Autonomous Vehicles to Evolve to a New Urban Experience

DELIVERABLE

D6.2 Methodology for safety evaluation

Co-funded by the Horizon 2020 programme
of the European Union

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 769033

Disclaimer

Document Information

Grant Agreement Number	**769033**
Full Title	Autonomous Vehicles to Evolve to a New Urban Experience
Acronym	AVENUE
Deliverable	D6.2 Methodology for safety evaluation
Due Date	31.12.2021
Work Package	WP6
Lead Partner	CEESAR
Leading Author	Clément VAL
Dissemination Level	restricted

Document History

Version	Date	Author	Description of change
0.1	28.12.2021	C.VAL (CEESAR)	First version
1.0	12.10.2022	C.VAL (CEESAR)	Final version

Table of Contents

Acronyms

ADAS	Advanced Driving Assistance Systems
ADS	Automated Driving Systems
AI	Artificial Intelligence
AM	Automated Mobility
API	Application Protocol Interface
AV	Automated Vehicle
BM	Bestmile
BMM	Business Modelling Manager
CAV	Connected and Automated Vehicles
CB	Consortium Body
CERN	European Organization for Nuclear Research
D7.1	Deliverable 7.1
DC	Demonstration Coordinator
DI	The department of infrastructure (Swiss Canton of Geneva)
DMP	Data Management Plan
DSES	Department of Security and Economy - Traffic Police (Swiss Canton of Geneva)
DTU test track	Technical University of Denmark test track
EAB	External Advisory Board
EC	European Commission
ECSEL	Electronic Components and Systems for European Leadership
EM	Exploitation Manager
EU	European Union
EUCAD	European Conference on Connected and Automated Driving
F2F	Face to face meeting
FEDRO	(Swiss) Federal Roads Office
FOT	(Swiss) Federal Office of Transport
GDPR	General Data Protection Regulation
GIMS	Geneva International Motor Show
GNSS	Global Navigation Satellite System
HARA	Hazard Analysis and Risk Assessment
IPR	Intellectual Property Rights
IT	Information Technology
ITU	International Telecommunications Union
LA	Leading Author
LIDAR	Light Detection And Ranging
MEM	Monitoring and Evaluation Manager
MT	MobileThinking
OCT	General Transport Directorate of the Canton of Geneva
ODD	Operational Domain Design
OEDR	Object And Event Detection And Response
OFCOM	(Swiss) Federal Office of Communications
PC	Project Coordinator
PEB	Project Executive Board
PGA	Project General Assembly
PRM	Persons with Reduced Mobility
PSA	Group PSA (PSA Peugeot Citroën)
PTO	Public Transportation Operator
PTS	Public Transportation Services
QRM	Quality and Risk Manager
QRMB	Quality and Risk Management Board
RN	Risk Number
SA	Scientific Advisor
SAE Level	Society of Automotive Engineers Level (Vehicle Autonomy Level)
SAN	(Swiss) Cantonal Vehicle Service
SDK	Software Development Kit
SLA	Sales Lentz Autocars
SMB	Site Management Board
SoA	State of the Art
SOTIF	Safety Of The Intended Functionality
SWOT	Strengths, Weaknesses, Opportunities, and Threats.
T7.1	Task 7.1
TM	Technical Manager
TPG	Transport Publics Genevois
UITP	Union Internationale des Transports Publics (International Transport Union)

VAAS	Vehicle Audio Alert Systems
V2I	Vehicle to Infrastructure communication
V2X	Vehicle to X (infrastructure, other vehicles) communication
WP	Work Package
WPL	Work Package Leader

Executive Summary

To gain relevance and therefore acceptance, automated minibuses will require higher operating-speeds and ability to operate without on board safety drivers, on more flexible routes. This causes significant safety challenges, which are addressed in AVENUE in the context of tasks 6.1 and 6.2.

Safety assessment in those tasks focuses on issues which are particular to automated minibuses. This corresponds to the recently introduced concept of "Safety of the Intended Functionality" (SOTIF), i.e. the identification and mitigation of threats resulting from inadequacy between one vehicle's capacities (e.g. situational awareness resulting from its sensors and perception algorithms, decision model, reaction time) and the conditions in which it is used (e.g. speed, weather, surroundings, other users' behaviour).

Within this context, a methodology has been developed. It relies on various kinds of data collection to identify and characterise threats, and numerical simulations to extrapolate findings to new conditions (e.g. improved vehicle performance, different operating contexts).

Following the design of that methodology, a catalogue of safety-relevant scenarios has been constituted. Those scenarios have been prioritised using a ranking algorithm relying on hundreds of votes by public transport operators' employees. Following extensive literature review, an injury risk study has built risk functions for both passengers and pedestrians in case, respectively, of harsh braking or collision. Finally, a simulation environment has been set-up in task 6.1, allowing virtual testing of an automated minibus model by staging aforementioned safety-relevant scenarios.

1 Introduction

AVENUE aims to design and carry out full-scale demonstrations of urban transport automation by deploying, for the first time worldwide, fleets of automated minibuses in low to medium demand areas of 4 European demonstrator cities (Geneva, Lyon, Copenhagen and Luxembourg) and 2 to 3 replicator cities. The AVENUE vision for future public transport in urban and suburban areas, is that Automated vehicles will ensure safe, rapid, economic, sustainable and personalised transport of passengers. AVENUE introduces disruptive public transportation paradigms on the basis of on-demand, door-to-door services, aiming to set up a new model of public transportation, by revisiting the offered public transportation services, and aiming to suppress prescheduled fixed bus itineraries.

Vehicle services that substantially enhance the passenger experience as well as the overall quality and value of the service will be introduced, also targeting elderly people, people with disabilities and vulnerable users. Road behaviour, security of the automated vehicles and passengers' safety are central points of the AVENUE project.

At the end of the AVENUE project's four-year period, the mission is to have demonstrated that automated vehicles will become the future solution for public transport. The AVENUE project will demonstrate the economic, environmental and social potential of automated vehicles for both companies and public commuters while assessing the vehicle road behaviour safety.

1.1 On-demand Mobility

Public transportation is a key element of a region's economic development and the quality of life of its citizens.
Governments around the world are defining strategies for the development of efficient public transport based on different criteria of importance to their regions, such as topography, citizens' needs, social and economic barriers, environmental concerns and historical development. However, new technologies, modes of transport and services are appearing, which seem very promising to the support of regional strategies for the development of public transport.
On-demand transport is a public transport service that only works when a reservation has been recorded and will be a relevant solution where the demand for transport is diffuse, and regular transport inefficient.
On-demand transport differs from other public transport services in that vehicles do not follow a fixed route and do not use a predefined timetable. Unlike taxis, on-demand public transport is usually also not individual. An operator or an automated system takes care of the booking, planning and organization.
It is recognized that the use and integration of on-demand automated vehicles has the potential to significantly improve services and provide solutions to many of the problems encountered today in the development of sustainable and efficient public transport.

1.2 Fully Automated Vehicles

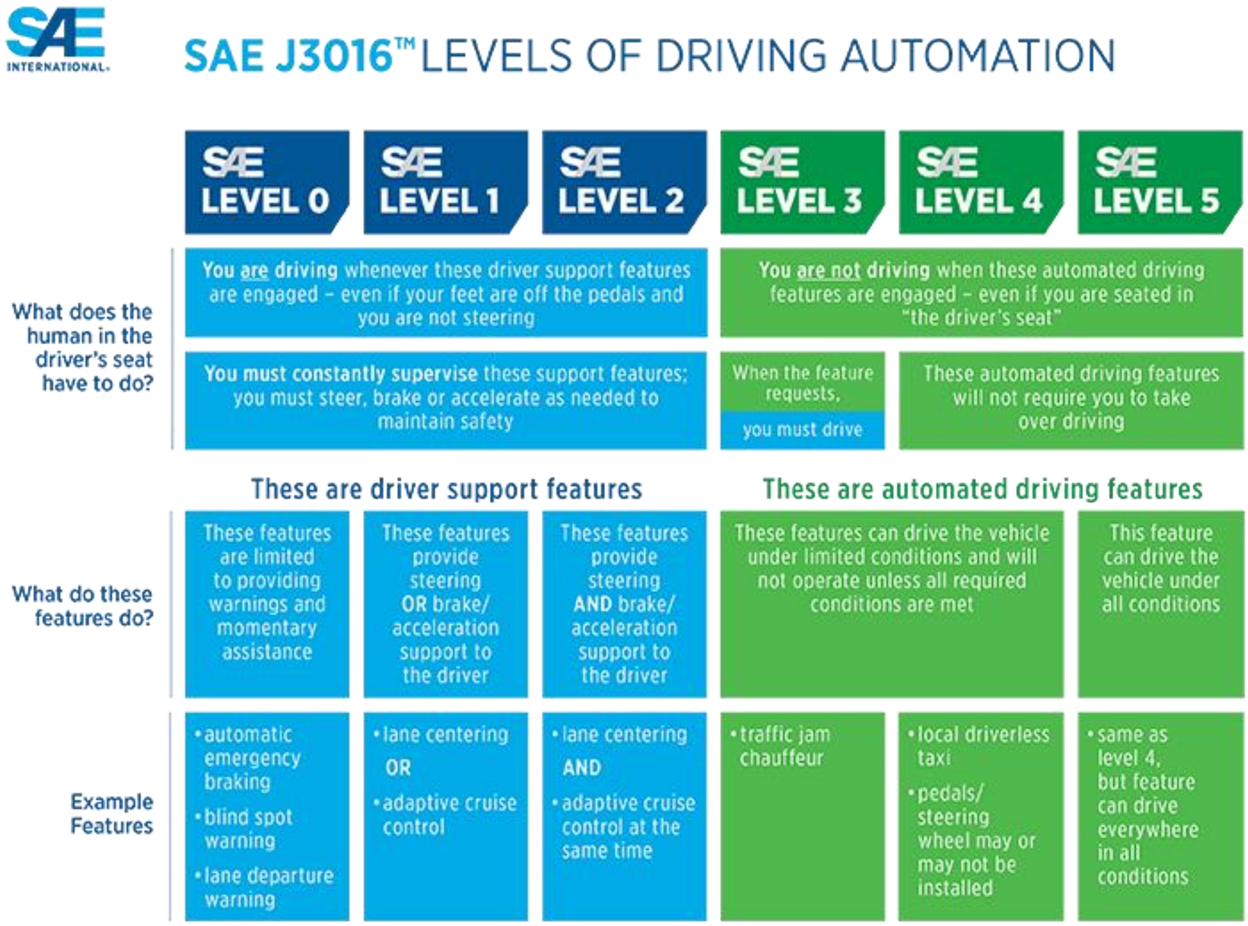
A self-driving car, referred in the AVENUE project as **a Fully Automated Vehicle** (**AV**), also referred as Autonomous Vehicle, is a vehicle that is capable of sensing its environment and moving safely with no human input.

The terms *automated vehicles* and *autonomous vehicles* are often used together. The Regulation 2019/2144 of the European Parliament and of the Council of 27 November 2019 on type-approval requirements for motor vehicles defines "automated vehicle" and "fully automated vehicle" based on their autonomous capacity:

- An "automated vehicle" means a motor vehicle designed and constructed to move autonomously for certain periods of time without continuous driver supervision but in respect of which driver intervention is still expected or required
- "fully automated vehicle" means a motor vehicle that has been designed and constructed to move autonomously without any driver supervision

In AVENUE we operate ***fully Automated minibuses for public transport***, (previously referred as Automated minibuses, or Autonomous buses), and we refer to them as simply *automated minibuses* or *the AVENUE minibuses.*

In relation to the SAE levels, the AVENUE project will operate SAE Level 4 vehicles.



©2020 SAE International

1.2.1 Automated vehicle operation overview

We distinguish in AVENUE two levels of control of the AV: micro-navigation and macro-navigation. Micro navigation is fully integrated in the vehicle and implements the road behaviour of the vehicle, while macro-navigation is controlled by the operator running the vehicle and defines the destination and path of the vehicle, as defined the higher view of the overall fleet management.

For micro-navigation Automated Vehicles combine a variety of sensors to perceive their surroundings, such as 3D video, LIDAR, sonar, GNSS, odometry and other types of sensors. Control software and systems, integrated in the vehicle, fusion and interpret the sensor information to identify the current position of the vehicle, detecting obstacles in the surround environment, and choosing the most appropriate reaction of the vehicle, ranging from stopping to bypassing the obstacle, reducing its speed, making a turn etc.

For the Macro-navigation, that is the destination to reach, the Automated Vehicle receives the information from either the in-vehicle operator (in the current configuration with a fixed path route), or from the remote control service via a dedicated 4/5G communication channel, for a fleet-managed operation. The fleet management system takes into account all available vehicles in the services area, the passenger request, the operator policies, the street conditions (closed streets) and send route and stop information to the vehicle (route to follow and destination to reach).

1.2.2 Automated vehicle capabilities in AVENUE

The Automated vehicles employed in AVENUE fully and automatically manage the above defined, micro-navigation and road behaviour, in an open street environment. The vehicles are automatically capable to recognise obstacles (and identify some of them), identify moving and stationary objects, and automatically decide to bypass them or wait behind them, based on the defined policies. For example with small changes in its route the AVENUE mini-bus is able to bypass a parked car, while it will slow down and follow behind a slowly moving car. The AVENUE mini-buses are able to handle different complex road situations, like entering and exiting round-about in the presence of other fast running cars, stop in zebra crossings, communicate with infrastructure via V2I interfaces (ex. red light control).

The mini-buses used in the AVENUE project technically can achieve speeds of more than 60Km/h. However this speed cannot be used in the project demonstrators for several reasons, ranging from regulatory to safety. Under current regulations the maximum authorised speed is 25 or 30 Km/h (depending on the site). In the current demonstrators the speed does not exceed 23 Km/h, with an operational speed of 14 to 18 Km/h. Another, more important reason for limiting the vehicle speed is safety for passengers and pedestrians. Due to the fact that the current LIDAR has a range of 100m and the obstacle identification is done for objects no further than 40 meters, and considering that the vehicle must safely stop in case of an obstacle on the road (which will be "seen" at less than 40 meters distance) we cannot guarantee a safe braking if the speed is more than 25 Km/h. Note that technically the vehicle can make harsh break and stop with 40 meters in high speeds (40 -50 Km/h) but then the braking would be too harsh, putting the vehicle's passengers at risk. The project is working in finding an optimal point between passenger and pedestrian safety.

Due to legal requirements a **Safety Operator** must always be present in the vehicle, able to take control any moment. Additionally, at the control room, a **Supervisor** is present controlling the fleet operations. An **Intervention Team** is present in the deployment area ready to intervene in case of incident to any of the mini-busses.

1.3 Preamble

1.3.1 Scope and relation with other tasks

Making automated minibuses relevant in the public transportation landscape requires improving quality of service (higher operating speed, on-demand service) and reducing dependency on human operators (i.e. transition from on-board safety operators to remote monitoring). **This poses serious safety and security challenges, which are the focus of WP6.**

Passengers and other road users safety is addressed in tasks 6.1 and 6.2. Task 6.1 aims at assessing safety in a controlled environment (test tracks and simulation), whereas 6.2 concentrates on actual field operations and related hazards. Both tasks are intimately interleaved in a common methodology which is explicated in this document.

Security is addressed in task 6.3, which focuses on making the services provided within AVENUE robust to hacking attempts (i.e. cybersecurity), but also supports development of automatic detection of threats to passengers security through, for instance, automated video processing.

