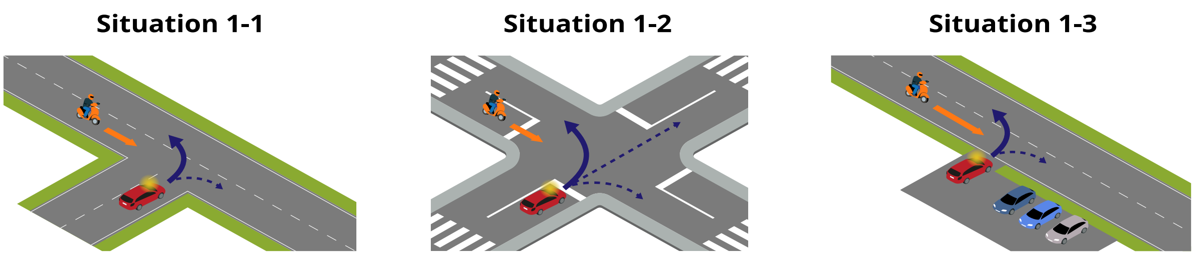


Figure 120: Road type situations for crossing without visual obstruction

According to the GIDAS database, every third Participant A (32.3%) had a View obstruction in the accident type 302.[5] Therefore, two different situations will be addressed.

2-1 No obstruction: Both Participants A and B are generally visible to each other while approaching the potential conflict zone.

2-2 With obstruction: Due to any kind of obstacle, such as a building or another

[5] GIDAS dataset from 30.06.20 weighted to Germany 2019, https://www.gidas.org/start.html

road user, Participant A and Participant B have limited or no view of each other until Participant A arrives at the junction.

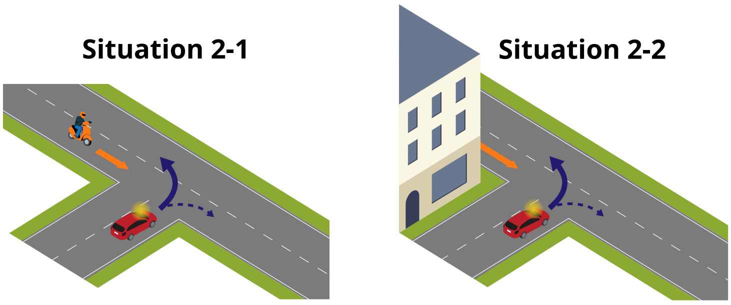


Figure 121: Road type situations for crossing without (left) and with View obstruction (right)

6.2.4. Use Case Scenarios

Scenario 1:

The starting situation of scenario 1:

Participant B (PTW) is on a right-of-way road following Participant C (here: blue car). Participant A (here: red car) is coming from the perpendicular road. The red car giving right of way cannot see Participant B, because it is hidden behind Participant C. Buildings or vegetation may further hinder the view. The main challenge of this scenario is a View obstruction due to a non-permanent obstacle, such as a car in this example.

The following figures will make use of dashed arrows to indicate potential driving directions of a vehicle that is currently stopped and solid arrows for actual driving directions/trajectories of a vehicle in motion.

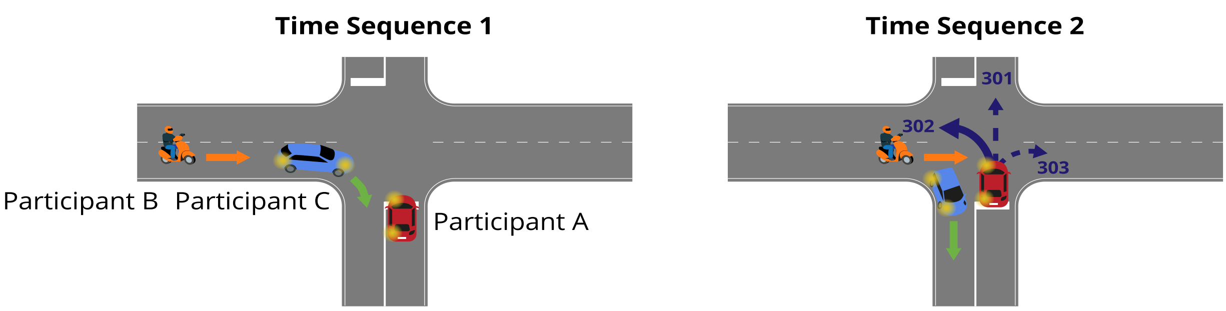


Figure 122: Scenario 1 – Participant A and Participant B cannot see each other due to View obstruction caused by Participant C (based on accident types 301, 302, 303 in the GIDAS database)

Special characteristics of scenario 1:

Since Participant C indicates its right turn (turn signal), the waiting Participant A presumably receives the signal to drive off. Participant C, as perceived by Participant A, will not cross the direction of travel of Participant A. Participant B is not visible to Participant A. For this reason, Participant A could already (early and thus causing a collision with Participant B) proceed with the planned driving manoeuvre, i.e. drive off/turn off.

Participant C turning right can also cause the distance between Participants B and C to be reduced due to the speed reduction associated with the turning manoeuvre, thus creating an even more unfavourable angle of view. In addition, a right-turning Participant C may at the same time entice Participant B to drive up closer in the lane (to the left), further worsening the already poor view from Participant A towards Participant B.

In this situation, it is possible that Participant B will continue to drive straight past Participant C while the vehicle is still turning to the right. In doing so, Participant B assumes that Participant A has noticed him/her and is therefore waiting. It is also possible that Participant B has not yet noticed Participant A. Often fatal misunderstandings, or a mixture of lack of perception and misinterpretation, cause these types of the situations.

Scenario 2:

The starting situation of scenario 2:

Participant A wants to turn left. Participant C, who is approaching from the left and has the right of way, crosses the intersection (here: blue car) and thereby obscures Participant B who is driving past the stationary vehicles and has the right of way to cross the intersection.

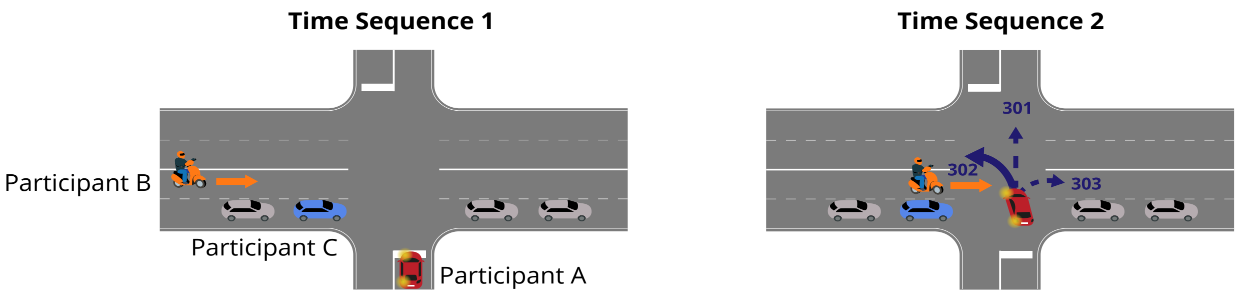


Figure 123: Scenario 2 – Participant A wants to enter the intersection, Participant C (here: grey car) keeps a small distance from the vehicle ahead (here: blue car) and thereby obscures Participant B who just wants to drive past the stationary vehicles (based on accident types 301, 302, 303 in the GIDAS database)

Special characteristics of scenario 2:

Participant C is standing with other participants in the right lane of a four-lane road with two lanes per driving direction in the crossing area. In the right lane, there is almost no distance between the participants, which makes it even more difficult for Participant A to gain a direct line of sight on Participant B. A fast start and left-turn by Participant A looking to enter the vacant opposite lane makes a collision with Participant B possible, who is passing the standing participants in the free left lane and cannot see Participant A or sees him/her very late.

Scenario 3:

The starting situation of scenario 3:

Participant A wants to turn left. Participant C, who is approaching from the left and has the right of way, crosses the intersection and attracts Participant A's attention while Participant B is approaching the intersection from the right.