It is worth noting that safety and security are vast domains which can only partially be addressed within the scope of such project. **The activity in WP6 therefore concentrates on threats which are specific to automated minibuses**. WP6 aims at supporting operations during the AVENUE project to ensure that current best-practices are applied, but also at improving the state of the art and **provide advice which can be used in future deployments**. Therefore, WP6 doesn't focus on issues which are very specific to AVENUE (e.g. specific vehicle model used in operations), but rather aims at providing universal findings and recommendations.

This deliverable D6.2 describes the methodology for safety evaluation and the implementation work carried out during the project. It notably includes our vision for injury risk assessment for both passengers and pedestrians exposed to a collision with an automated minibus, and the development of a ranked catalogue of safety-relevant scenarios which should be the basis of future safety assessments. It also presents activities which, being part of the overall methodology, were developed and demonstrated, but only applied at the scale permitted by the project.

Relation to other tasks and deliverables

Relations to other work packages are detailed in the subsequently presented methodology. Several deliverables from WP2 and WP7 have provided inputs used in the current document.

D2.16 - First Trials use cases specification and evaluation plan provides the first description of goals, planning and operational ambitions per demonstrator along with the associated challenges. It provided WP6 with the initial inputs allowing designing safety-related scenarios based on the planned infrastructure and operating conditions for the vehicle.

D2.17 - Second Trials use cases specification and evaluation plan specifies and adjusts the use cases defined in D2.16, providing WP6 with more detailed operating descriptions.

D7.1, D7.4, D7.7, D7.10 – First Iterations Large Scale Pilot Use Case Demonstration Report presents, for each one of the 4 demonstrators (Geneva, Lyon, Copenhagen and Luxembourg, respectively) the first feedback for operations on each one of the sites.

D6.4 - Controlled environment vehicle safety evaluation report describes task 6.1 activities, which is part of the overall methodology presented here.

1.3.2 Objectives

Small and medium sized, shared automated vehicles (i.e. automated minibuses) seem like a promising way to address some public transport operators' issues, notably offering a service on low traffic/peripheral routes, where traditional busses would not be economically viable or not flexible enough.

The AVENUE project aims at demonstrating the suitability and efficiency of the use of small and medium automated vehicles for different transport models that are under development in Europe. Its goals are not only to assess the safety of automated vehicles in public transports, but also to demonstrate the economic, environmental and social advantages of automated vehicles for both the exploiting companies and the users, opening the way for a full scale adoption of automated vehicles in public transport after the end of the project.

Four experimentation/demonstration sites are part of the project and are managed by public transport operators in Lyon, Geneva, Luxembourg and Copenhagen. The current approach in using vehicles is rather cautious: minibuses operate at low speed, on predefined routes with no or very little traffic, under the constant supervision of on-board safety stewards. Of course, this seriously limits the relevance of such minibuses, both in economic and quality of services terms. To demonstrate any relevance, their flexibility needs to be improved (on-demand service, which were implemented within AVENUE), they should be able to use existing infrastructure and share it with other road users, they should operate at higher speed, and they should not depend on on-board personnel. This of course poses many safety challenges: interactions with other actors will become more complex; the environment might be less known and predictable; while higher speeds make collisions potentially fatal (cf. Figure 1 below).

~reserved lane →	open street	more complex interactions
~10kph →	40kph	fatal injury risk in collision
fixed route →	on demand	less known environment
in-vehicle operator →	remote monitoring	everything in the hands of a computer wired to a few sensors….

Figure 1. Automated minibuses safety challenges

Ultimately, vehicle manufacturers and public transport operators share the responsibility to provide a safe service to their passengers, but also to other road users. This encompasses multiple challenges, each of which has to properly be addressed:

- **Functional Safety:** prevent system failure resulting in injury;
- **Crashworthiness:** protect occupants from crashes;
- **Operational Safety:** e.g. avoid hurting passengers with automatic doors;
- **Non-collision Safety:** e.g. avoid exposing passengers or personnel to electrical hazard;
- **Safety Of The Intended Functionality:** properly handle situations met on open road.

Among these challenges, the last one is the most specific to automated minibuses. With nobody behind the wheel, proper situational awareness and swift response to danger from embedded systems are crucial to ensure safety. **Automated minibuses must not only present at least the same performance as a human driver in assessing and reacting to threats, but they must also exhibit to other road users a behaviour which makes sense to them and doesn't lead to conflict or risky behaviour.**

Whereas the first four safety challenges are already well understood and addressed within the domain of traditional transportation by way of norms, best practices and regulations, *Safety Of The Intended Functionality* (SOTIF) is relatively recent. It is described in the context of Advanced Driving Assistance Systems and low level automation in (The International Organization for Standardization (ISO), 2019), but is still a work in progress regarding higher level automation.

Within AVENUE, using feedback and data from the field tests, description of future plans, and a mix of simulation and physical testing, tasks 6.1 and 6.2 from WP6 aims at:

- Identifying situations which might cause safety problems when the operational design domain of the minibuses is extended.
- For those situations, expose the relationship between vehicle capabilities and the situations that can safely be addressed (e.g. which speed can be attained using current vehicle technology in a pedestrian-dense environment; which change in vehicle capability needs to be implemented before using the minibus in mixed traffic…)

WP6 will concentrate its effort on safety issues which are specific to automated minibuses, and in the most generic way, using the vehicle currently used in the project (NAVYA Arma) and the test sites' routes as reference points.

This implies that WP6 will favour studying *Safety Of The Intended Functionality* (SOTIF) of "an" automated minibus, rather than functional safety of the specific vehicle used in the project.

Although lack of functional safety would inevitably lead to serious accidents, it is the responsibility of a vehicle manufacturer to properly implement and validate their product against its specifications, an issue which is certainly not specific to automated vehicles and already understood and addressed in norms such as ISO 26262 (The International Organization for Standardization (ISO), 2018) and common systems' engineering practices.

WP6's aim is not to specifically address crashworthiness (i.e. the capacity to protect its occupants in the event of a severe collision) of the vehicle used in the project. Despite the common perception that autonomous or automated vehicles magically "won't crash" thanks to the embedded technology, it is our opinion that those vehicles will be exposed to crash risks at least as severe as any kind of vehicle, and as such, the same care that is taken to protect occupants of any kind of vehicle should be taken. Some autonomous vehicles actors address this issue by adapting their systems on readily available passenger cars or vans, which already comply with strict occupants' protection standards (WAYMO, 2018). Conversely, occupants in an automated minibus such as NAVYA's Arma can take a much wider range of positions compared to passenger cars, which creates a very challenging environment. This is addressed in this deliverable in the context of harsh brakings. However, a proper crashworthiness assessment would, additionally, require multiple destructive crash tests and extensive numerical testing campaigns, which would be extremely vehicle-specific and are completely out of financial reach of the project.

In conclusion, automated minibus manufacturers should take great care in ensuring functional and passive safety of their vehicles. Public transport operators, authorities, and the general public should not accept less than the state of the art in that respect. **This might be problematic**, given the current size and revenue of said manufacturers, in comparison to the substantial resources that traditional vehicle manufacturers have dedicated and are still dedicating to their vehicles' safety. However, tasks 6.1 and 6.2 in WP6 decided to focus on risks which are *particular* to the limitations of automated vehicles compared to conventional ones.

Our main goals when designing the methodology herein introduced were to:

- Develop a *system* approach, which considers the vehicle, its passengers, its route and environment and their interactions as conjointly contributing to risk;
- Design a *generic* approach, which can be used to gauge the risks associated with the current, already implemented, vehicle and routes, but which can also be used before considering evolutions to both vehicle and routes (e.g. helping answering questions such as "What needs to be changed on the vehicle when riding at a given speed in a specific kind of environment?")

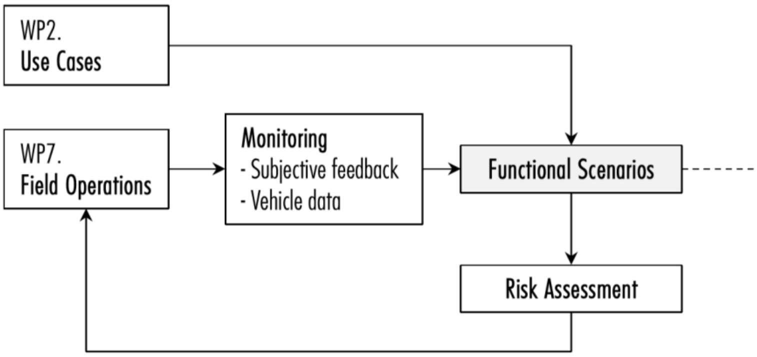
The following chapter presents the methodological approach retained for this safety study. Subsequent chapters detail the implementation work that has been carried out following this approach.

2 WP6 methodology overview

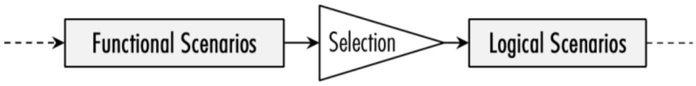
2.1 Outline

The methodology presented here was developed during the first months of the project. It relies on multiple skills (objective and subjective data collection and analysis, safety critical scenarios definition and categorization, injury risk assessment, computer simulations…), which are brought by WP6's partners. More specifically:

- Both subjective and objective data are collected from the test sites (WP7) and combined with use cases (i.e. future plans, WP2) to identify safety relevant scenarios. Based on those scenarios, a preliminary safety assessment can be carried out.

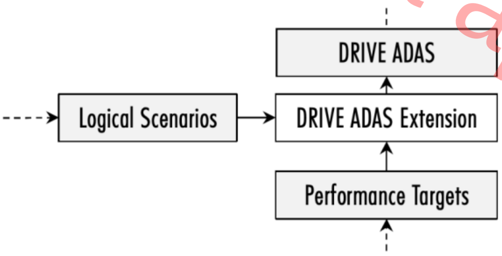


- Safety-relevant scenarios which are specific to automated minibuses are selected and further described, in a quantitative way (i.e. by measurable parameters and their possible range and/or distribution).

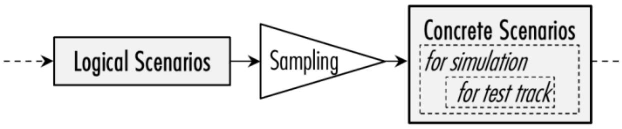


- An injury risk study, considering the geometry of automated minibuses is carried out. It delivers risk functions based on the most important parameters (e.g. passengers injury risk during a braking, based on their position and deceleration profile).

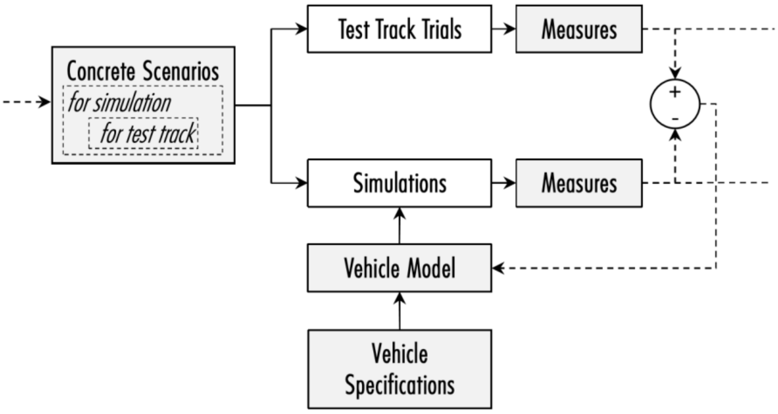
- Relevant scenarios are detected and the associated Key Performance Indicators are compared to Performance Targets. This relies on AVL DRIVE ADAS, in task 6.1.



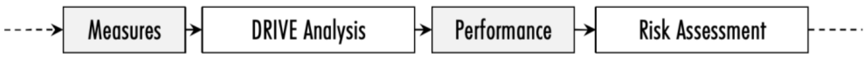
- Some instances of the relevant scenarios are sampled (i.e. parameters values fixed), either to sweep the entire parameter space and build a representative set for a comprehensive risk estimation, or to explore boundary conditions (i.e. conditions where the desired outcome is known, e.g. “avoid hurting any pedestrian that would run in front of the vehicle within a 10m headway or more”).



- Those scenarios are simulated, and some of them reproduced on a test track, to improve the vehicle model used in the simulation.



- Results from those controlled environment tests and simulations are run through AVL-DRIVE ADAS to provide a refined safety assessment.



The complete process is summarised in Figure 2 below, which also delineate tasks 6.1 and 6.2 perimeters. The successive steps are further developed in subsequent sections.

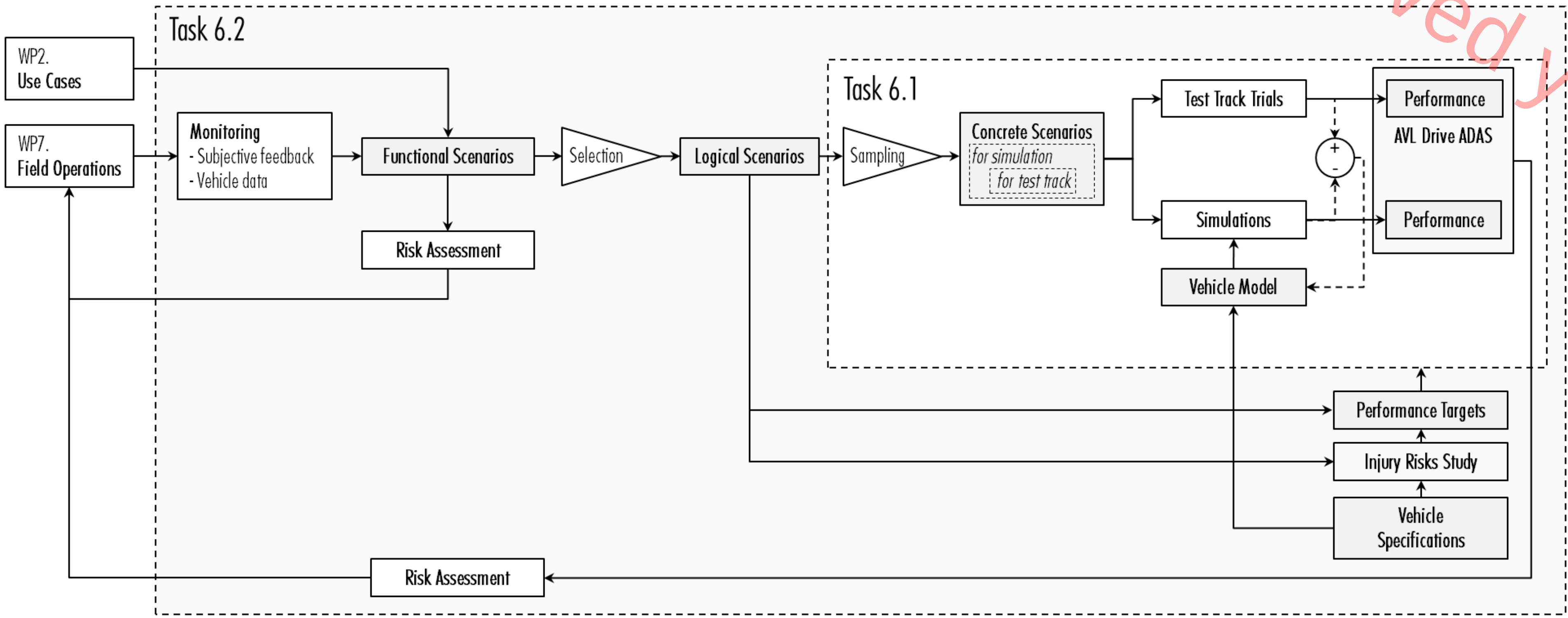


Figure 2. Tasks 6.1 and 6.2 methodology and interactions

2.2 Field data collection

Little feedback exists on the operation of automated minibuses. It is therefore important to benefit from the unique opportunity that AVENUE presents to collect such feedback from the field, in the diverse environments in which the vehicles operate.

Data collection aims first at identifying situations which currently pose problems (e.g. disengagement situations, which require the intervention of the safety stewards, or situations which result in harsh braking), but also emerging problems, which will cause concern when the operational design domain will be extended (e.g. when speed will be risen).

These situations are then described and classified as "high-level" functional scenarios (see definition Section 2.3 below). The importance of each situation is finally graded in terms of expected frequency and criticality.

This data collection starts first with simple means:

- Gather existing incident reports from public transport operators and vehicle manufacturer;
- Circulate a functional scenario template at public transport operators and vehicle manufacturer to list situations which they deem relevant in terms of safety;
- Organise focus groups with safety stewards in each test site to gather first-hand knowledge from them.

In a second step, the proposal was to systematically collect data during operations in all four test sites, which would have provided more quantitative indicators. The data to collect consist of:

- Dynamic behaviour of the vehicle: speed, acceleration and angular speeds.
- Global state of the decision layer: automated mode vs. manual control takeover, target speed.
- Activation of actuators (accelerating, steering, and brake)
- Geographical coordinates and attitude of vehicle (Longitude, Latitude, Bearing)
- Video feeds (both inside and outside the vehicle) to understand the circumstances of the events.
- Post-fusion objects detected by the vehicle, characterised, at least, by their centre of mass and closest point position relative to the vehicle, their speed, their classification and their relevance.

As trips are repeated on known routes, this detailed data collection can initially be concentrated on relatively short periods. Triggers are implemented to detect situations of interest, notably harsh braking and disengagement, which allows further analysis. This data collection complements the more subjective means of data collection (questionnaires & focus groups) in order to:

- Identify situations categories which might have been overlooked by subjective data collection;
- Provide quantitative assessment of situations occurrences;
- Measure parameters in occurrences of scenarios which will be selected for further description as logical scenarios (see definition in Scenarios creation section below).

2.3 Scenarios creation

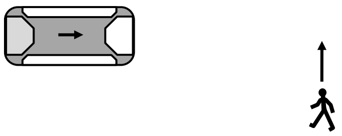
Relying on aforementioned data collection as well as literature (again to avoid overlooking any potentially relevant situation), a scenarios catalogue is constituted. Depending on the expected use of a scenario and the corresponding description level needed, three categories of scenarios are defined, as per (Menzel, Bagschik, G., & Maurer, A. M., 2018):

- *Functional Scenarios*: functional scenarios consist of a high-level description of a safety-relevant situation. It describes the actors (vehicles, pedestrians…), the environment and the overall timeline/steps of the situation. It is documented as a pictogram and a textual description. Subjective data collection (questionnaires, focus groups) can be enough to constitute most of the functional scenarios catalogue, but more systematic and objective measures help ensuring nothing is overlooked.
- *Logical Scenarios*: a logical scenario describes in a quantitative manner the **parameter space** of a functional scenario. It therefore lists the variables/parameters of interest and the range of values that each of them can take. Parameters are considered of interest if they have an impact in the outcome of the situation, for instance if they affect the perception/decision of the automated vehicle, or because their values will directly be linked to an injury risk (e.g. original travel speed affects an eventual collision speed). A logical scenario ideally provides distributions for each parameter and multivariate distributions between parameters, to account for inter-parameters correlations. Such correlations can be imposed by system design (e.g. passengers' position and vehicle speed are both parameters of a logical scenario; a system inside the vehicle prevents it from running above a certain speed until all passengers are sat). It can also result from variation in behaviour depending on actors or environment characteristics (e.g. walking speed and height are characteristics of a pedestrian; children are more likely to run in front of a vehicle than an adult, therefore situations with a pedestrian running are more frequent when pedestrian height is smaller). Describing scenarios in such a manner is necessary to assess the relevance / importance of a specific set of parameters, and therefore give a weight to a concrete scenario (see below). Extensive data collection is required to construct such scenario description. This requirement is the justification for detailed and systematic vehicle data collection.
- *Concrete Scenarios:* a concrete scenario is a specific instance of a logical scenario, associated with the corresponding parameters values. An actual measured event or a specific run of a simulation are concrete scenarios.

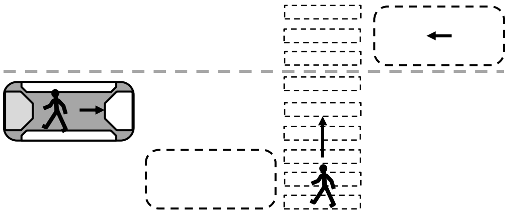
To illustrate those notions, an example is given in Table 1 below.

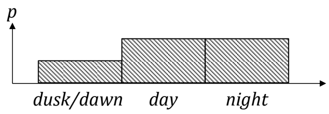
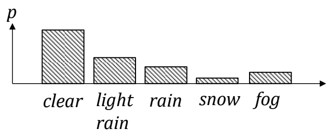
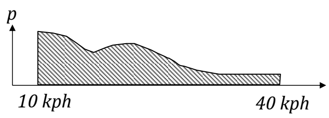
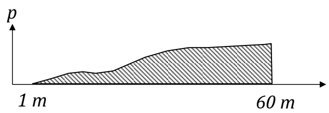
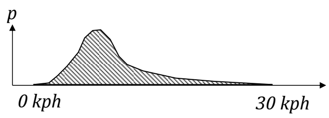
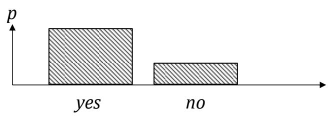
Table 1. Distinction between functional, logical and concrete scenarios

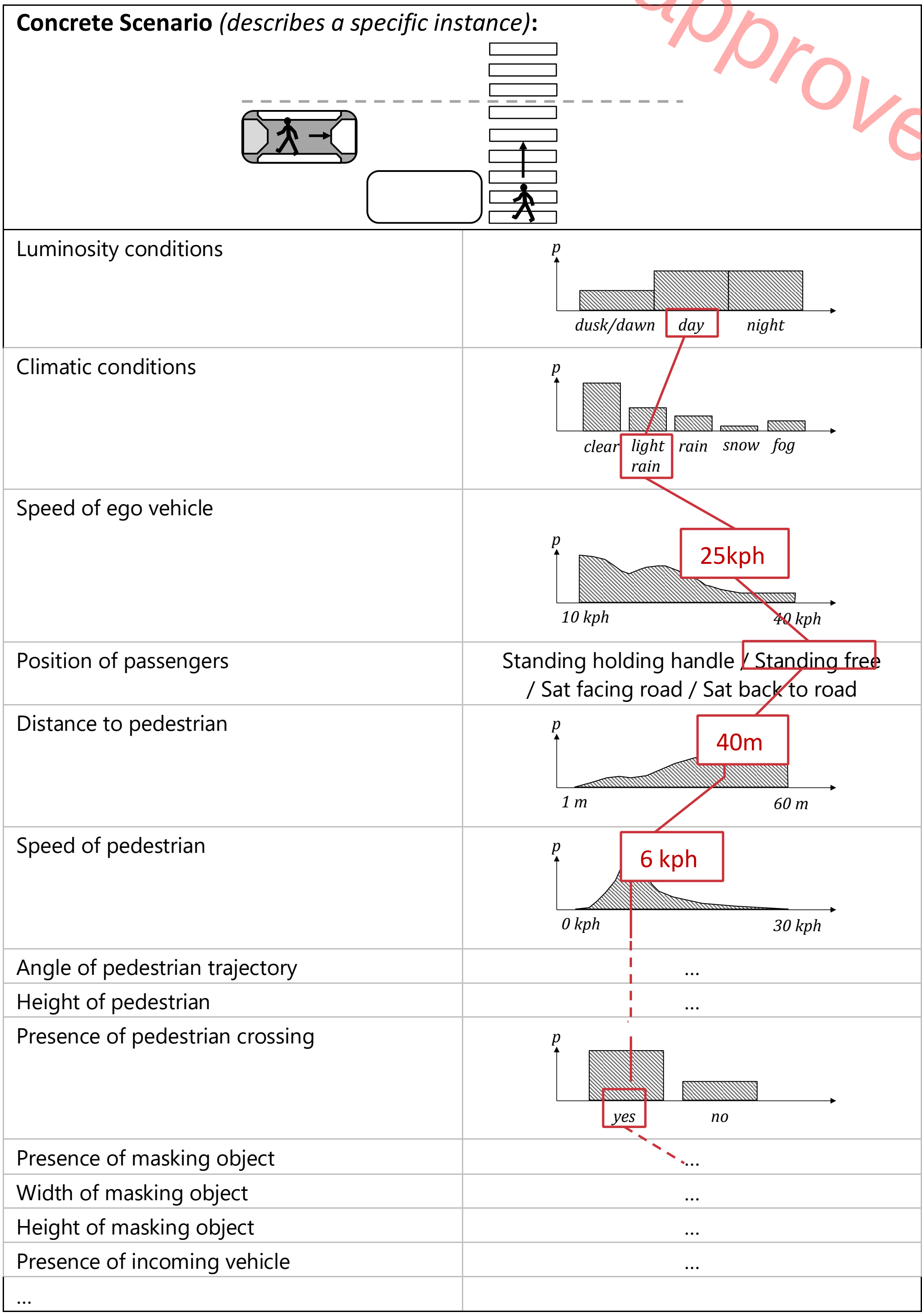
Functional Scenario *(describes the situation in a generic way)*:
Giving way to pedestrian crossing road.



Logical Scenario *(identifies important parameters and their possible values)*:



Luminosity conditions	
Climatic conditions	
Speed of ego vehicle	
Position of passengers	Standing holding handle / Standing free / Sat facing road / Sat back to road
Distance to pedestrian	
Speed of pedestrian	
Angle of pedestrian trajectory	…
Height of pedestrian	…
Presence of pedestrian crossing	
Presence of masking object	…
Width of masking object	…
Height of masking object	…
Presence of incoming vehicle	…
…	


Concrete Scenario *(describes a specific instance)*:
Luminosity conditions
p
dusk/dawn
day
night
Climatic conditions
p
clear
light rain
rain
snow
fog
Speed of ego vehicle
p
25kph
10 kph
40 kph
Position of passengers
Standing holding handle / Standing free / Sat facing road / Sat back to road
Distance to pedestrian
p
40m
1 m
60 m
Speed of pedestrian
p
6 kph
0 kph
30 kph
Angle of pedestrian trajectory
...
Height of pedestrian
...
Presence of pedestrian crossing
p
yes
no
Presence of masking object
...
Width of masking object
...
Height of masking object
...
Presence of incoming vehicle
...
...

2.4 Injury risk assessment

It is crucial, within our study, to acquire the capacity to estimate the severity of injury stemming from incidents (e.g. harsh braking) or accidents (collision), depending on their parameter's values (e.g. position, jerk and deceleration, speed at impact…).

As previously explained, our study largely focuses on safety issues which are particular to automated vehicles.

We consider being collided by other vehicles a definite probability, likely raised by the currently reported tendency of experimental automated minibuses to perform unexpected harsh braking or to stop. However, assessing crashworthiness of a vehicle is largely dependent on countless design parameters (materials, construction, restraint systems…) and therefore very vehicle-specific. It requires performing multiple physical (crash) tests and simulations. As much as crashworthiness' importance should be emphasised, vehicle-specific studies cannot be the focus of AVENUE, and performing crash tests certainly is too expensive for the project. As a result, no assessment of crashworthiness for the vehicles used in the project will be performed within AVENUE.

Other injury risks, such as being stuck in an automatic door or being electrocuted by high voltage exist, but they won't be treated either, as they're not particular to automated vehicles.
Consequently, AVENUE firsts concentrate on the following risks:

- Injury risk for passengers in case of harsh braking;
- Injury risk for vulnerable road users (pedestrians) in case of collision.

This allows treating some of the riskiest situations, including some where multiple risks have to simultaneously be accounted for, such as realising an emergency braking to avoid or mitigate a collision with a pedestrian.

Figure 3. Pedestrian front collision / emergency braking situation

This activity produces, both for passengers and pedestrians, injury risk estimations as a function of relevant dynamic parameters (e.g. jerk and deceleration of braking for passengers / collision speed for pedestrians, cf. Figure 4 below). Injury risk is given as probability to sustain a certain injury level, when possible using a standard scale such as Abbreviated Injury Scale (AIS) (AAAM, 2015) (e.g. risk given as probability of AIS ≥ 3 for head injury).

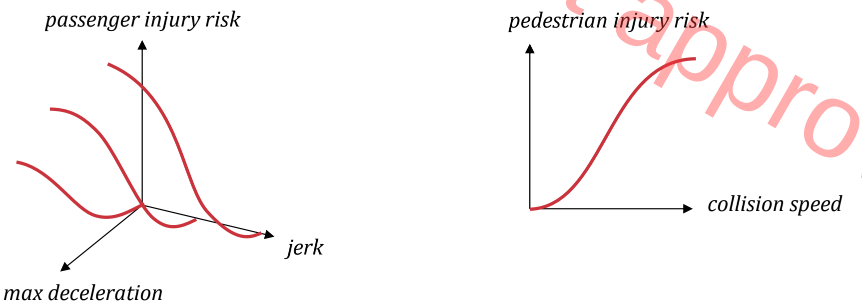


Figure 4. Risk (e.g. AIS ≥ 3 probability) as a function of dynamic parameters

The study spans several configurations, both for passengers and pedestrians, prioritising configurations which seem the most risk-inducing (cf. Figure 5 below). Therefore, multiple risk estimation functions such as those illustrated in Figure 4 are created.

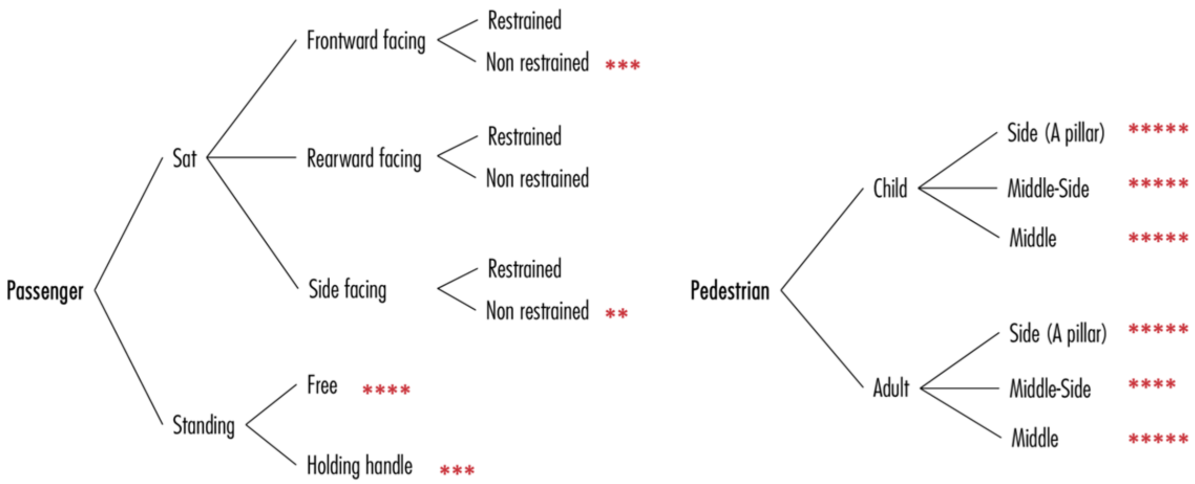


Figure 5. Configurations considered in the injury risk study. Red stars represent most critical and therefore prioritized configurations

The study relies as much as possible on existing literature, but also on finite-element simulations of braking/crash conditions. Those simulations use numerical models of crash test dummies, and the actual geometry of the vehicle used in the project, provided by NAVYA. However, as actual mechanical characteristics of materials employed in the construction of this specific vehicle are not known, and since the aim is to provide generalizable results, simple generic materials models were used for each part (e.g. windscreen material is defined as standard automotive windscreen material).