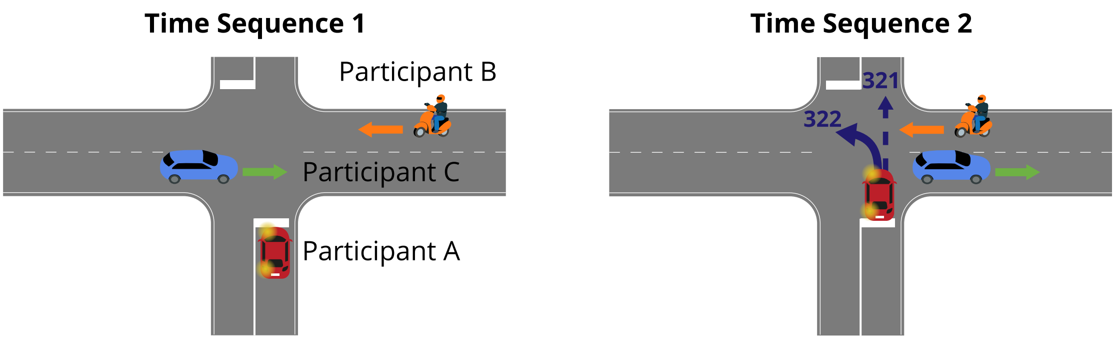


Figure 124: Scenario 3 - Participant A wants to turn left, Participant C approaches from the left and attracts Participant A's attention, therefore Participant A does not notice Participant B approaching from the right side (based on accident types 321, 322 in the GIDAS database)

Special characteristic of scenario 3:

Participant A could potentially see Participant B, but is distracted by Participant C. It is a matter of attention allocation or insufficient situation awareness, which means an insufficient analysis of the traffic situation. Therefore, Participant A begins to enter the intersection without noticing Participant B.

This scenario is evidence of the frequently occurring case of distraction as well as an obstructed view of Participant B (here: the narrow PTW) in the final phase of the scenario. In general, when turning left or crossing a junction, distraction and failing to see other vehicles is always a danger (both due to attention allocation or View obstruction). Such situations can be worsened in poor or difficult lighting conditions (e.g. sun glare, light-dark fields on forest roads).

6.2.5. Alert Principle

6.2.5.1. ADAS Only

Assuming that onboard sensors might recognise the other participant in Cross traffic rather late, an active intervention (AEB) seems the most likely possibility for accident avoidance or mitigation. This application should primarily run in Participant A's vehicle, which fails to give way to Participant B.

6.2.5.2. ADAS + C-ITS

An advisory V2X notification should increase situation awareness and direct driver/ rider attention towards other traffic participants entering the junction, to avoid Participant B not being observed/noticed by Participant A. Therefore, Participant A should be assisted in appropriately judging the remaining time to safely enter the junction. Information on the direction of Participant B could increase the acceptance of the application. If the advisory information is not considered, an active intervention of an onboard AEB system in the passenger car combined with a warning could mitigate the situation.

6.3. Left Turn Assist

The Left turn scenario is identified by two or more road users in an oncoming traffic situation, with one of the participants intending to turn left. This type of accident with PTW participation happens most often in urban areas (79%) and at crossings (43%), with the traffic regulation 'right of way' (51%).[1]

The one trying to turn may misjudge the speed and distance of the one coming straight, or not notice it at all. Due to right-of-way violations, the scenario ends in a collision.

6.3.1. Background

According to the GIDAS database, this accident type 211 is the most frequent scenario within the category of Left turn accidents. Due to this prevalence, the chapter will focus on descriptions of accident type 211, but is valid for some of the other accident types as well.

6.3.1.1. Objective/ Desired Behaviour

The left-turning vehicle as the main accident causer will be addressed. According to the GIDAS database, the median differential speed between the two vehicles involved is 92km/h. Furthermore, in 50% of all analysed cases, a TTC[6] calculation was not possible earlier than a TTC of 1.5s. Given these boundary conditions, active intervention would have the highest expected safety benefit, followed by a warning with the aim of increasing driver/rider situation awareness and stopping the turning manoeuvre (for research from the passenger car domain see also Neukum, 2011, and Winner, Hakuli, Lotz and Singer, 2015). Providing an advisory notification will likely not prevent the accident due to the limited time resulting from the accident configuration.

6.3.1.2. Expected Benefits

The described Left turn use case is based on analysis of accident type 211. According to the GIDAS database, this accident type is one of the most common involving a PTW and another vehicle as the main causer. More than a third (35%) of cases involved in accident type 211 are seriously injured. Furthermore, 3% of this accident type results in fatalities. Applications which prevent or mitigate Left turn accidents have high potential to save lives or reduce injuries.

6.3.2. Actors and Relations

6.3.2.1. ADAS Only

[6] GIDAS-PCM 2020-1, https://www.vufo.de/gidas-pcm/

In the example described, Participant A is a car which is about to turn left and is obligated to wait. The car is equipped with onboard ADAS, such as camera and radar. Participant B is a PTW which is going straight and entitled to the right of way. The car is using active intervention such as AEB, which will be accompanied by a warning.

6.3.2.2. ADAS + C-ITS

In this example, Participant A is a car which is about to turn left. The car is equipped with onboard ADAS and C-ITS enabling direct communication between the participants (V2X – Communication). Therefore, the car is receiving and processing the V2X messages sent by the other participants. The car is providing active intervention such as AEB based on onboard sensors, which will be accompanied by a warning. Participant B is a PTW going straight and entitled to the right of way. The PTW is equipped with a V2X communication unit and is sending regular CAMs.

6.3.3. Traffic Situations

As described above, the use case focuses on a conflict which arises in left turning traffic. The motivation to address this use case comes from accident type 211, with a left-turning Participant A. The following chapters explain possible situations more in detail.

6.3.3.1. Road Type

1-1: Left turn at Crossing: Participant A is turning left at a crossing while Participant B is coming from the opposite direction.

1-2: Left turn at T-junction: Participant A is turning left at a T-junction while Participant B is coming from the opposite direction.

1-3: Left turn at Property exit: Participant A is turning to the property exit while Participant B is coming from the opposite direction.

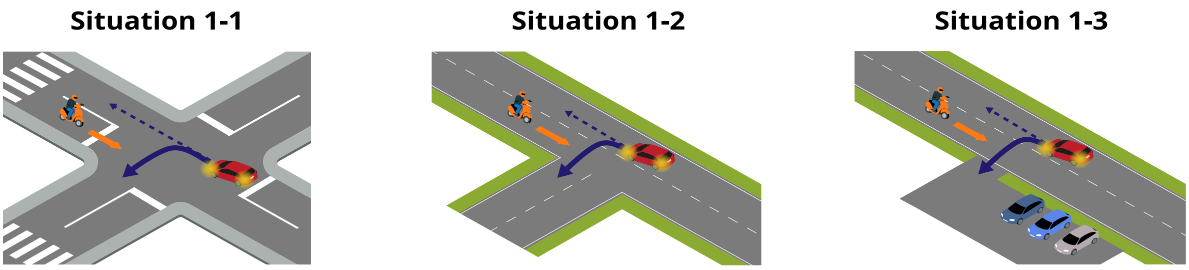


Figure 125: Road type situations for left turn scenarios

According to the GIDAS database, nearly 18% of Participant A entries had a View obstruction within the accident type 211. Possible View obstructions are waiting, starting or driving vehicles. Therefore, two different situations will be addressed.

2-1: No obstruction: Both Participants A and B are generally visible to each other while approaching the potential conflict zone.

2-2: With obstruction: Due to any kind of obstacle, such as another road user, Participant A and Participant B have limited or no visibility towards each other until Participant A turns left.

Situation 2-1 **Situation 2-2**

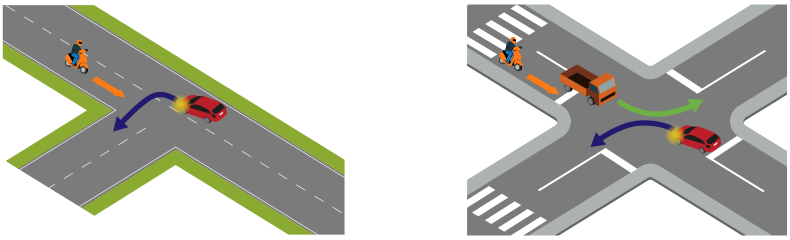


Figure 126: Road type situations for left turn without (left) and with View obstruction (right)

6.3.4. Use Case Scenarios

Scenario 1:

The starting situation of scenario 1:

Participant B (PTW) is going straight and has right-of-way. Participant A (red car), driving on the same priority road but in the opposite direction, is about to turn left at the intersection (left turn indicator on), but the oncoming PTW is covered by the blue car (Participant C) from Participant A's point of view. The main challenge is the View obstruction due to a non-permanent obstacle(s) (here: car(s)).