2.5 Performance targets definitions

Performance targets may be defined for each logical scenario. They largely consist of safety goals (e.g. “the vehicle should stop before any contact when a pedestrian crosses at 20 meters or more from the vehicle”, “no injury above AIS 2 should ever be sustained by a passenger”), which means setting thresholds on various Key Performance Indicators (KPIs) for each scenario.

As defining performance targets might require accepting a certain level of risk to allow the implementation of the service, their definition entirely is under the responsibility of public transport operators.

Logical scenarios detection, calculation of KPIs and assessment of performance targets being attained (or not) are implemented in AVL-DRIVE ADAS software[1], allowing automatic analysis of test track trials and simulation measures.

2.6 Concrete scenarios sampling

In order to carry out test track trials and simulations, concrete scenarios must be sampled out of logical scenarios. Ideally, extensive data collection and modelling would allow describing the entire activity of the minibuses as logical scenarios, as well as those scenarios entire parameters space, including dependencies between parameters (i.e. conditional probabilities). Systematic sampling (e.g. Monte Carlo) for tests and simulations would then allow a probabilistic risk assessment.

As simple statistical comparisons of automated vehicles safety performance versus human driven vehicles performance would require hundred millions to hundred billions of kilometres to demonstrate any safety benefit (Kalra & Paddock, 2016), it is therefore considered such data-based modelling approach likely to be the only approach being both practical and sufficient. However, resources within AVENUE and limitations in data collection didn't allow even such activity to take place at full scale. Therefore, concrete scenarios are manually sampled to allow exploring most frequent and/or most feared conditions, as defined by, and under the responsibility of public transport operators.

2.7 Test track trials

To claim any credibility, simulations need to be confronted (and then tuned to match) to real situations. Test tracks allow observing the reactions of the actual vehicle to events which can be produced without any safety concern using dedicated infrastructure and dummies and/or soft targets to represent vulnerable road users and surrounding vehicles.

However, although test track trials were planned in Task 6.1, the project did not allocate specific funding for facility and equipment renting, neither for the necessary on-site support. The solution was to use a previously existing test dataset, created during initial safety assessment of the minibus by KEOLIS.

[1] AVL-DRIVE ADAS is proprietary software from AVL. It allows, from measures such as speed, positioning and headway, to automatically detect a variety of scenarios and grade the performance of the system in handling them. It currently supports level 2-3 systems available on passenger cars (e.g. traffic jam / highway chauffeur) and corresponding scenarios. It was extended within AVENUE to support scenarios which are specific to automated minibuses.

2.8 Simulations

Test track trials are the reference from which simulations can interpolate and to a lesser degree extrapolate, to cover a much higher variety of situations.

Simulations were initially planned to be carried out with the CARLA simulator (Dosovitskiy, Ros, Codevilla, Lopez, & Koltun, 2017). This tool allows simulating a virtual environment including infrastructure geometry, traffic lights, other road actors, various weather conditions, among others. In which, through an API, an automated vehicle can be modelled and used.

The automated vehicle model represents not only mechanical aspects such as weight and grip, but also the geometry of sensors positioning, models those sensors in various ways (determined by the necessary precision) and integrates algorithms to perform data fusion and supervision of the vehicle (i.e. decision layer).

Within the context of this methodology, the plan is to create a simplified model of both sensors and embedded software. For instance, although CARLA allows fully simulating rotating LIDARs to provide complete point clouds, and therefore allows acting as a test bench for low level objects detection algorithms, we rather intend to model such sensors by a set of simpler rules (e.g. as soon as a certain percentage of an object is in direct sight and within range of the sensor, we consider it to be detected).

This simpler model will therefore rely on a manageable set of parameters, allowing testing hypothetical evolutions of the vehicle such as e.g. changing sensors positioning, adding additional sensors, and improving obstacles behaviour prediction.

Figure 6. Urban driving scene, as simulated by CARLA tool

Simulations produce outputs such as speed, acceleration, relative position to obstacles, in a wide variety of scenarios. Those outputs are then given as inputs to AVL-DRIVE ADAS, which calculates KPIs and compare them with performance targets, allowing:

- Public transport operators to assess whether the current capabilities of the vehicle are compatible with their plans;
- Vehicle manufacturers to experiment with potential evolutions of their product, to allow new use cases to be addressed.

2.9 Risk assessment

As previously exposed, financial constraints, the urgency to explore hidden challenges associated with automated minibuses, and a desired reusability of project results for new vehicles / routes dictate that tasks 6.1 and 6.2 from AVENUE focus on:

- Safety Of The Intended Functionality (SOTIF),
- for automated, urban minibuses,
- in a high level, generic way.

This is just one component, necessary but not sufficient to address the full spectrum of safety hazard, which also includes:

- Functional Safety
- Crashworthiness
- Operational Safety (e.g. avoid hurting passengers with automatic doors)
- Non-collision Safety (e.g. avoid exposing passengers or personnel to electrical hazard)

Moreover, even within the confines of SOTIF, the scale of the effort doesn't allow carrying out a complete probabilistic risk assessment. However, the currently offered methodology allows:

- Identifying and addressing main threats;
- Setting performance targets and ensuring they can be reached with current technical choices;
- Assessing relative benefits of diverse potential evolutions to the vehicle.

It will also lay possible foundations for "at scale" safety assessment, as described in, e.g. (WAYMO, 2018).

The following chapters describe the implementation work carried out, the difficulties encountered and results which could be obtained nonetheless.

3 Scenarios identification and ranking

As previously explained, the first step of the methodology was to rely on the experience of the public transport operators to identify relevant scenarios for the study. To help focus the topic on the Safety Of The Intended Functionality, a simple definition of a relevant scenario was devised, relying on the simple behaviour of the automated minibus. As the latter is designed to follow a predefined path akin to a "virtual rail" while respecting a predefined speed profile, and adapt to external events by either reducing the speed or slightly altering the path, we defined a relevant scenario, in the specific context of an automated minibus, as: "***any situation in which, had the minibus continued its nominal trajectory and speed, a collision would have occurred".***

Operators' feedback was collected in multiple complementary ways to constitute a **catalogue** of scenarios following this definition, and then rank the scenarios by criticality.

3.1 Incident reports

The first and seemingly most obvious way to identify relevant scenarios is to analyse incidents actually happening during the operations.

No harmonised data collection initially existed within AVENUE regarding incident reports, each operator keeping track of the encountered problems in a different way. KEOLIS, for instance, has implemented an app which safety drivers can use to describe the various issues they meet; TPG operators rather use a paper form. These provide feedback not only regarding safety-relevant events, but also and mostly regarding the many technical difficulties met during operation. Furthermore, with the exception of serious incidents which lead to complete reports being written, most interesting events are not traced with a sufficient precision for WP6 use. For instance, as seen in D7.1 deliverable, many automatic braking events are encountered and are marked as "caused by other road users' behaviour", but little is known about the precise circumstances which lead to these events.

As a starting point, operators have been asked by WP6 to provide feedback on previous frequent or severe issues they might have had in previous operations with the same minibus. Although undoubtedly useful, this data also had limitations in the sense that the exact driving environment was not necessarily being described, and on the fact that many technical issues, out of WP6's scope, were reported.

This leads us to realise the following:

- Current test sites and vehicle implementation meet a lot of technical challenges leading to a lot of minor incidents which are unrelated to safety;
- The presence of safety drivers and a very conservative automation (low speed, very early braking in presence of obstacles) currently ensure a rather good level of safety but make potential threats hard to identify.

A centralised data collection tool was however developed to collect any potentially relevant incident.

It appeared to public transport operators as an online questionnaire with multiple possible paths, depending on answers provided to initial questions.

It was implemented and available in both English and French, as three out of four test sites were in French speaking countries.

Public transport operators and especially safety stewards were invited to complete the questionnaire each time they encountered an "event that had surprised, impressed or even frightened them", while they were in charge of the minibus, and while it was operating in automated mode.

After selecting the test site in which the incident happened, users where presented an appropriate map, where they could selected the exact **location** of the incident (Figure 7)

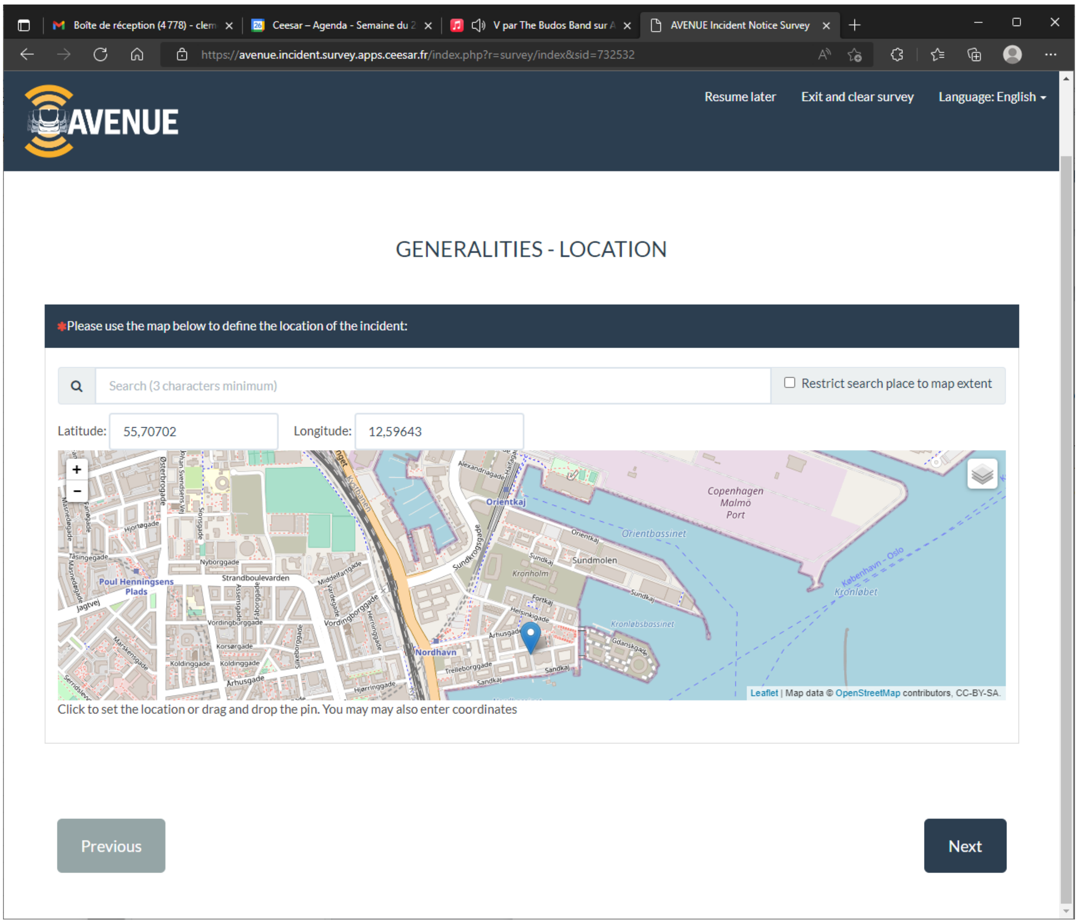


Figure 7. Location selection

They could then select the **date and time** with an appropriate widget, describe the **weather conditions** with non-excluding modalities and an optional free-text field, and **daylight conditions** between "Daylight", "Dawn / dusk", "Night with public lights on", "Night without public light".

The next section allowed them to describe **static obstacles**, again with multiple non-excluding modalities and an optional free-text field.

They would then enter the **amount of other road users**, which contributed to the scenario, and were prompted, for each of them, to select the **type of road user** or vehicle in a drop-down menu.

They would then be prompted to select the **initial manoeuvre of the minibus** at the incident onset among multiple possibilities (including an optional free-text field), and the **initial manoeuvre of *each* other road user**, in a similar way.

A free text field allowed providing **any additional relevant information about the situation before the incident**.

A **global description of the incident** was then requested (free-text) and users were asked to upload a **schema of the incident** in the form of an image file.

The next question inquired whether the **automated mode stopped automatically** and if not, **if the safety steward took over control** manually.

Each road user's manoeuvre during the event had to be described, again using pre-defined modalities or a free-text field.

In the event of a **collision**, its **characteristics** could be described (Figure 8).

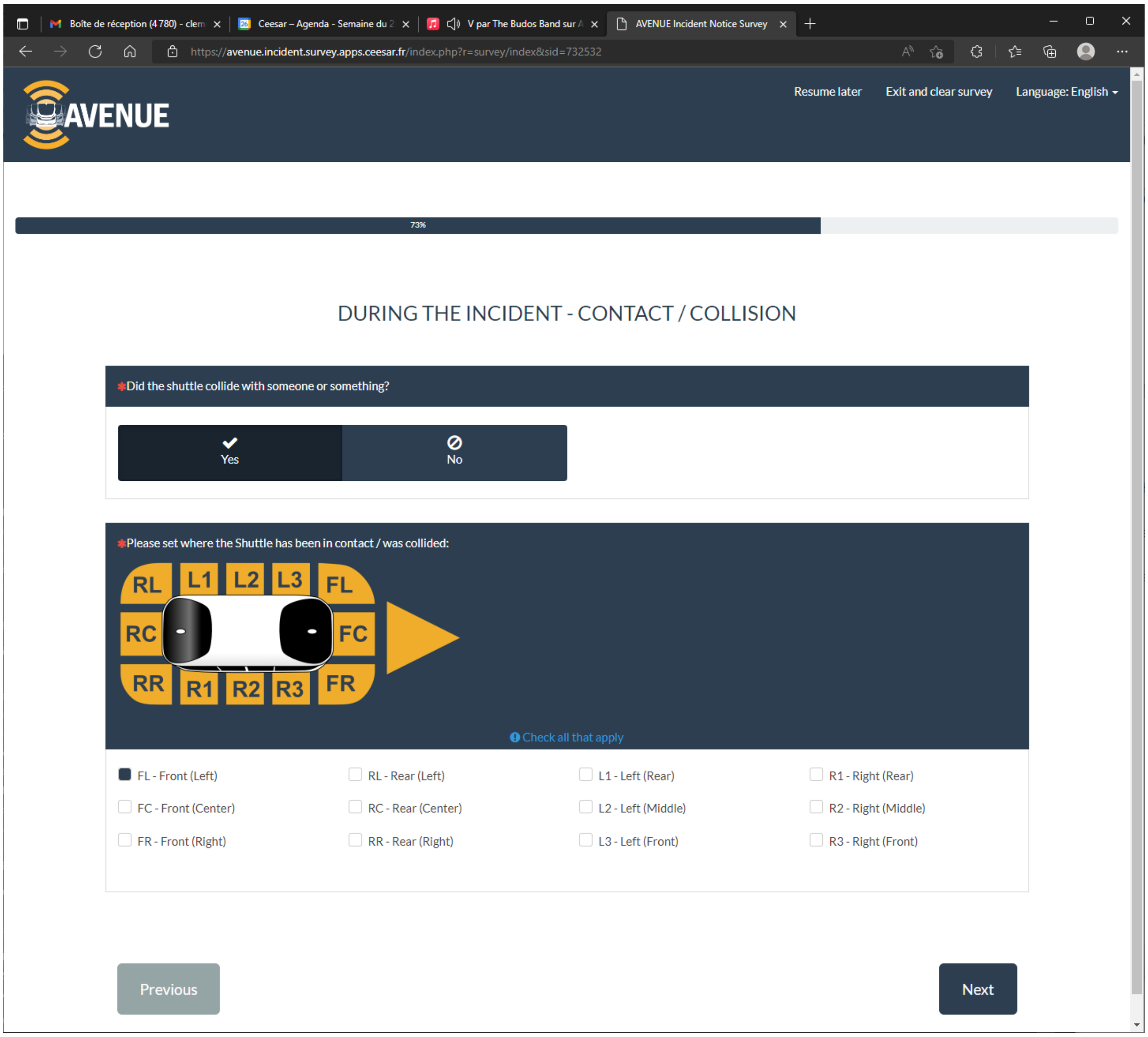


Figure 8. collision description

The **emotional and physical condition** of both passengers and safety steward could then be described, and any potentially useful additional information could be provided, either as free text or uploaded document(s).