Time Sequence 1 **Time Sequence 2**

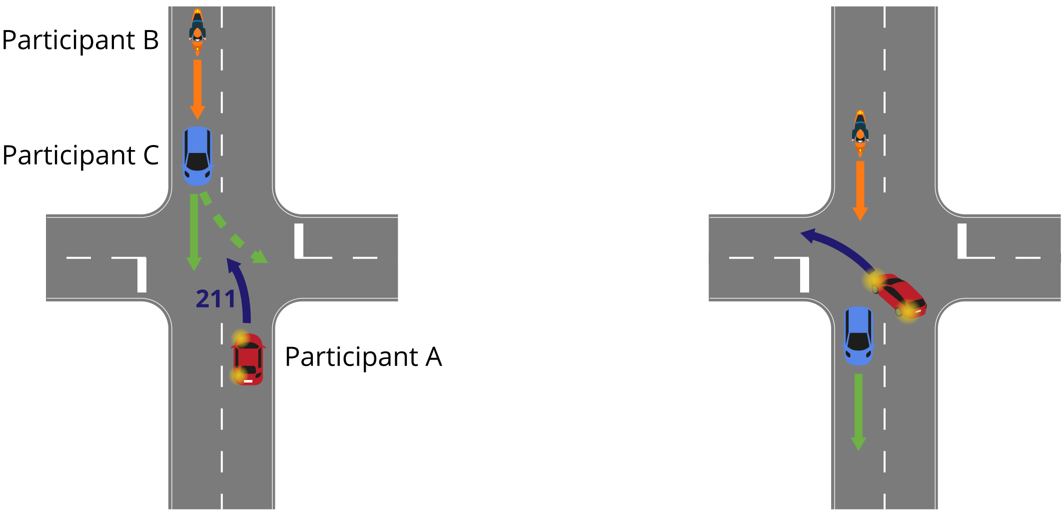


Figure 127: Scenario 1 – Participant A and Participant B cannot see each other due to the View obstruction caused by Participant C (based on accident type 211). The dashed arrow indicates a possible alternative trajectory of Participant C. Time Sequence 2 is indicating Participant C going straight

Special characteristics of scenario 1:

As soon as Participant C has passed the intersection, the waiting Participant A presumably feels safe to drive off, as Participant B is only visible quite late for Participant A. This manoeuvre causes a potential conflict with Participant B.

If Participant C is turning left, the distance between Participants B and C could further be reduced due to the speed reduction associated with the turning manoeuvre, thus creating an even more critical situation. At the same time, a left-turning Participant C may entice Participant B to drive up closer in the lane (to the left), further worsening the already poor view from Participant A towards Participant B.

Scenario 2:

The starting situation of scenario 2:

Participant A wants to turn left. Participant C (here: blue car), who is approaching from the opposite direction and has the right of way, crosses the intersection and thereby obscures Participant B driving past the stationary vehicles who has the right of way.

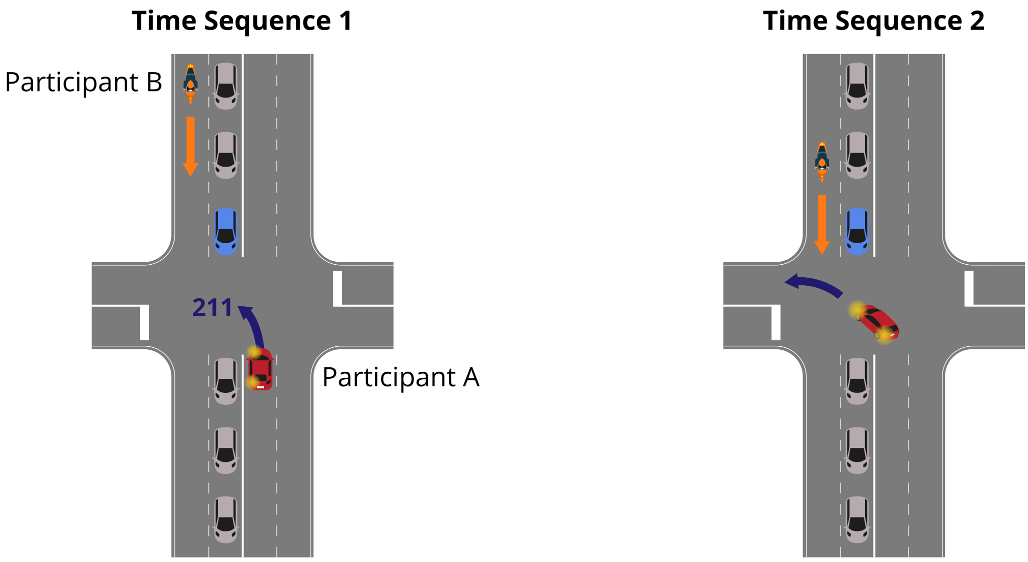


Figure 128: Scenario 2 – Participant A is about to turn left, Participant C (here: grey car) keeps a small distance from the vehicle ahead (here: blue car) and thereby obscures Participant B who wants to drive past the stationary vehicles (based on accident type 211)

Special characteristics of scenario 2:

Participant C is standing with other participants in the left lane of a four-lane road with two lanes per direction (as seen from the driver's point of view). In the left lane, there is almost no distance between the vehicles, which makes it even more difficult for Participant A to gain a direct line of sight on Participant B. A fast start and left-turn of Participant A to enter the vacant opposite lane makes a collision with Participant B possible, who is passing the standing vehicles in the free right lane and cannot see Participant A or sees him/her very late.

6.3.5. Display/Alert Principle

6.3.5.1. ADAS only

Due to the rather short available time (TTC = 1.5 sec) active intervention using AEB functions seems the most likely possibility for accident avoidance or mitigation. Additionally, an imminent warning should contain an auditory tone and visual feedback. The visual feedback can contain a generic warning icon, but also a PTW-specific warning, which can increase acceptance but is not expected to create a reaction time benefit.

6.3.5.2. ADAS + C-ITS

Due to the rather short available time (TTC = 1.5 sec) an imminent crash warning should trigger immediate reaction (i.e. braking). Therefore, the warning should contain an auditory tone in addition to any visual feedback. The visual feedback can contain a generic warning icon but could benefit from a PTW-specific warning icon in the event of View obstruction (e.g. PTW obscured by a truck), to avoid Participant A not noticing Participant B – i.e. receive assistance to recognise the obscured vehicle (here: PTW) and avoid the collision. Automated Brake Activation based on onboard sensors and a CAM would mitigate the situation.

7. Technology Solutions for Use Cases

This section is dedicated to cellular technology solutions for the use cases.

7.1. Role of Uu

Use cases related to Connected Powered Two-Wheelers (CPTW) can be implemented using direct communication (e.g., V2V/V2I) and/or cellular network communication (e.g. V2N/V2N2V/V2N2I). 5GAA has advocated for a complementary approach between direct communication (via PC5) and mobile network communication (via Uu) for the viable introduction of C-V2X, and active discussions about how to utilise the Uu interface and network communication for various V2X services including CPTW are ongoing in different WIs. Also, 5GAA members have discussed how Uu V2X can be used to complement direct communication. In this subsection, a description of how Uu V2X complements direct communication and how Uu V2X helps the more efficient implementation of CPTW are provided.