The final question inquired about the **frequency** of this or similar incident.

Everything was done to reduce the friction to answer the questionnaire, its design was responsive, to allow answering it from a mobile device, potentially on-site. Coming back and resuming documenting an incident was possible as well. Operators were invited multiple times to contribute to the resulting database.

Despite those efforts, and although each operator logged in at least once in the incident report portal, only one incident was fully described, by Keolis' teams, in Lyon. It describes a situation where **the minibus crossed a red light** and had to be manually stopped in an emergency. This is a typical example of a *functional safety* issue: for technical reasons (questionable reliability of V2I communication) the system[2] didn't behave in accordance with its own high level requirements. As already explained, functional safety issues are 1/not specific to automated or autonomous vehicles; 2/ highly depend on manufacturer-dependent implementation details; 3/ the subject of many well-documented engineering methodologies. They therefore are not the focus of this work, and this incident, as concerning as it is, was not further studied.

3.2 Focus groups

The main rationale behind organising focus groups is to identify safety issues which WP6's partners haven't thought about, but which would be obvious to anybody currently in charge of safety on a daily basis (i.e. safety drivers/stewards).

3.2.1 Methodology

Focus groups consist of open but guided discussions between groups of safety drivers and an interviewer/moderator, around the topic of safety. They ideally gather between 4 and 8 participants, which:

- Cover diverse personalities (age, gender, attitude toward technology, attitude toward risk…);
- Are from the same hierarchical level, to allow each of them to freely express themselves;
- Carry out shifts covering the entire range of operating time.

Within the context of WP6, the discussion is to cover the following topics:

- Perceived importance of safety among other issues;
- Identification of current most safety-critical events;
- Identification of potential threats resulting from a higher operating speed;
- Identification of potential threats resulting from monitoring to be performed remotely.

[2] To be clear, it is very probable that each component in the system (red light, transceiver, minibus…) behaved exactly as specified. However, as a system, the combination of those components failed to meet the simplest of requirement: not to cross red lights.

This discussion is then followed by a workshop where relevant safety-relevant scenarios are discussed and pinned on a map of the minibuses' route.

The moderator is assisted by a 'note taker' who doesn't initially participate in the discussion but takes note of all contributions. At the end of the discussion, the note taker gives a synthesis on each topic of discussion, while participants are invited to correct, refine or complement their contributions.

The complete outline designed to support WP6 focus groups is detailed in Appendix A, page 92. This outline was not designed to be presented to participants, but was a detailed remainder of the themes and questions that the moderator was to address.

Focus groups were planned for the first semester of 2020. One could be organised at the Lyon test side, just days before Covid-related lockdowns stopped everything. Its main results are presented below.

3.2.2 Lyon focus group results

This focus group was carried out by CEESAR with the collaboration of Keolis on March 6th 2020, at the AVENUE site of "Groupama Stadium" in the city of Lyon. Only 2 safety stewards participated in the discussion, in addition to AVENUE's Keolis contributor Quentin Zuttre (no hierarchy link exists between Quentin and the operators).

Those were both conventional bus drivers, who share their time between conventional bus lines and automated minibuses. One of them also operated on the "Confluence" test-site, a test-site predating AVENUE, but using the same type of automated minibus.

3.2.2.1 Perceived importance of safety among other issues

When questioned about their job as an "automated minibus attendant", they described it as "welcoming passengers and ensuring the safety of the vehicle, which is designed to normally drive on its own".

When first starting this job, they felt apprehension at the idea of being driven by a robot, but were reassured by the limited speed of operation. They were also surprised by the joystick used as a mean to manually drive the bus.

For them, the most important part of their job is **welcoming and accommodating passengers**, give **feedback on the vehicle's behaviour**, and finally to **ensure safety**.

They appreciate being part of an experiment and being able to discuss it with passengers. They also appreciate the quietness of the automated minibus line in comparison to the very busy bus lines they usually drive on.

On the negative side, they resent being considered as "traitors" by their colleagues, who think that autonomous vehicles will replace them and that they will lose their jobs, and they find their job sometimes quite boring, on account of the quietness of the location which was chosen for the experiment.

The difficulties they encounter most are related to **technical issues with the minibus**, some of them preventing them to provide proper service to passengers. This results in stressing situations where they have to ask passengers to exit the vehicle, apply some procedure to attempt solving the problem, make passengers come back into the vehicle, only to experience the problem again minutes later.

Overall, they express **both satisfaction and frustration** at some aspects of their jobs, but **safety does not appear to be a major concern**.

3.2.2.1 Safety concerns

Questioned more specifically about concerns they might have regarding safety, they describe situations where other road users cross in front of the minibus "as if it was a game", overtake the minibus in an aggressive way, or enter the roundabout while the minibus is crossing it, although they're not allowed to do so. In such situations, they **anticipate that a harsh braking will happen and warn the passengers accordingly**. They sometime think that they would have handled such situations in a smoother way, but rather than attributing harsh braking to poor anticipation from the minibus, they trust the vehicle's sensors and wonder if they sometimes underestimate themselves the risks in conventional driving.

They have been afraid in some instances such as other vehicles cutting-in aggressively, but consider that similar situations also happen with conventional buses. They prefer letting the minibus handle situations by itself, warning passengers of harsh braking before it happens, rather than taking over manual control with the joystick, which they consider hard to use to control the vehicle and not advisable. They however pay a lot of attention to passengers' safety by **making sure that they're properly sat and restrained at all time**.

3.2.2.1 Higher speed achievability

For them, a higher speed would not really be achievable with the current state of the technology. The vehicle would need to better anticipate situations such as being overtaken, to avoid harsh braking when the overtaking vehicle is moving further away. They don't see the vehicle going at 50 km/h anytime soon.

They don't see much advantage in running at a higher speed in the area they operate in either, and they don't think it could reduce other road users' aggressive behaviour anyway.

3.2.2.1 Remote monitoring achievability

Safety stewards feel that many situations today make their presence in the minibus essential: they are needed to **manually overtake obstacles on the road**, to **restart the vehicle after unexplained stops** or differential GNSS issues, and they need to **control the amount of passengers inside the minibus**.

Pending technical issues resolution, they feel that without an operator on board, **passengers would not properly seat in the vehicle**, which is a major safety concern. They also feel remote monitoring would not dispense the company with intervention teams being close enough to intervene on site when necessary.

3.2.2.1 Circuit specific difficulties

After the focus group, a small workshop was organised around a large format print of the circuit, where operators could easily point out specific places in which certain situations occur, that are or could become unsafe as well as 'hot spots' for recurrent safety-related situations. This allowed discussing issues where the ***environment***, both static and dynamic, causes issues, and focus less on *technical* issues, which frustrates the operators the most.

The main issues identified regarding the environment vs. the minibus' behaviour are as follows:

- **Trash Plastic bags** on the adjacent sidewalks are considered as obstacles on the path when strong winds are present (triggers harsh braking);
- **Incorrectly parked vehicles** (i.e. vehicles in parking spots but not completely inside the lines), are an issue in straight line portions of the itinerary (require manual override to overtake them);
- **Other vehicles not respecting the red traffic light** on the left turn as well as on the roundabout;
- **Pedestrians crossing** even when they have the red light;
- **Pedestrians on the sidewalk** are sometimes considered as obstacles (triggers harsh braking);
- **Other vehicles overtaking then cutting in** (triggers harsh braking).

3.2.3 Conclusion on focus groups

As has been said, only the first focus group, in Lyon, could be organised just before Covid 19 triggered lock downs all over Europe. Those both disrupted public transport operators' operations, and prevented travel. Feelings also were mixed after the first focus group about their relevance *at this stage* to identify Safety Of The Intended Functionality issues: the vehicle was not very mature then, and technical issues were safety stewards' most pressing and expressed concern.

3.3 Expertise

As direct feedback in the form of incident reports and focus groups proved less practical and/or efficient than hoped for, both for Covid-related reasons (halt on operations, unavailability of minibus operators) and technical reasons (reliability issues related feedback overshadowing everything else), the really successful way to obtain a list of relevant functional scenarios at that stage ended up being **expertise**: expertise from accident researchers (and related literature) and expertise from public transport operators' engineers, who initially defined and deployed the test-sites participating in AVENUE.

A simple template was created to describe functional scenarios. It contained the following fields:

- **Scenario name / Description**: a simple sentence describing the interaction;
- **Pictogram**: a "top view" representation of manoeuvres and relevant infrastructure elements;
- **Category(ies)**: tags describing the type of "aptitude" of the minibus challenged by the scenarios;
- **Other road user(s)**: list of the road users category to which the scenario could apply;
- **Infrastructure**: relevant characteristics of the infrastructure for the scenario;
- **Trajectory other road user(s)**: list of manoeuvres that can be expected from other road users;
- **Trajectory AV:** manoeuvre of the automated minibus.

WP6 partners initially relied on deliverables from WP2 and WP7 to gain knowledge on the operations that the minibuses were to perform, and the environments in which they would evolve, to draft a first list of relevant scenarios. This list was then augmented by pre-existing knowledge from driver behaviour studies, including Naturalistic Driving Studies (NDS) such as the UDRIVE project (UDRIVE Project, 2017) where Safety Critical or Safety Relevant Events (SCE or SRE) were extracted in urban environment driving. Analogously, accident databases such as the French VOIESUR database and the IGLAD project (IGLAD Project, 2018) were also used, as well as the "Waymo Safety Report" (WAYMO, 2018). This resulted in **a scenario catalogue**, built in as systematic a way as possible.

This scenario catalogue was communicated to and then further discussed in multiple interviews with public transport operators' staff to consolidate the list and avoid overlooking any relevant scenario.

A **centralised database**, accessible in a custom-designed online tool, was built to create and maintain the scenario catalogue.

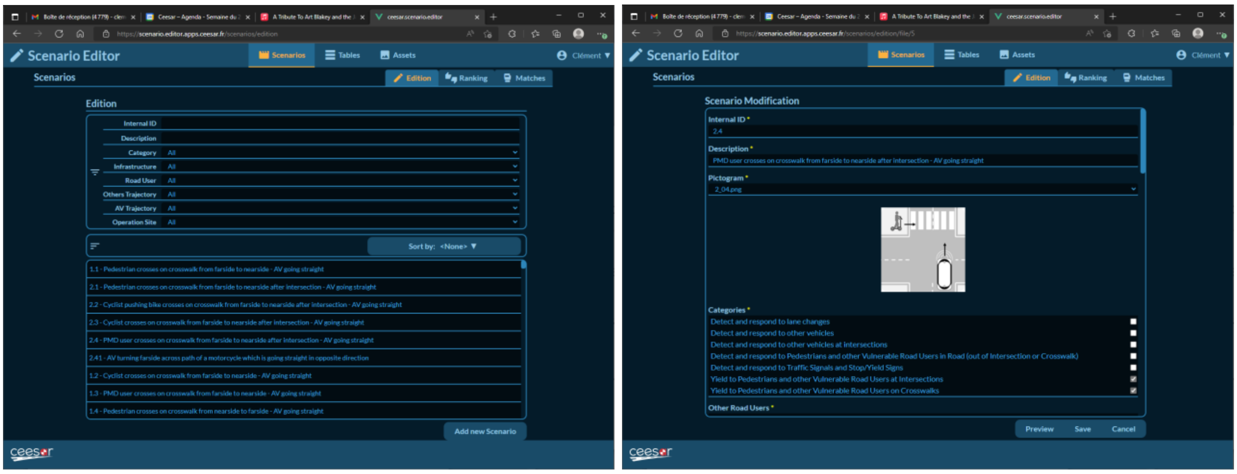


Figure 9. Administration interface for the centralised database of scenarios

In the end, the consolidated scenario catalogue consists of **189 independent scenarios**. Those are listed in Annex B, starting at page 97.

3.4 Scenarios ranking

The aforementioned work produced a vast functional scenario catalogue, with 189 scenarios. Systematic data collection (see chapter 4 page 34) would allow:

- (possibly) extending the list by analysing every harsh braking and disengagement and matching the circumstances with the list;
- Ranking them by frequency of apparition and criticality (by e.g. computing minimum Time To Collision for each instance);
- Characterising interactions in each instance (even non critical ones), reconstructing multi-parameters distributions for each scenario, which could later give a weight to each simulation.

However, as we'll see, data collection and analysis on a sufficient scale was not feasible in AVENUE. Asking public transport operators to directly rank 189 scenarios by criticality was not practical either. An innovative approach was therefore devised, to allow public transport operators to rank the scenarios, from their experience, in a practical and maybe even fun way.

3.4.1 Methodology

This approach relied on a Bayesian rating system not dissimilar to that of the Elo system used to rate chess players: by accumulating and combining results from each chess match performed by chess players over their career, Elo provides a rating allowing ranking each player, and matching players by skill when organising matches.

The TrueSkill algorithm (Herbrich, 2007) is a more modern and generalised rating system and was used in AVENUE to: 1/ "organise matches" between (similarly ranked) pairs of scenarios; 2/ use the outcome of the matches to iterate toward a consolidated ranking of scenarios.

A new web application was implemented, relying on the same infrastructure and database as the scenario management application introduced previously. It presented users with a continuous succession of pairs of scenarios to compare (Figure 10 below). Scenarios were presented in the form of large clickable "cards" where the pictogram and scenario description appeared in a prominent way, while a small "Draw!" button allowed avoiding having to pick a "winner" between two scenarios that would really be considered equivalent. Declaring a draw, although supported by the algorithm, doesn't help with the ranking. Cards appeared and disappeared with fun animations to help with users' engagement.