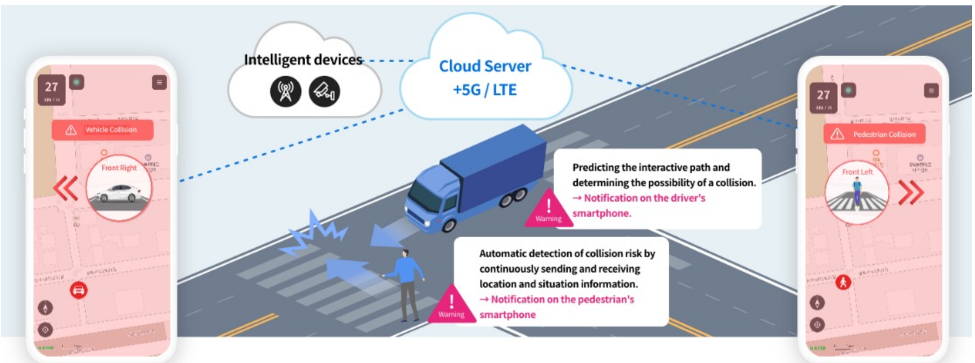


Figure 129: Cellular network communication based ITS services

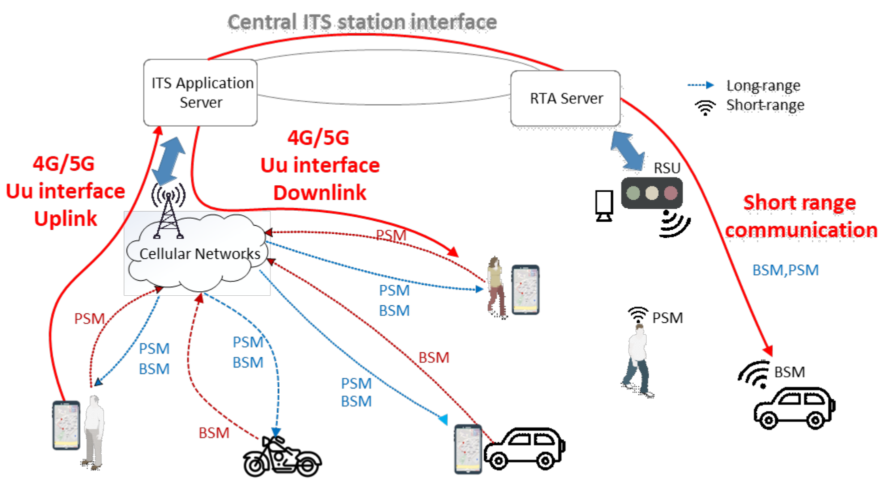
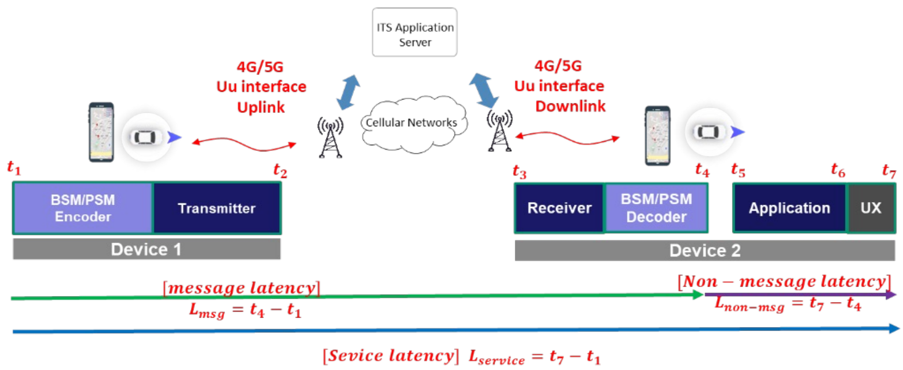


Figure 130: Integration of cellular network communication and direct communication

For Uu V2X-based CPTW, the software application installed in smartphones enables information exchange with the ITS application server via 4G/5G mobile network communication, as shown in Figure 129. Also, as depicted in Figure 130, the ITS application server can connect various ITS players (vehicles, RSUs, pedestrians, PTWs, e-bikes) not only via mobile network communication but also using direct communication, and thus Uu-based V2X systems and direct communication-based V2X systems are combined in this integrated architecture. Therefore, PTW riders carrying devices that support only Uu-based communication can be efficiently protected based on information exchange between the Uu V2X devices and short-range communication-based V2X devices, when there is a nearby RSU. In the integrated system described, the PTW riders can protect (and be protected by) other vehicles and road users more efficiently, and the PTW-related accidents can be further reduced. Also, it should be noted that motorcyclists are one type of VRU (e.g. VRU profile 3 in [1]), not vehicles.



Service latency	Message related latency	Non-message related latency
96.94msec	43.59msec	53.35msec

Figure 131: E2E latency measurement in Uu V2X

One of the issues regarding the cellular network communication-based ITS service support is latency. To verify the feasibility of Uu V2X in terms of latency, the initial measurement result of E2E latency for Uu-based VRU protection was provided in [Ref 2]. In the measurement, the average message and non-message-related latency were 43.59msec and 53.35msec, respectively. Also, it was concluded that the total service latency, which includes those in the application and UX, can be considered acceptable for the support of basic safety services including collision warning, as it maintained below 100msec. Also, different from connection-less direct communication (e.g. DSRC, LTE-V2V/V2I/V2P), Uu V2X is connection-oriented communication. Therefore, a connection recovery strategy is required in case communication between the PTW rider and server/MEC is lost. Additionally, as Uu V2X is connection-based communication, the server can track each device communicating with it. Thus, the current privacy/security solutions defined for connection-less communication may not be suitable for Uu V2X, and the use of security credential management system (SCMS) seems not to be needed in the device-to-server communication via Uu interface.

7.1.2. Data Processing at Server/MEC in Uu V2X

As can be seen in the figure below [Ref 2], 5GAA WG2 discussed two types of data processing model, and the processing (e.g., collision assessment, path prediction) is carried out in the cloud and UE device, such as a smartphone, respectively. For example, when considering collision assessment as the data processing needed for CPTW, in Alt 1 in the Figure 129 below, the assessment can be done in the cloud based on the data collected there, while the assessment is performed on the smartphone of the PTW rider using the information received from the cloud in Alt 2. These two alternatives can be used adaptively in a hybrid way, depending on the capability/status of UE devices and the real-time workload of the server.

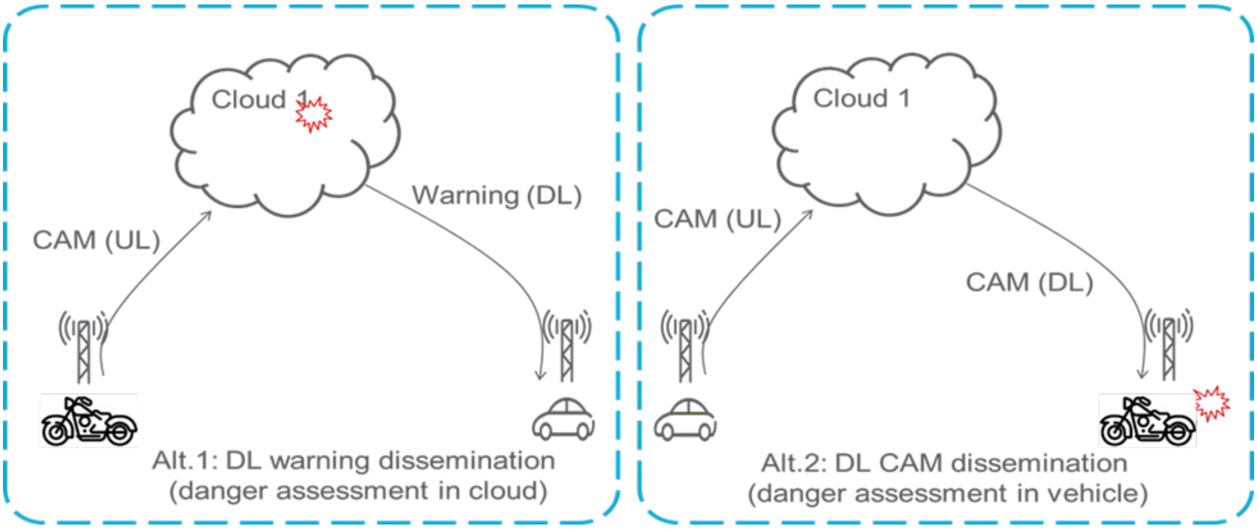


Figure 132: Two different types of collision assessment model [Ref3]

Figure 132 illustrates two different frameworks that could be aimed at cloud-based collision assessment. In the left scheme, the cloud receives road user safety information (sent to the cloud via uplink) and determines collision assessment and hazard potential. When the cloud identifies the risk, then the result of the analysis (collision warning and its attributes) would be disseminated to the relevant service subscribers (users) using a downlink. In the right-hand model, the cloud would be responsible for the dissemination of other road users' information in the form of CAM or BSM and the vehicle remains in charge of risk assessment and collision avoidance analysis and determinations.

During the accuracy performance measurements by CMC, it was observed that the path prediction by the UE device could not meet the accuracy requirement of the prediction needed for CPTW, as shown in the following figure evaluating whether the error distance between the predicted point and the actual point at a certain time in the future is smaller than the threshold (evaluation factor). In this case, the error distances are smaller than the threshold only at the time before t2. The possible range of motion depends strongly on the speed of the vehicle. The faster the vehicle, the less spontaneously a strong change of direction can be performed. The slower the vehicle, the stronger a change of direction can be made.

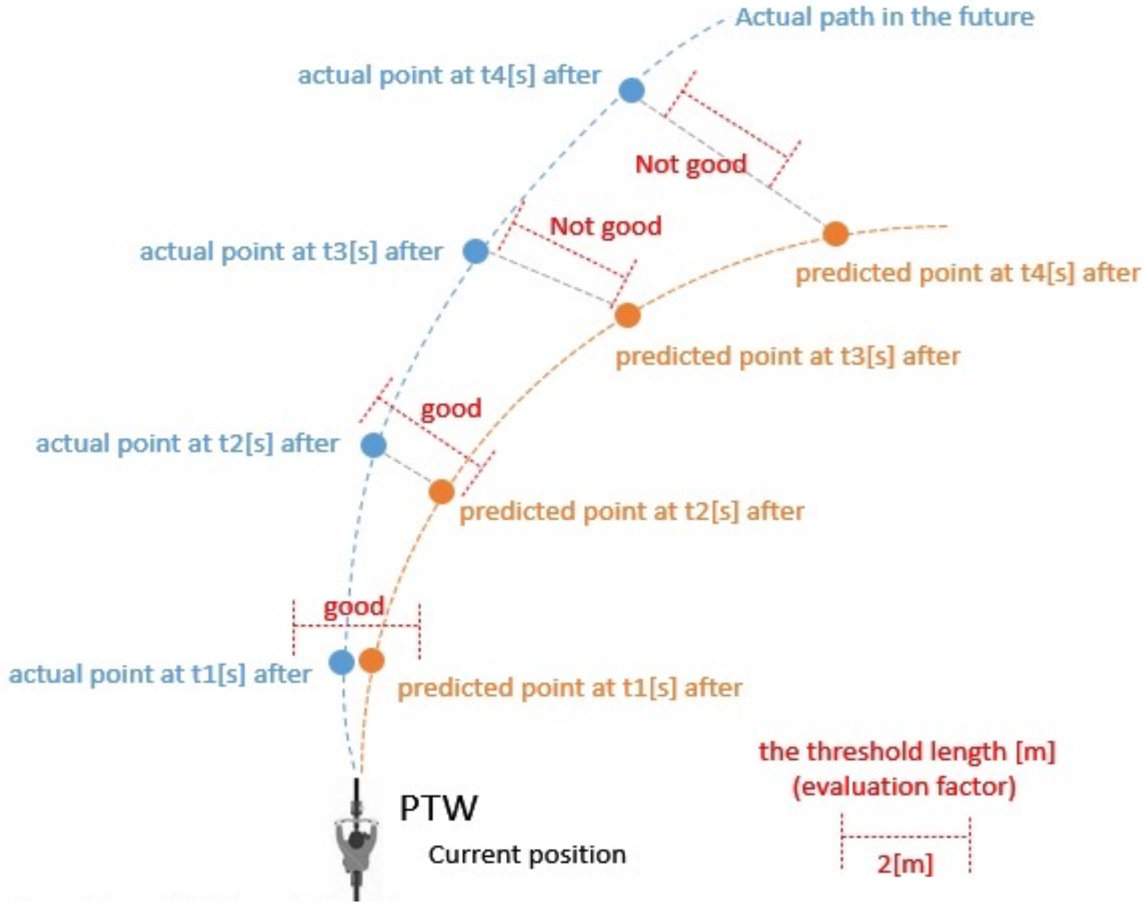


Figure 133: Performance of path prediction at UE device

In Uu V2X, as the UE devices are connected to the cloud/MEC, the path prediction can be performed there, as in Alt. 2, and this operation can be a potential solution to increase the prediction accuracy. For example, the path prediction via the cloud/MEC can be beneficial when the UE device is in the following situations, in particular:

- When the UE device has limited data processing/computing capability
- When the battery of the UE device is low
- When the level of accuracy/precision of the UE device's sensors is not sufficient to satisfy the requirement of CPTW-related services
- When the complexity of path prediction is getting higher, due to driving environments of the PTW, e.g.
  - When the PTW is running on a winding road
  - When the PTW is going into (and coming out of) a curve

– When the PTW is driving near roadworks or an accident area

It should be noted that the path prediction with the help of server/MEC can be seen as a service for correction/verification/calculation of the predicted path of PTW riders. For this service, the server/MEC sends a message containing PTWs' predicted path calculated/corrected by the server/MEC using the message formats defined by current ITS standards (e.g. BSM, CAM) or a new message for correction/calculation of predicted path and position. The new message could include information about the ID of a PTW device, the predicted path of a PTW calculated/corrected by the server/MEC, and the corresponding time instance. Also, negotiation between a PTW device and server/MEC might be needed to decide whether to start the service and allow the server/MEC to generate/send messages containing PTW information, such as the predicted path calculated/modified by the server/MEC. Further discussion on details of this potential solution and other solutions would be needed. Also, performance evaluation of the potential solutions could be required in a follow-up WI or other 5GAA WIs.

7.2. Role of Side-link [PC5]

7.2.1. Role of Side-link

CPTW-related use cases can be implemented using direct communication (V2V/V2I) with the PC5 interface. 3GPP and ETSI have defined the PC5 interface for LTE-V2X mode 4 [11] and NR-V2X mode 2 [12]. LTE-V2X is in the ETSI Release-1 specification set along with ITS-G5 (IEE 802.11p). NR-V2X is in the ETSI Release-2 specification set along with ITS-G5 (IEEE 802.11bd). These technologies operate in the unlicenced band 47.

7.2.2. The Role of Side-link for Communication

Side-link can be deployed for V2V and V2I use cases requiring short-range communication (e.g. left turn assist). Advantages of PC5 communication are:

- Very low latency compared to network-based communication
- In the case of NR-V2X, messages can be sent as broadcast, groupcast or unicast depending on the requirements of each use case

7.2.3. The Role of Side-link for Discovery

Discovery is the ability of a PC5-enabled device to detect another in proximity. This could be applied to CPTW use cases. For example, in a left turn assist use case a car driver could be warned of an approaching motorcycle, even if not visible (non-line of sight). Many accidents happen because the PTW is not seen. The relative position of the PTW to the other actors can also be calculated.

7.2.4. Go To Market

The PC5 side-link solution requires that all actors in the use case have PC5 capable and enabled devices. It is expected that market penetration of PC5 in cars will increase. For the CPTW, the PC5-enabled device could be an embedded unit in/on the PTW or the rider's smartphone. Both are possible from a standards viewpoint.

7.3. Role of 5G MEC

CPTW-related use cases can be implemented using network-based communication (V2N2V/V2N2I) with the Uu (5G) interface and the Multi-Access Edge Computing. MEC infrastructure brings scalable compute and storage within Mobile Network Operator's (MNO) network, which allows for lower latency, security, and local context. 5G and MEC enable the low-latency and high-throughput required to support CPTW use cases where even milliseconds are critical. These technologies operate in MNO-licensed spectrum bands.

7.3.1. The Role of 5G and MEC for Communication

5G and MEC can be deployed for V2N2V and V2N2I use cases (e.g. left turn assist). Advantages of Uu communication are:

- Nearly ubiquitous connectivity and lower latency using existing network infrastructure
- Allows for very specific messages targeted to the endpoint