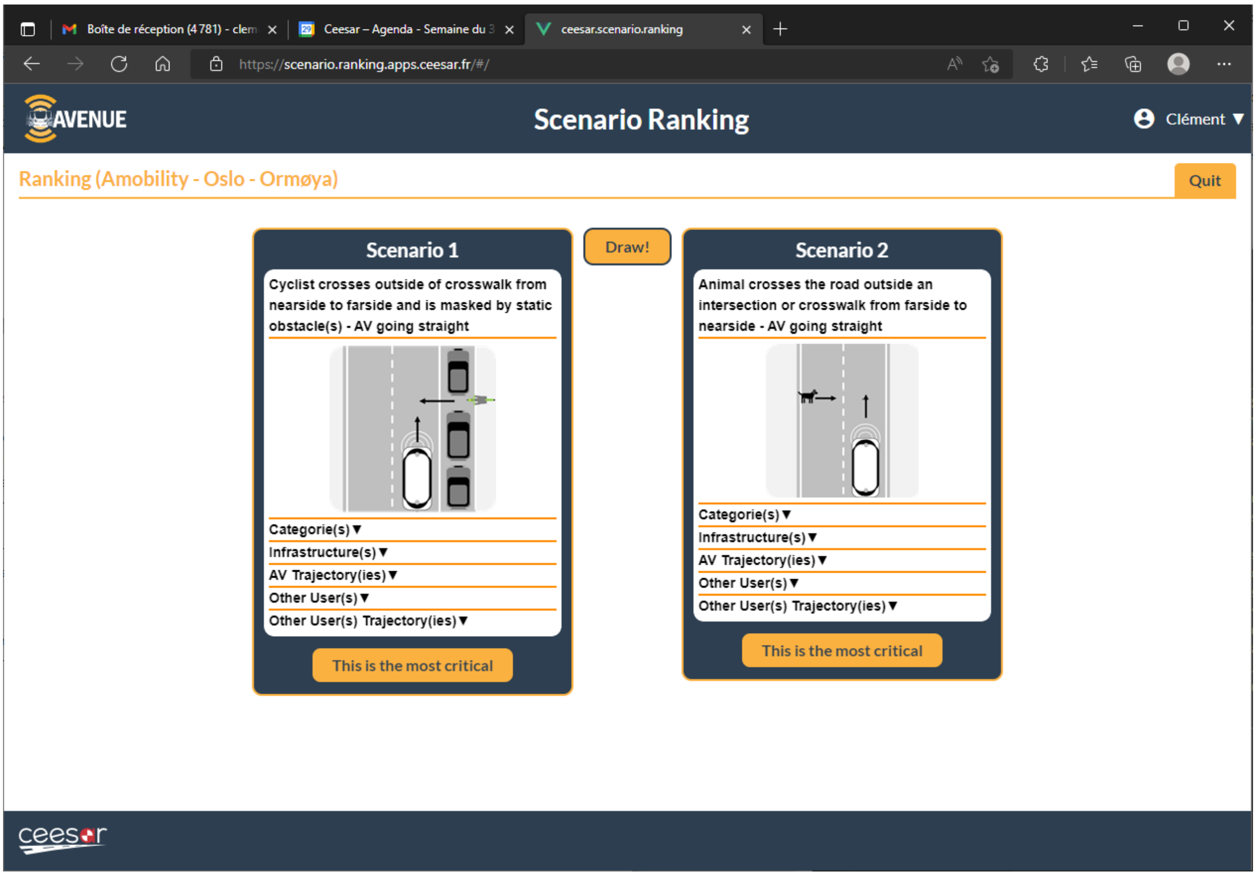


Figure 10. Scenario ranking: match interface

The instructions were designed to minimise users declaring a draw, and encourage them to rank them both in terms of *criticality* and *likeliness to happen*. They read as follows:

"With your contribution, this tool will help ranking scenarios according to theirs criticality. For each pair of situation, ***please choose the one which seems, to you, most likely to result one day in an accident****. Please take the necessary time for each comparison to choose, relying on your own experience, the most critical scenario. If you really think, after proper consideration, that both situations are equally critical, you can express that with the Draw! Button."*

Multiple users from each test site could contribute, but independent ranking per test site were done, to allow for specificities to appear. Users could stop and resume ranking anytime they wanted, and were encouraged to contribute in multiple short sessions, whenever they would take a break from their usual occupation.

The TrueSkill algorithm is designed in such a way that although initially scenarios are paired for comparison in a random way, pairs selected for subsequent matches correspond to scenarios of similar ranking. The ranking slowly stabilises and converges as matches are made.

3.4.2 Results

Amounts of contributions varied significantly by test site (Figure 11 below). At less than a hundred comparisons for close to two hundreds scenarios to rank, results from TPG can't be used and are therefore not presented. Ranking from Amobility should also be considered with caution.

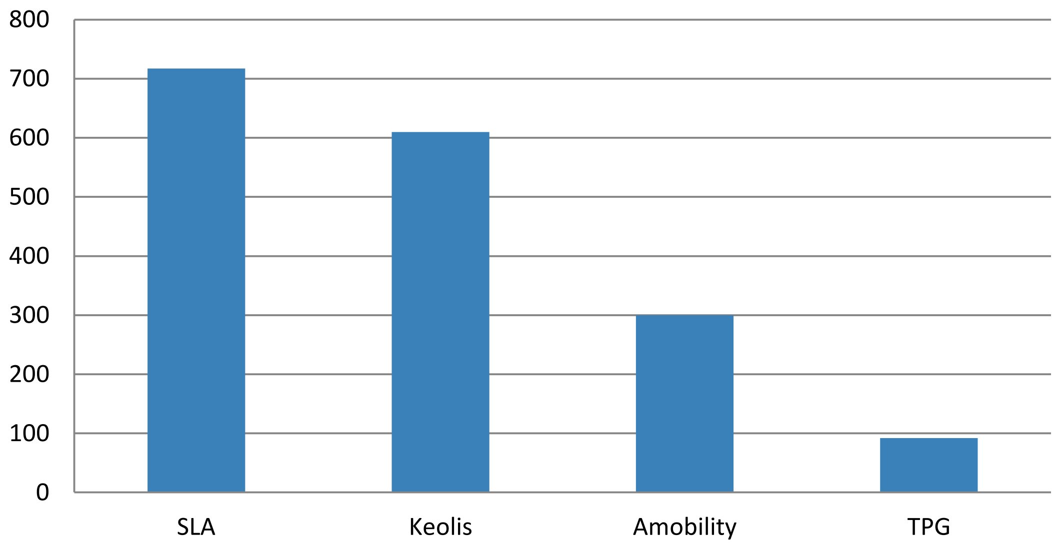


Figure 11. Quantity of matches performed per test site

Top 10 scenarios from Sales Lentz, Keolis and Amobility are represented in Table 2, Table 3 and Table 4 below.

Table 2. Sales Lentz top 10 scenarios

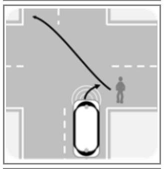
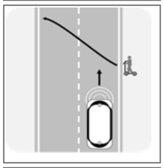
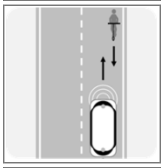
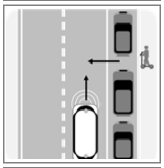
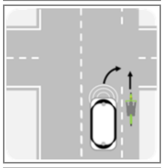
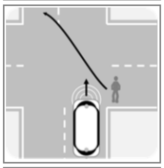
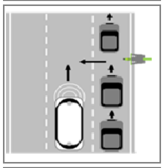
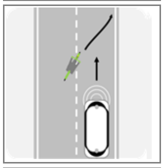
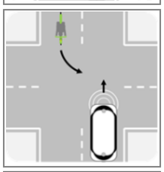
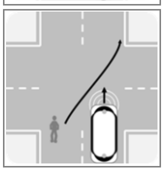
Rank	Pictogram	Scenario
1		Pedestrian crosses diagonally from nearside to farside, back facing AV - AV turning nearside
2		PMD user crosses diagonally the road outside an intersection or crosswalk from nearside to farside, back facing AV - AV going straight
3		PMD user is in the same lane as AV walking towards AV - AV going straight
4		PMD user crosses outside of crosswalk from nearside to farside and is masked by static obstacle(s) - AV going straight
5		Cyclist going straight on bicycle lane and AV turning nearside across path at intersection
6		Pedestrian crosses diagonally from nearside to farside, back facing AV - AV going straight
7		Cyclist crosses outside of crosswalk from nearside to farside and is masked by moving obstacle(s) - AV going straight
8		Cyclist crosses in front of AV
9		AV going straight while a cyclist turning across path from farside to nearside
10		Pedestrian crosses diagonally from farside to nearside, back facing AV - AV going straight

Table 3. Keolis top 10 scenarios

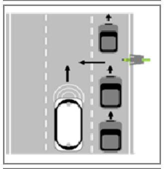
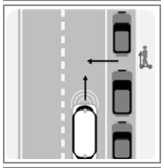
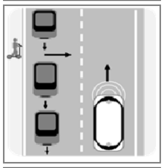
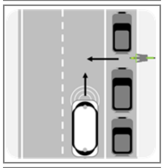
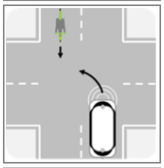
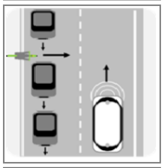
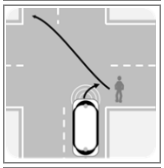
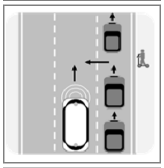
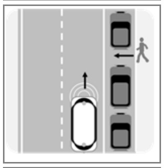
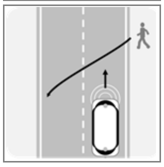
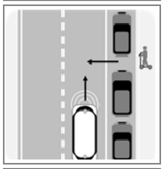
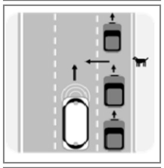
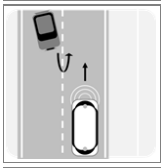
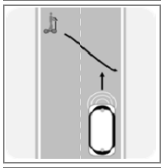
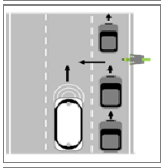
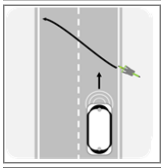
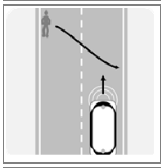
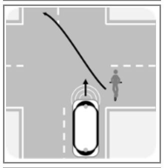
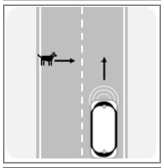
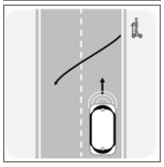
Rank	Pictogram	Scenario
1		Cyclist crosses outside of crosswalk from nearside to farside and is masked by moving obstacle(s) - AV going straight
2		PMD user crosses outside of crosswalk from nearside to farside and is masked by static obstacle(s) - AV going straight
3		PMD user crosses outside of crosswalk from farside to nearside and is masked by moving obstacle(s) - AV going straight
4		Cyclist crosses outside of crosswalk from nearside to farside and is masked by static obstacle(s) - AV going straight
5		AV turning farside across path of a cyclist who is going straight in opposite direction
6		Cyclist crosses outside of crosswalk from farside to nearside and is masked by moving obstacle(s) - AV going straight
7		Pedestrian crosses diagonally from nearside to farside, back facing AV - AV turning nearside
8		PMD user crosses outside of crosswalk from nearside to farside and is masked by moving obstacle(s) - AV going straight
9		Pedestrian crosses outside of crosswalk from nearside to farside and is masked by static obstacle(s) - AV going straight
10		Pedestrian crosses diagonally the road outside an intersection or crosswalk from nearside to farside, front facing AV - AV going straight

Table 4. Amobility top 10 scenarios

Rank	Pictogram	Scenario
1		PMD user crosses outside of crosswalk from nearside to farside and is masked by static obstacle(s) - AV going straight
2		Animal crosses outside of crosswalk from nearside to farside and is masked by moving obstacle(s) - AV going straight
3		U turn from the opposite vehicle
4		PMD user crosses diagonally the road outside an intersection or crosswalk from farside to nearside, front facing AV - AV going straight
5		Cyclist crosses outside of crosswalk from nearside to farside and is masked by moving obstacle(s) - AV going straight
6		Cyclist crosses diagonally the road outside an intersection or crosswalk from nearside to farside, back facing AV - AV going straight
7		Pedestrian crosses diagonally the road outside an intersection or crosswalk from farside to nearside, front facing AV - AV going straight
8		PMD user crosses diagonally from nearside to farside, back facing AV - AV going straight
9		Animal crosses the road outside an intersection or crosswalk from farside to nearside - AV going straight
10		PMD user crosses diagonally the road outside an intersection or crosswalk from nearside to farside, front facing AV - AV going straight

It appears, unsurprisingly, that **vulnerable road users** (pedestrians, cyclists, personal mobility devices users) are the primary concern of public transport operators. In an important amount of cases (4 for Sales Lentz, 7 for Keolis, 4 for Amobility), **visibility masks** created either by the infrastructure or other vehicles also are a concern. It is worth noting as well that in the vast majority of cases, the minibus would not be considered responsible for the accident. It is however expected, in most European countries, that 'stray' vulnerable road users in urban environments may pop up more or less anywhere, and heavier vehicles also are expected to anticipate such situations and adapt.

4 Vehicle data analysis

Although subjective data collection provides insights in a cost-effective way, it is subject to bias and habituation: continuous past improvements and resolution of technical issues, or the simple fact that the safety driver can avoid any serious issue at any time, intervening without really thinking about it, may lead interviewed parties to think that “things are good enough now”, when they’re really not.

By contrast, continuous acquisition of vehicle data is the gold standard to establish *substantiated* and *quantitative* learnings from a pilot deployment. It allows first, by examining in detail the reasons behind each harsh braking or disengagement, to identify the situations which are currently not handled in a satisfactory way. It also allows collecting and characterising behavioural patterns of other road users around the vehicle, to constitute logical scenarios which can be used in simulation.

For technical and organisational reasons, data collection was performed in AVENUE in a limited scale, but the data pipeline which has been developed and is presented here, would allow reaching those goals at a much higher scale, provided that data is made available.

4.1 Data collection

As previously exposed, the desired dataset would consist of: the dynamic behaviour of the vehicle, its location, the state of its automation and its actuators, multiple video feeds, and the identification and dynamic behaviour of other actors surrounding it.

Budget didn’t allow for the development and deployment of a dedicated data logging equipment, which would have had to rely on the vehicle’s own data streams anyway. The vehicle itself logs most if not all that is needed, albeit for a short period, after which the data is automatically deleted. It was therefore decided to rely on this existing data logging feature.

The logging capabilities, and restrictions in data sharing, allowed *partial* fulfilment of the aforementioned data requirements:

- Dynamic behaviour of the vehicle was fully measured;
- Global state of the decision layer (auto / manual) is known, but the reasons for the transitions from auto to manual, or the reasons for braking are not known;
- Activation of actuators were not provided
- Location of the vehicle was provided, not as latitude, longitude, bearing in a global reference, but in a local reference system of Cartesian coordinates in meters, which actually makes them more directly usable in the context of a small, known circuit.
- Video feeds were not provided for personal data protection reasons (blurring could not be done, so videos are simply not collected).
- Post-fusion objects detected by the vehicle were available. They however comprised both static objects (infrastructure) and moving objects (other road users) without any form of distinction or categorisation (e.g. pedestrians, bicycles, cars etc.) for moving objects.

The biggest obstacle to at-scale data collection, however, was the lack of any form of automated process for data retrieval: retrieving data required the vehicle to be immobilised for data extraction, which required simultaneous manual intervention both at the operation site and at the central monitoring site. Data could then slowly be copied to an external media, which had to be sent to the vehicle manufacturer for data filtering. An excerpt limited to **10 hours of operations at the Copenhagen site** was agreed upon. It was collected and sent to CEESAR for exploitation.

4.2 Pre-processing, import into SALSA

Exactly 10 hours of data were provided, in the form of 42 folders, each containing multiple files. Each folder corresponded to a “trip” lasting an average of 860s. Most of them corresponded to one loop around the Copenhagen circuit, some also comprised the trip to or from the parking space, and a few were very short in duration and didn’t correspond to actual vehicle operation.

Each folder contained 12 files: each stream of data (vehicle dynamics and location; auto/manual mode; objects detection) had several files (description of content, index, and actual data stream), and the folder also contained files which provided information to date and synchronise the different streams.

Software to **parse** and **merge** the content of those files was developed. The first two streams (vehicle dynamics and location; auto/manual mode) were relatively straightforward to parse. Each frame of data in the corresponding binary file having the same size and content, it was therefore just a matter of properly slicing arrays of bytes to map them to the correct information, cast them to the correct datatype and then assign them the correct timestamp. Post-fusion objects were a little bit more challenging to deal with: each frame could contain any quantity of objects, and each object’s contour could be constituted of any quantity of vertices, which meant that each frame could consist of any number of non-aligned bytes.