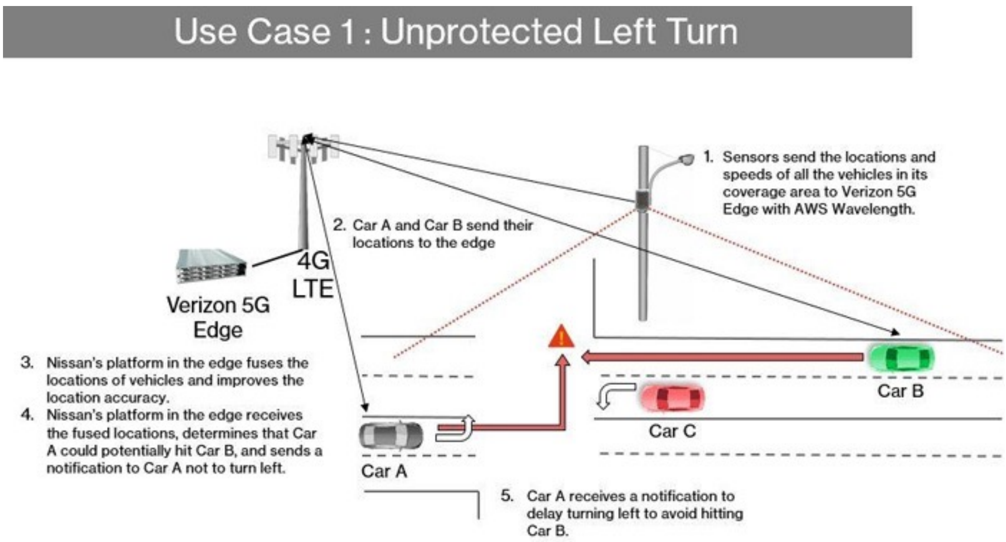


Figure 134: Graph on unprotected left turn use case

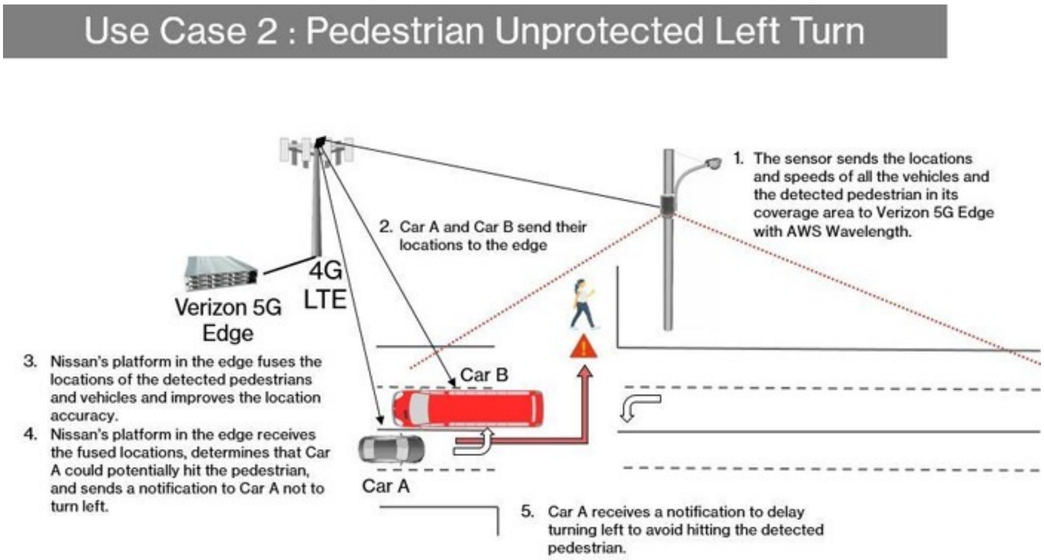


Figure 135: Graph on pedestrian unprotected left turn use case

7.3.2. The Role of Uu for Positioning

Network-based positioning technology can be used to provide satellite navigation (GNSS) correction to provide cm-level positioning accuracy. This could be applied to CPTW use cases. For example, in a left turn assist use case a car driver could be warned of an approaching motorcycle with a high level of accuracy, even if not visible (non-line of sight). Many accidents happen because the PTW is not seen. But in this case, the relative position of the CPTW to the other actors can also be calculated.

7.3.3. Go To Market

Through the network-based solution utilising licensed commercial spectrum with V2X application servers and 5G MEC, MNOs can provide an efficient and scalable solution that leverages technology already widely used by both pedestrians and drivers. A network based V2X solution leverages the existing 5G network, in which MNOs substantially invests year after year. Using the mobile network also enables the use of a software-based interface, reducing deployment and maintenance costs incurred with physical roadside infrastructure. Furthermore, newer network technology keeps data processing closer to the edge of the network, reducing latency and enabling support for all but the most latency sensitive V2X applications. Lastly, using a network V2X solution employs one of the most commonly owned and used pieces of technology in the world – the mobile phone – which will speed up deployment and adoption while reducing costs. These reasons make network V2X technology a fundamental pillar of CPTW safety.

7.4. Role of Mobile/Handheld Devices

For protection of VRUs including PTW riders, many 5GAA members tried to exploit smartphone capabilities because they are ubiquitous (carried in the pocket of most people). More specifically, a software application is installed in the smartphones of VRUs and can connect PTW riders with other ITS stations including vehicles, infrastructures and ITS application servers via 4G/5G network communication and/or direct communication. According to [4], most PTW-installed devices are not equipped with network communication connectivity interfaces. However, if the PTW rider carries a smartphone, the rider can inform other road users of his/her presence and status, and he/she receives information about other road users and possible accidents/risks via Uu V2X, as explained in subchapter 4.1.

Also, the smartphone can be used as HMI for CPTW services. For example, the phone screen can be used to show warning messages received by other smartphones or PTW-installed devices. As another example, users can receive audio, visual and haptic alerts using their smartphones, and the notification method for the warnings can be customised by the users simply by adapting settings on the VRU protection service application installed.

In addition to smartphones and mobile apps, many motorcycles riders use dedicated navigators that provide traffic/road information (please note that navigation systems are aftermarket supply and some, but not all, are connected). Such devices, if connected, could also be leveraged to increase protection and penetration.

Due to the typically less infrequent use of PTWs, such as in the winter when it is not possible or too dangerous to ride, their electronics can be powered off for long periods of time, especially compared to other ITS devices. However, for certificate management (e.g., AT, ECTL, CRL update) PTWs need to connect to Public Key Infrastructure (PKI) at least once in the interval range of one week to three months. If PTW cannot connect to PKI in a timely manner, the ATs will expire and PTW will no longer be able to sign the messages it sends, and the ECTL will not be updated. This, in turn, means the PTW will lose its ability to validate ATs for received messages signed by other ITS stations. A problem that can be solved by managing the certificate via Uu V2X using a smartphone serving as a communication proxy.

8. Verification

C-ITS technology is poised to transform the way we travel on roads, with the potential to significantly enhance safety, efficiency, and convenience. However, ensuring the reliability and safety of connected vehicles requires a rigorous testing methodology that thoroughly evaluates their performance under various scenarios.

To ensure the reliable and safe operation of Connect Vehicles, it is imperative to develop use cases that closely resemble realistic scenarios, encompassing a diverse range of parameters, such as different weather and lighting conditions, varying speeds and trajectories of the vehicles involved, and other uncertain factors that can significantly affect vehicle performance. Furthermore, the adopted methodology must incorporate precise and robust evaluation criteria that accurately gauge the performance of the vehicle being tested in a wide range of scenarios, facilitating the identification of areas for improvement and enabling engineers to optimise their systems accordingly. The incorporation of such rigorous and comprehensive evaluation criteria is paramount to guaranteeing that vehicles are equipped with the necessary capabilities to operate effectively in diverse, real-world situations.

This chapter delves into the topic of testing use cases involving cross-traffic and left-turn assist. Specifically, it explores various approaches and methodologies that can be used to accurately simulate real-world scenarios and evaluate the performance of vehicles in these situations. The discussion will focus on the testing of connected motorcycles, and highlights the key considerations and challenges associated with testing such use cases.

Furthermore, it presents various evaluation criteria and metrics that can be employed to assess the performance of vehicles in cross-traffic and left-turn assist scenarios and examines the significance of these criteria in the development of safe and reliable vehicles.

The tests descriptions are technology agnostic (Uu, PC5 & ADAS).