The pre-processor developed for the occasion also included computation, on the fly, of a limited quantity of metadata, and creation of bounding boxes for detected objects, to facilitate further use.

Data was written as .mat (MATLAB) files, each containing the decoded and merged content of one initial folder. Great care was taken in the quality of implementation, resulting in reliable and fast decoding (a few seconds for each initial folder), which would allow large scale data processing.

The dataset was then imported in SALSA. SALSA (Smart Application for Large Scale Analysis), a CEESAR development, is both an application and a framework, dedicated to time history data processing and analysis. It seamlessly manages large datasets and allows different kind of users to query and visualise data, annotate it in various ways, but also to develop and test algorithms which will create new data, deriving from the originally imported data. SALSA has been developed with collaboration in mind, allowing multiple users to use the same dataset concurrently. SALSA manages every operation, such as storage, processing or annotation, ensuring traceability for every single byte, and consistency of the whole dataset. SALSA has initially been developed during the H2020 UDRIVE project and has been continuously improved since. It now is used by VEDECOM Institute, Université Gustave Eiffel, Renault Group and Stellantis car manufacturers, to manage millions of kilometres of driving data, notably for driving scenarios extraction and characterisation, and naturalistic driving data reduction.

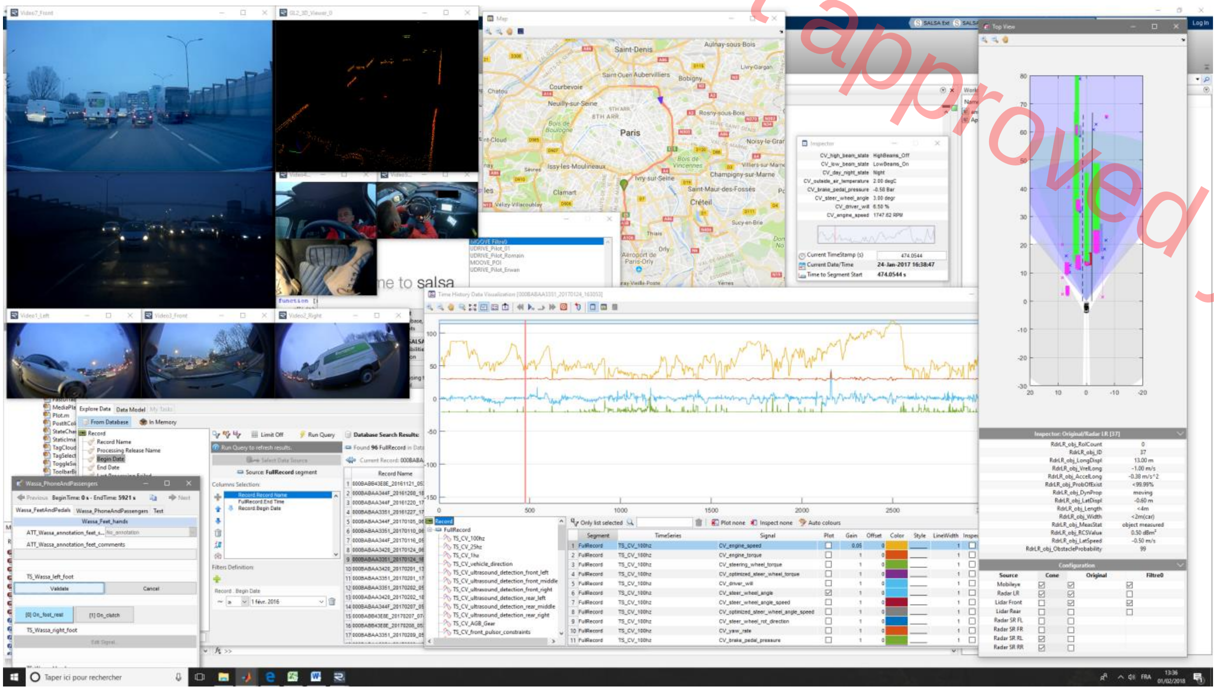


Figure 12. SALSA graphical user interface

Using SALSA to exploit a 10 hours-long dataset might seem a bit overkill, but we could benefit from its interactive development capabilities to quickly test and validate our algorithms, and again, our objective was to develop a data pipeline which would have the capability to treat data at scale.

To facilitate algorithm development while allowing manual annotation in the absence of videos, a specific visualisation plugin was developed (Figure 14). It represents on a top view the map of the circuit, the location of the automated minibus and the detected objects, and allows selecting each individual object to get its instantaneous measures' values (including those which were defined and implemented by the user). It is synchronised with the main time-history visualisation window, and allows real time playback of data.

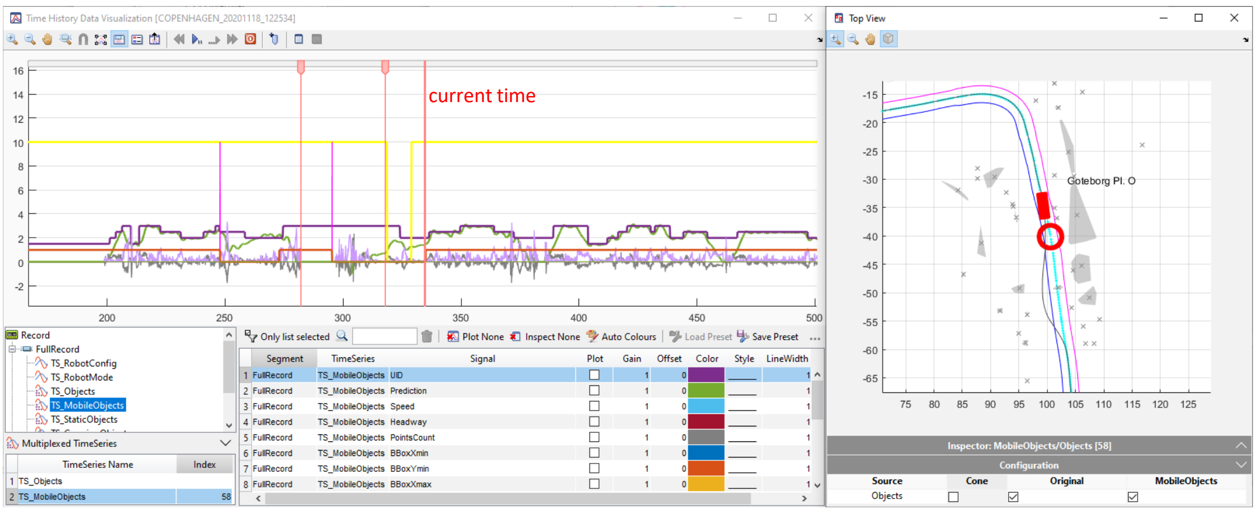


Figure 13. Time history visualization and top view plugin

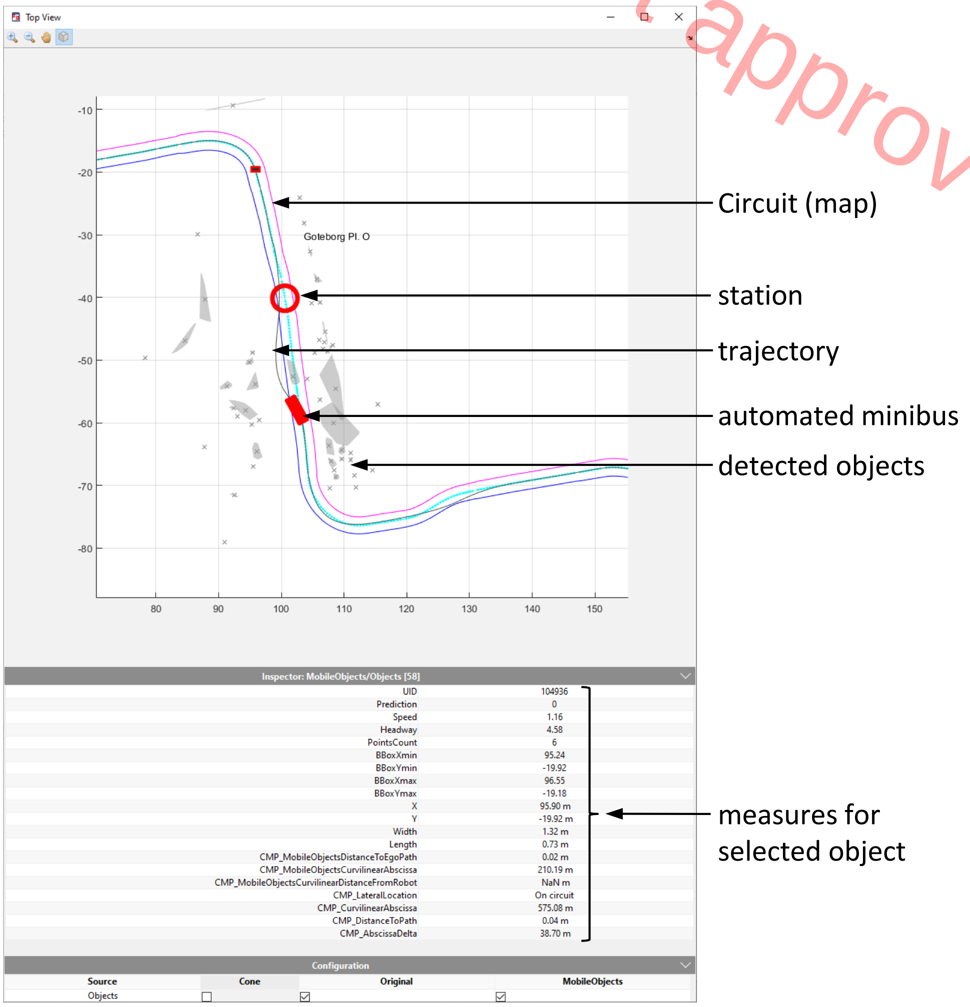


Figure 14. Visualization plugin

4.3 Processing

Once imported in SALSA, data was further processed to allow subsequent analysis.

4.3.1 Objects filtering

The first step of treatment consists of specific filtering for detected objects. As been already written, no distinction is made between static and mobile objects: a pedestrian or a car is represented in the same way as a piece of detected infrastructure, and nothing allows easily distinguishing them. In addition, dozens of objects are detected simultaneously, and depending on their relative position with the vehicle, their contour might present itself in a different way in each frame. Luckily, efficient tracking algorithms are implemented in the vehicle's embedded software, and one object at one specific instant can be linked to another one, existing before or later, through a unique identifier. However, the same object can be provided in any position in objects' list, that position changing from one frame to the next, and the same 'unique' identifier can also be reused several times, for different objects. It therefore really is difficult, at that initial stage, to work with individual objects trajectories. As a result, objects' data was processed in the following way:

1. A *really* unique identifier was assigned to each object: when the same identifier was reused several seconds after the object using it disappeared, a fresh identifier was given instead.
2. **Static** objects and mobile objects were separated: we considered that an object was static if its **speed** was **below 3 km/h for at least 80% of its lifetime**.
3. 'Relevant' **mobile** objects were identified: we consider that an object is mobile and **relevant** if:
    a. It **is not static**
    b. It **exists for at least 1s**
    c. It **enters the minibus lane** (which depends on the map-matching, see below)
4. Relevant mobile objects were consolidated: object properties (location, speed, contour…) for each individual object, during its lifetime, were consolidated, each in its own data container, which avoids having to jump around from frame to frame using the unique identifier and results in much simpler algorithms when using objects.

2434 individual 'relevant' mobile objects where detected in the 10 hours dataset.

4.3.2 Map Matching

A detailed map of the circuit was provided as an XML file. It used the same Cartesian reference system as the dynamic data. It consists of a list of *nodes*, some of which are the stations, connected by *edges* (portions of road). Each edge has attributes such as its width, can be applied some rules (e.g. maximum operation speed), and has a shape defined in the form of a list of *waypoints*. The minibus' programmed path and lane boundaries could hence be reconstructed by correctly parsing and interpreting the file. The map is represented in the visualisation plugin.

A **map matching algorithm** was specifically developed to deal with the specific way that the data is represented (Cartesian coordinates in meters). This allowed to obtain, for a specific trajectory and at each instant, its position relative to the minibus lane (inside, outside on the left, outside on the right, lateral distance to the lane centre), the corresponding curvilinear abscissa along the minibus path, and the corresponding rules (e.g. maximum speed).

This map-matching was applied not only to the automated minibus trajectory, but **also to each individual detected object**. This allowed filtering out non relevant objects which never entered the lane (see above), but also added information to both the minibus and objects' data in relation with the infrastructure, using the same reference, which was invaluable to implement scenario detection and characterisation.

Since the circuit corresponds to a simple closed loop, the algorithm itself is rather simple (projection of object's barycentre to the closest line connecting two waypoints), and would need to evolve in the case of a mesh-like map. However, given the amount of waypoints, of objects, and the relatively high frequency of the data, optimisations were necessary to allow fast operation:

- Repeated queries when the object was not moving were avoided
- Routines were optimised and implemented in C (the rest of the treatments are done in MATLAB)

4.3.3 Data enrichment

Following these initial treatments, additional signals could be derived:

- **Minibus in circuit** (*boolean*). This allows separating data corresponding to actual operation, from data corresponding to trips from or to the parking space.
- **Discomfort scale** (%). Using the formula identified during the injury risk study, the discomfort indicator was calculated from the minibus' longitudinal acceleration (the jerk was calculated by deriving the acceleration after applying a 200ms moving average filtering to smooth out vibrations).
- **Disengagement** (*boolean*). We considered that disengagement happened when the minibus was in the circuit, and switched from automatic to manual mode, after having been in automatic mode for at least a second. Reminder: we have no way to know whether the change is triggered by the safety driver or the minibus itself.
- **Harsh Braking** (*boolean*). We considered that there was a harsh braking when the discomfort scale was above 50% for more than 100ms.

4.3.4 Scenarios detection

The initial treatments also allowed the implementation of scenario detection algorithms. As a relevant example, the 'object crossing' scenario was implemented. Its detection relied on a relatively simple set of rules:

1. The object goes from 'left of the lane' to 'inside lane' to 'right of the lane' OR from 'right of the lane' to 'inside lane' to 'left of the lane' *in a continuous movement*.
2. While the object is *inside the lane*:
   a. Its absolute curvilinear abscissa doesn't vary by more than 5 meters (i.e. the trajectory is somewhat perpendicular to the lane)
   b. Its curvilinear abscissa relative to the minibus is positive (i.e. the object crosses *in front* of the minibus).
   c. The minibus also is inside the circuit.

Once these rules were implemented, characterisation of the scenario, by a simple set of parameters was also done. Those parameters are:

- The beginning of the crossing (i.e. when the object enters the lane)
- The end of the crossing (i.e. when the object exits the lane)
- The direction of the crossing (from *left to right* or from *right to left*, from the minibus' perspective)
- The minibus' speed at the beginning of the crossing
- The relative curvilinear abscissa at start (i.e. distance, *along the minibus' path* between the minibus and the object's project on the minibus' path)
  <u>*Note:*</u> *the time headway can be calculated by dividing the last parameter by the second to last.*
- The crossing speed (maximum speed reached by the object inside the lane)
- The object's size, defined as the maximum diagonal of the object's bounding box during the crossing.

<u>Note:</u> as the contour of the object changes depending on its position relative to the minibus' sensors, there's not guaranty that it is seen in its entirety at any specific time. We attempted to implement more complex algorithms to reconstruct the objects' contour by 'accumulating' all the frames during their lifetime. However this proved inconclusive as false detections sometime happening for a frame or two destroy the shape, rendering the effort useless.