8.1. Test Description and Test Execution

8.1.1. Common requirements

To evaluate the cross-traffic and left-turn use cases the following requirements must be met during the execution of the tests:

- Only C-ITS messages generated by the Device Under Test and Remote Vehicles should be present during the test
- The test vehicles should be equipped with an alert system to notify the drivers of any potential danger
- The test vehicles should be able to move at different speeds, up to a maximum of 20km/h

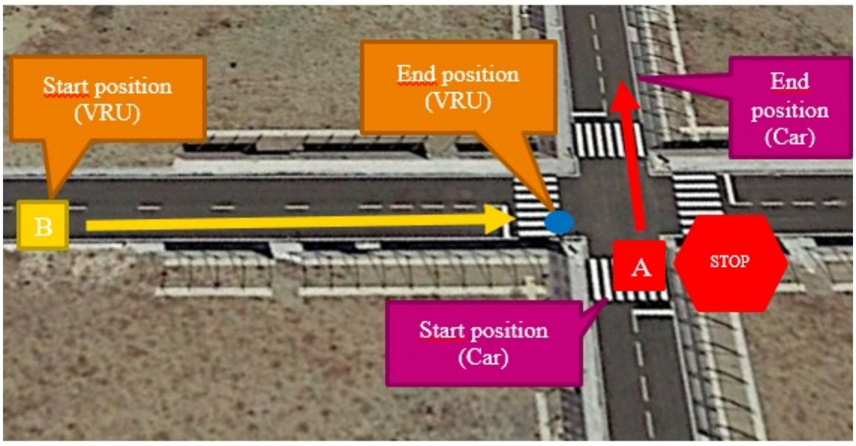
- The vehicles should be able to move in different directions to test the different variations of the scenario
- The test environment should be controlled, meaning that no other vehicles or obstacles should interfere with the test
- The tests should be conducted in different weather conditions (e.g., sunny, rainy, foggy) to evaluate the performance of the vehicles in different situations
- The tests should be conducted at different times of the day (e.g., morning, afternoon, evening) to evaluate the performance of the vehicles in different lighting conditions
- The test results should be documented and analysed to identify any issues or areas for improvement in the vehicles or the scenario
- The test set-up should provide reproducible test results

8.1.2. Cross Traffic Use Cases

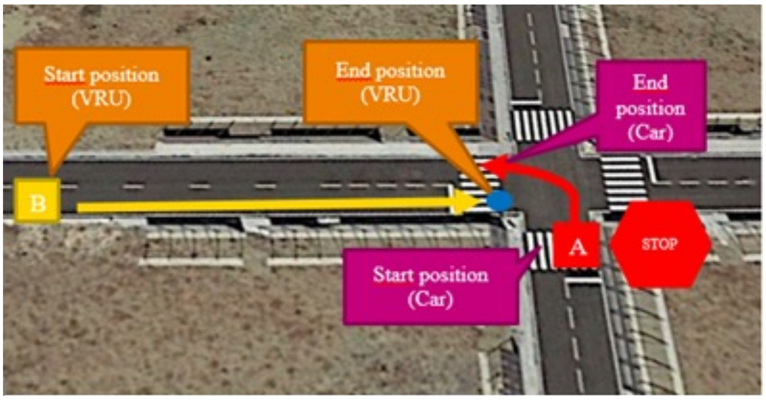
There are five main test cases for this scenario according to the accident type: intersection from the left side (accident type 301, 302 and 303) or the right side (accident type 321 and 322).

The following test sequence aims to identify any issues or problems that may exist during the cross-traffic scenario testing, thus ensuring the vehicle meets the necessary safety standards:

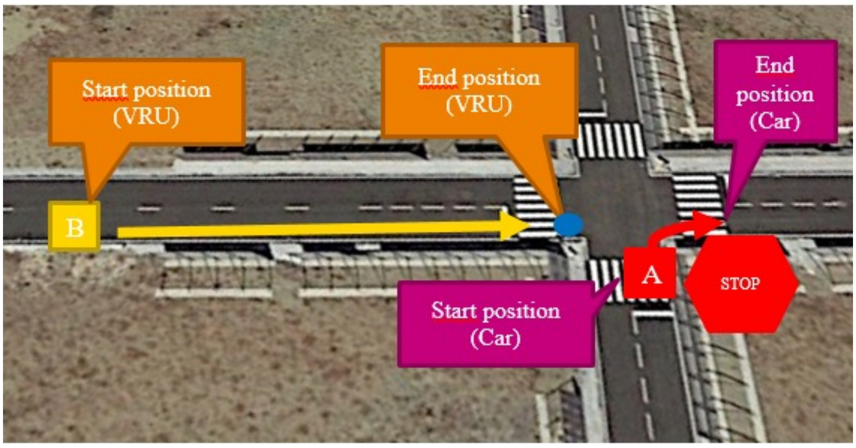
1. Set up the Test Environment: Prepare a test environment that closely resembles the intersection described in the test cases. Ensure that the environment includes all the relevant traffic signs (STOP) and road markings.
2. Configure the Vehicles: Prepare the vehicles to simulate the behaviour described in the test cases. Vehicle A: Car, Vehicle B: Two-wheeler vehicle.
   - TC_Crossing_ 301: The car ('A' vehicle) is stopped at the intersection when a TW vehicle 'B' is approaching the intersection from the left side. Assuming vehicle 'A' does not see TW vehicle 'B', 'A' enters the intersection causing a dangerous situation. Set vehicle 'A' to start from a stopped position at the intersection, and set TW vehicle 'B' to approach the intersection from the left side according to:



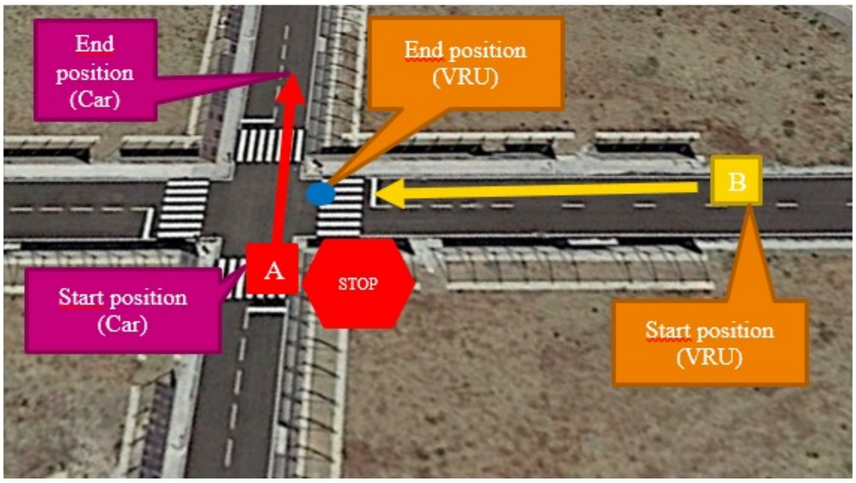
- TC_Crossing_ 302: The car ('A' vehicle) is stopped at the intersection when a TW vehicle 'B' is approaching the intersection from the left side. Assuming vehicle 'A' does not see TW vehicle 'B', 'A' enters the intersection causing a dangerous situation. See the (Path 2: case 302) image, to know which is the path to follow in the test. Set vehicle 'A' to start from a stopped position at the intersection, and set TW vehicle 'B' to approach the intersection from the left side according to:



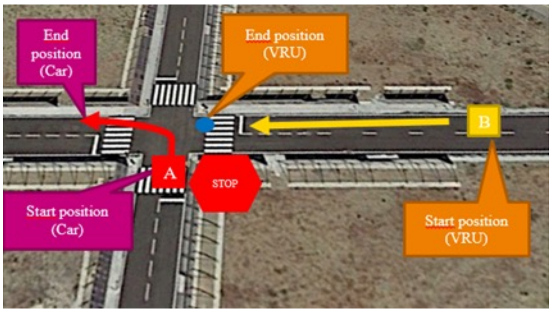
- TC_Crossing_ 303: The car ('A' vehicle) is stopped at the intersection when a TW vehicle 'B' is approaching the intersection from the left side. Assuming vehicle 'A' does not see TW vehicle 'B', 'A' enters the intersection causing a dangerous situation. See the (Path 3: case 303) image, to know which path to follow in the test. Set vehicle 'A' to start from a stopped position at the intersection, and set TW vehicle 'B' to approach the intersection from the left side according to:



- TC_Crossing_ 321: The car ('A' vehicle) is stopped at the intersection when a TW vehicle 'B' is approaching the intersection from the right side. Assuming vehicle 'A' does not see TW vehicle 'B', 'A' enters the intersection causing a dangerous situation. See the (Path 4: case 321) image, to know which path to follow in the test. Set vehicle 'A' to start from a stopped position at the intersection, and set TW vehicle 'B' to approach the intersection from the right side according to:



- TC_Crossing_322: The car ('A' vehicle) is stopped at the intersection when a TW vehicle 'B' is approaching the intersection from the right side. Assuming vehicle 'A' does not see TW vehicle 'B', 'A' enters the intersection causing a dangerous situation. See the (Path 5: case 322) image, to know which path to follow in the test. Set vehicle 'A' to start from a stopped position at the intersection, and set TW vehicle 'B' to approach the intersection from the right side according to:



3. Execute the Test Case: The Intersection Collision Warning (ICW or IMA) application must be running on the device installed in the car ('A' vehicle). The data logging system (video and GNSS position) has to be running during the whole test.

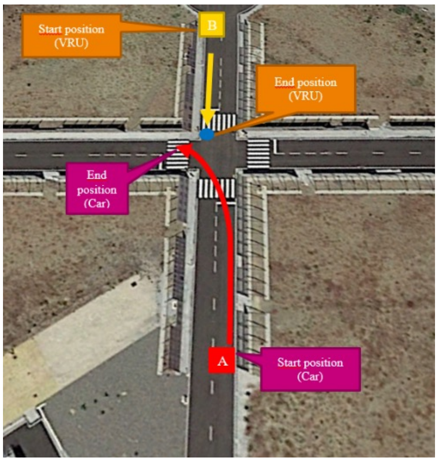
Test Sequence			
Test Sequence:	**Step**	**Type**	**Description**
	1	Configure	Vehicle 'A' has to move to its initial position.
	2	Configure	TW vehicle 'B' has to move to its initial position.
	3	Check	TW vehicle 'B' indicates the start of the "false positive verification test". Note: Check that no alert is triggered when the car ('A' vehicle) is stationary during the test.
	4	Procedure	TW vehicle B travels from the starting point to the end point at a maximum speed of 20km/h.
	5	Check	Check that there are no alerts on either vehicle A or TW vehicle B HMI device. In case there is an alert, the test should be stopped and the existing problems should be checked.
	6	Configure	TW vehicle 'B' has to move to its initial position.
	7	Stimulus	TW vehicle 'B' indicates the start of the test.
	8	Procedure	TW vehicle B travels from the starting point to the end point at a maximum speed of 20km/h. Vehicle A starts to move when TW vehicle B is 10m from the crossing, and it moves to its final position.
	9	Check	Check that there is an alert on both vehicle A and TW vehicle B. Observe the results of the test cases, including any warnings or alerts generated by the vehicle's sensors/cameras and the speed, position and trajectories of each actor. Note any actions taken by the driver or the vehicle to avoid the dangerous situation.
	11	Procedure	Repeat steps 5-10 at least three times.
	12	Procedure	After the last repetition stop data logger system and save the recorded data.
	13	Verify	- Calculate TTC and verify that warnings give drivers enough time to react. - Verify that warnings match the specifics of each variant.

8.1.3. Left-Turn Use Cases

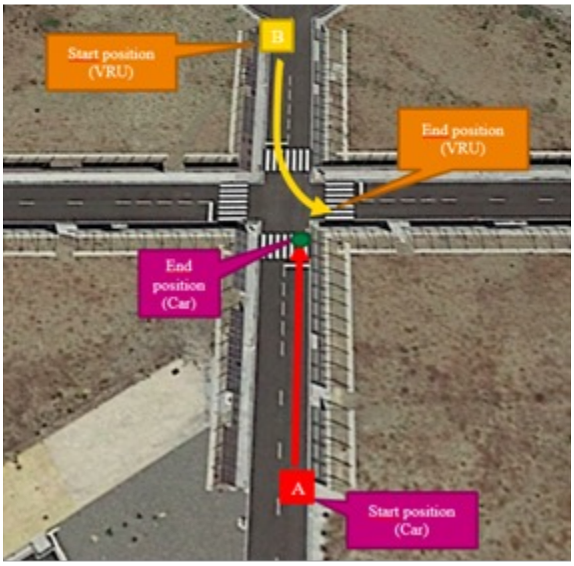
There are two main test cases for this scenario according to the accident type: type 211 and 351. The following test sequence aims to identify any issues or problems that may exist during the left-turn scenario testing, thus ensuring the vehicle meets the necessary safety standards:

1. Set up the Test Environment: Set up a test environment that closely resembles the intersection described in the test cases. Ensure that the environment includes all the relevant traffic signs and road markings.
2. Configure the Vehicles: Configure the vehicles to simulate the behaviour described in the below test cases. Set vehicle 'A' and vehicle 'B' to approach the intersection from the opposite sides. Vehicle A: Car, Vehicle B: Two-wheeler vehicle.
   - TC_Left_Turn_ 211: The car ('A' vehicle) is turning left at a crossing while TW vehicle 'B' is coming from the opposite direction. See the (Path 6: case 211) image, to know which path to follow in the test. Set vehicle 'A' to start from a stopped position at the A start point, and set TW vehicle

'B' at stopped position at the B start point according to:



- TC_Left_Turn_ 351: The TW vehicle ('B') is turning left at a crossing while vehicle 'A' is coming from the opposite direction. See the (Path 6: case 351) image, to know which path to follow in the test. Set vehicle 'A' to start from a stopped position at the A start point, and set TW vehicle 'B' at stopped position at the B start point according to:



3. Execute the Test Case: The Intersection Collision Warning (ICW or IMA) application must be running on the device installed in the car ('A' vehicle). The data logging system (video and positioning) has to be running during the whole test.

Test Sequence			
Test Sequence:	**Step**	**Type**	**Description**
	1	Configure	Vehicle 'A' has to move to its initial position.
	2	Configure	Vehicle 'B' has to move to its initial position.
	3	Check	TW vehicle 'B' indicates the start of the "false positive verification test". Note: The idea of this test is to verify that no alert is triggered when the car ('A' vehicle) is stationary during the test.
	4	Procedure	TW vehicle B travels from the starting point to the end point at a maximum speed of 20km/h.
	5	Check	Check that there are no alerts on either vehicle A or TW vehicle B HMI device. In case there is an alert, the test should be stopped and the existing problems should be checked.
	6	Configure	TW vehicle 'B' has to move to its initial position.
	7	Stimulus	TW vehicle 'B' indicates the start of the test.
	8	Procedure	TW vehicle B travels from the starting point to the end point at a maximum speed of 20km/h. Vehicle A starts to move when vehicle B is 10m from the crossing, and it moves to its final position.
	9	Check	Check that there is an alert on both vehicle A and TW vehicle B. Observe the results of the test cases, including any warnings or alerts generated by the vehicle's sensors/cameras and the speed, position and trajectories of each actor. Note any actions taken by the driver or the vehicle to avoid the dangerous situation.
	10	Procedure	Repeat steps 5-10 at least three times.
	11	Procedure	After the last repetition stop data logger system and save the recorded data
	12	Verify	- Calculate TTC and verify that the warning to the drivers gives them enough time to react. - Verify warnings match the specifics of each variant.

9. Conclusion and Future Work

Accident data analysis sheds light on the major risk factors contributing to motorcycle accidents. According to GIDAS data, the majority of the accident cases in the cross-traffic, lane-change, and left-turn categories were caused by other traffic participants, particularly cars, and motorcycle riders may not be able to effectively avoid such accidents unless the cars/vehicles realise the presence of a motorcycle in the vicinity.

One way to effectively register the presence of different road users on the road is through the adoption of C-ITS technologies which enable road users to communicate their safety critical information to one another through a wireless interface (over-the-air information exchange). This notion highlights the role that car manufacturers can play in improving the safety of roadways and road users including motorcycle riders.

Infrastructure can also play an important role in improving motorcycle rider safety by disseminating critical information about the road, including traffic light signal-phases and timing, and road geometry information to the vehicles.

For the benefit of CPTW safety, being able to leverage mobile networks and the huge ecosystem of V2X technology would mean faster deployment and adoption, cost reductions, and diverse software-based functionality. In various CPTW services, 4G/5G network communication over Uu interface can increase the safety of PTW riders by connecting the riders with other ITS stations including vehicles, infrastructure points, and ITS application servers. Most PTW-installed devices are not equipped with network communication modules, but the network communication-based CPTW services can be easily realised by installing software applications in the PTW rider's smartphone. When the CPTW services are provided via network communication, the smartphone can be used to support network communication, display messages/alerts, and manage certificates of PTW-installed devices.

Direct communication will play an important role for CPTW. Recent enhancements in standards have introduced the discovery feature of PC5-enabled CPTWs, to detect and be detected in non-line of sight situations, and the possibility for unicast and multicast in addition to current broadcast options. PC5 offers low-latency, direct communication – making it suitable for many use cases. As market penetration of PC5- enabled cars increases, implementation of PC5-enabled devices is set to greatly improve CPTW safety. The rider could carry a PC5-enabled device, but onboard implementation would be more resilient.

Thanks to the cooperation (MoU) with the Connected Motorcycle Consortium, an important exchange of ideas has taken place with the objective of advancing expertise and knowledge on powered two-wheelers and their relationship with C-V2X technologies.

5GAA is a multi-industry association to develop, test and promote communications solutions, initiate their standardisation and accelerate their commercial availability and global market penetration to address societal need. For more information such as a complete mission statement and a list of members please see https://5gaa.org

5GAA Automotive Association