An example of such a scenario automatic detection and characterisation is represented below. Each frame is separated by one second. The object (likely a pedestrian), crosses from left to right in front of the minibus at a speed of 1.8 m.s^{-1}. It enters the lane 8.5 m away from the vehicle, while the latter was advancing at 2.1 m.s^{-1}. The minibus stops.

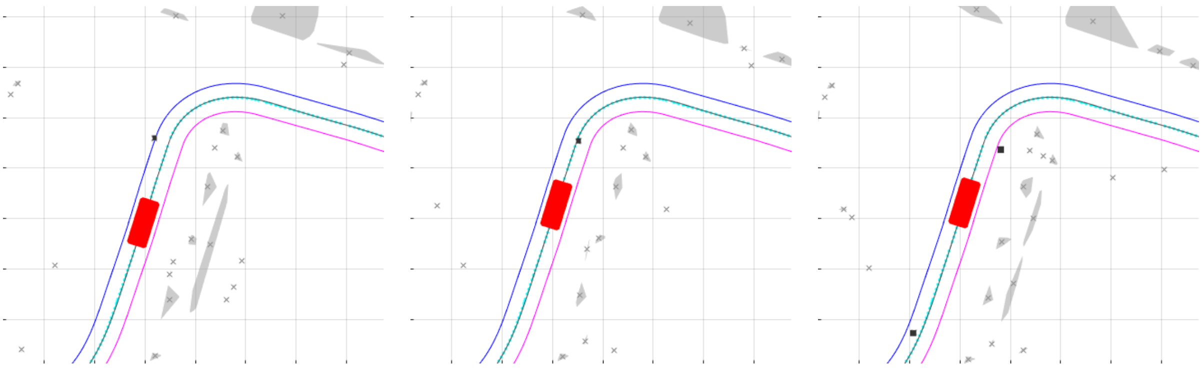


Figure 15. Example of an object crossing scenario.

4.4 Analysis

Although no general conclusion can be drawn from such a small dataset, analysis of disengagements, harsh braking, and crossing scenarios was performed. The data pipeline which has been set up allows the same analysis to be performed on a much larger scale, pending data availability.

4.4.1 General statistics

Out of the 10 hours which were collected (17 km), 3 hours 10 minutes (14 km) actually correspond to the minibus advancing on its circuit, 2 hours 42 minutes (12 km) being in auto mode.

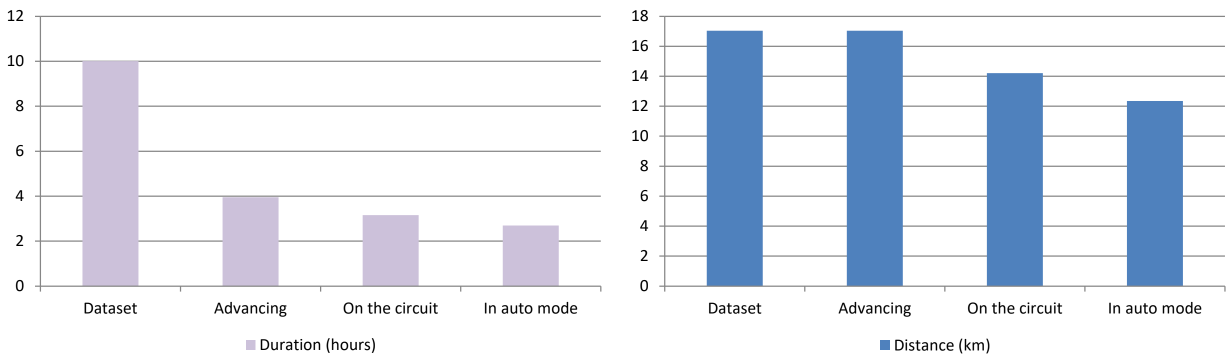


Figure 16. General statistics

4.4.2 Harsh braking

It is hoped that harsh braking events may allow identifying future problematic situations: an event where a harsh braking was necessary at low speed likely is to become critical at a higher speed.

Reminder: the data provided does not contain the entire internal state of the robot. ***We can't analyse the precise reasons for any action of the vehicle.*** *We are simply searching for interesting interaction situations and we consider that the vehicle harshly braking can signal such interesting situations.*

Only **8** harsh braking events could be identified in the dataset.

- For **4** of them, **no discernible reason to brake** could be identified from the data (e.g. no moving object on or about to be on the lane).
- **2** of them happen consecutively, separated by only 5 seconds: The vehicle had been switched to manual mode to overtake a static obstacle standing on the lane. After overtaking, the safety driver attempted to switch the vehicle back to auto mode while running it at 2 m.s^{-1}. In both instances, the vehicle did immediately brake for no apparent reason (no object in forward path). The driver finished the trip manually.
- The **2** remaining harsh braking events happen when the vehicle reaches static objects which are close to its lane.

Harsh braking events therefore are relatively rare, but at the current stage, don't seem to be a relevant indication that a complex situation is happening.

4.4.3 Disengagement

81 disengagements (vehicle switching or switched from auto to manual mode) were observed.

Most of them (50) are made to **overtake** objects (vehicles) standing in the way (Figure 17).

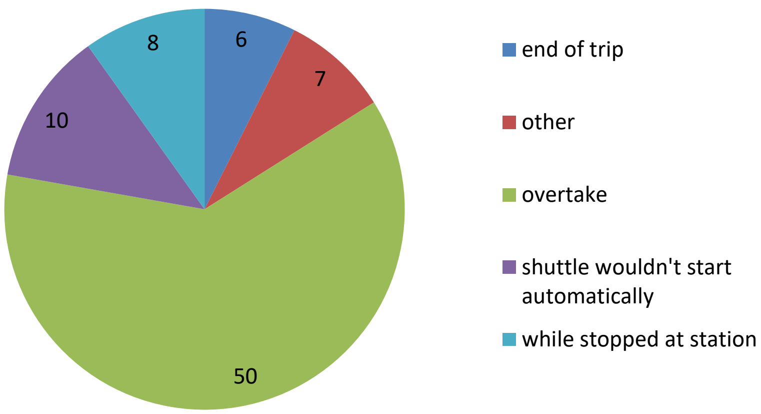


Figure 17. Disengagement causes

Most of those disengagements to overtake (36) are made **while the minibus is running** (i.e. speed above 0 m.s^{-1}, see Figure 18 below). Conversely, most of the others (26 out of 31) are made while the minibus is stopped.

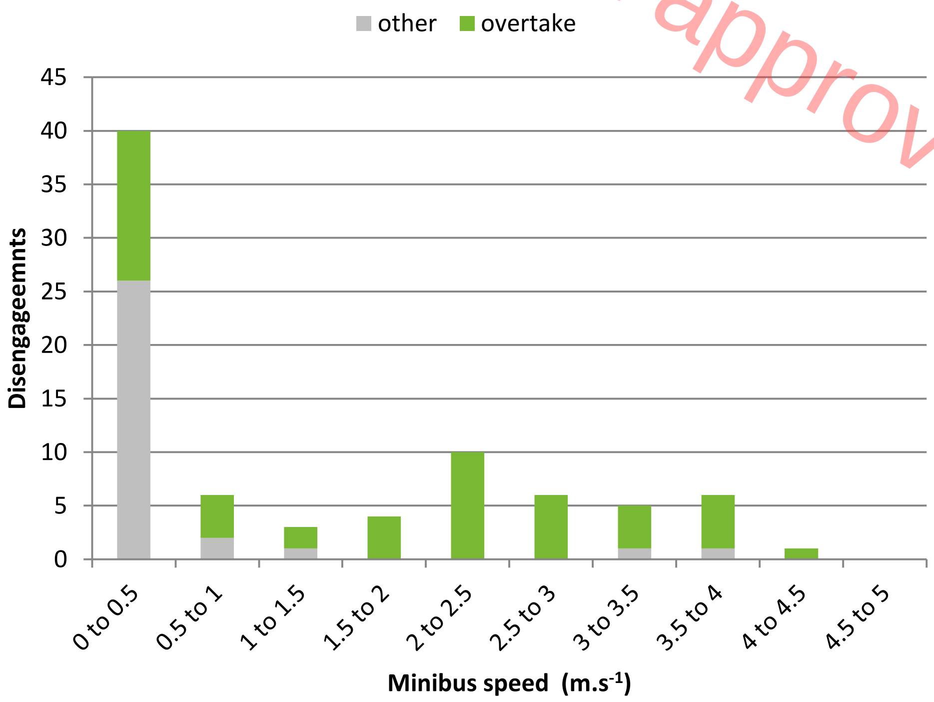


Figure 18. Minibus speed distribution at disengagements

The fact that the safety driver disengages the automation while still running when the need to overtake a static object arises, implies that quality of service was favoured over realism of the experimentation. In some instances, the minibus was manually driven for long stretches, to overtake several vehicles. This is acceptable, as a stopgap, as the ability for the minibus to overtake such static object was not yet implemented when the data was collected, but was on the short term roadmap of the vehicle's development. It however means that in this version, the automation was still used more as a level 2 driving assistance, requiring constant monitoring and regular takeover by the driver, rather than a proper level 4 system.

Other disengagements happen when the vehicle is stopped at the station (8 short disengagements), at the end of the trip (6), in instances when the minibus would not start automatically for unexplained reasons (10), in which case the safety driver would take over to resume and sometimes finish the trip, and for other reasons (7). Those other reasons included the following situations:

- Allowing passengers to ingress outside of the station, as an object is blocking the station.
- A pedestrian crossing in front of the minibus at swift speed (2 $m.s^{-1}$).
- A pedestrian is walking along the minibus' path and a vehicle is about to cross it. Auto mode is switched to off, and then the vehicle is stopped until the pedestrian and the other vehicle are out.
- Unclear reasons in 4 instances.

This means that at the stage of development the vehicle was in during data collection, out of 81 disengagements, only two of them corresponded to situations of interaction with other road users where the driver judged that manual intervention might be preferable to letting the minibus handling the situation by itself. At this stage, disengagements present a low 'level to noise' ratio. However, automatically filtering out disengagements while stopped and disengagements made to overtake static objects would result in a collection of situations worthy of further assessment, if data could be collected at a higher scale.

4.4.4 Object crossing scenario

As we've seen, harsh braking and disengagement analysis would require massive amount of data and clever filtering to identify the situations which will actually be problematic once the software gets more mature, and removing the safety driver or riding at higher speed might be considered as an option. This emphasise the importance of **simulations**, where new sensors and/or software can be tested against a virtual environment. This virtual environment and the actors who populate it, however, must be grounded in reality i.e. the actors' behaviour must be realistic, and the weight given to any set of simulation conditions when performing a global safety assessment must correspond to the actual probability to observe it in real life. This is the role of scenarios, described by multiple parameters whose distributions and dependencies must be modelled based on actual data. The sensors fitted to the automated minibus used in AVENUE, and its embedded fusion algorithms certainly are **good enough for such data collection**. We implemented the detection and characterisation of the 'object crossing' scenario as an example.

90 object crossing *concrete* scenarios were detected and characterised from the dataset. Those were equally distributed between crossing from left to right (46) and crossing from right to left (44).

As previously explained, we had no access to the objects' type's identification. However, we can infer from their size that most of the objects crossing in front of the minibus were pedestrians and bicycles.

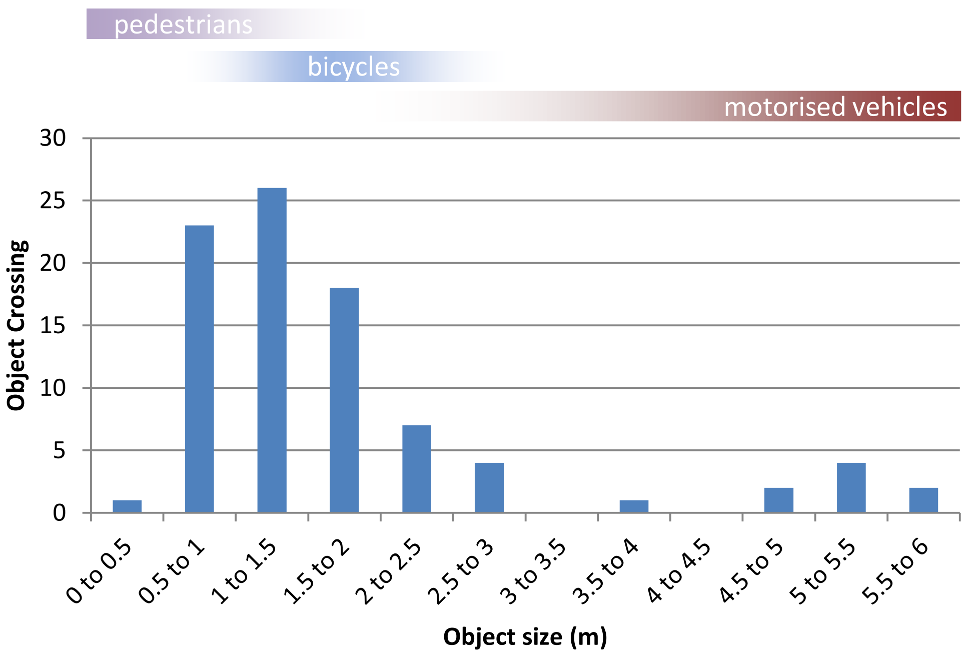


Figure 19. Crossing object size distribution

Nearly half of the crossings (40) happened while the vehicle was stopped. The others started while the vehicle was still running, up to 4 $m.s^{-1}$.

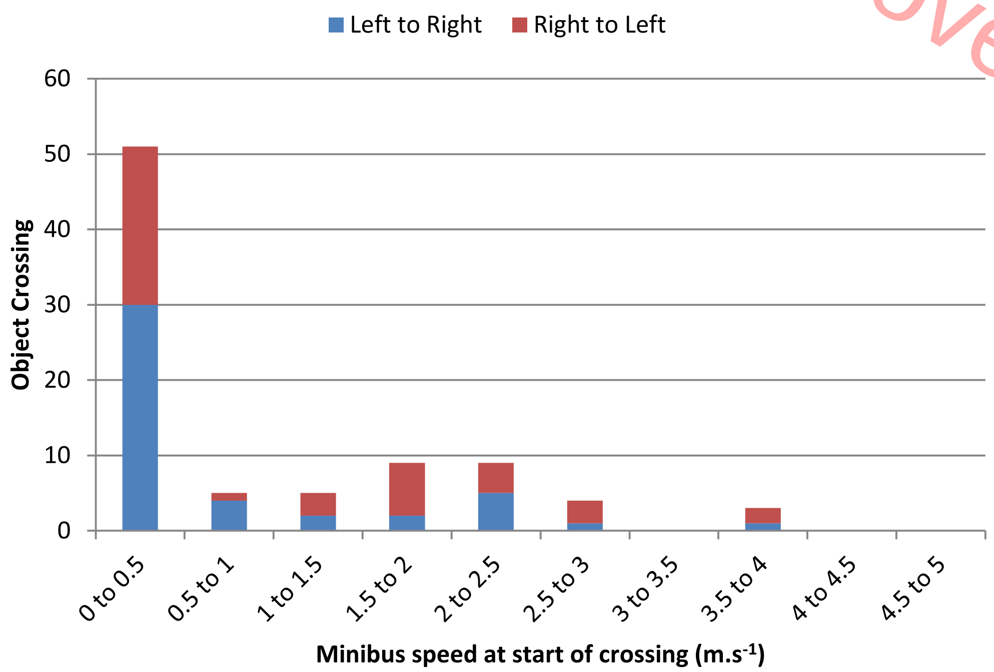


Figure 20. Distribution of minibus speed at start of crossing

Some crossings happened relatively close to the minibus, as seen below.

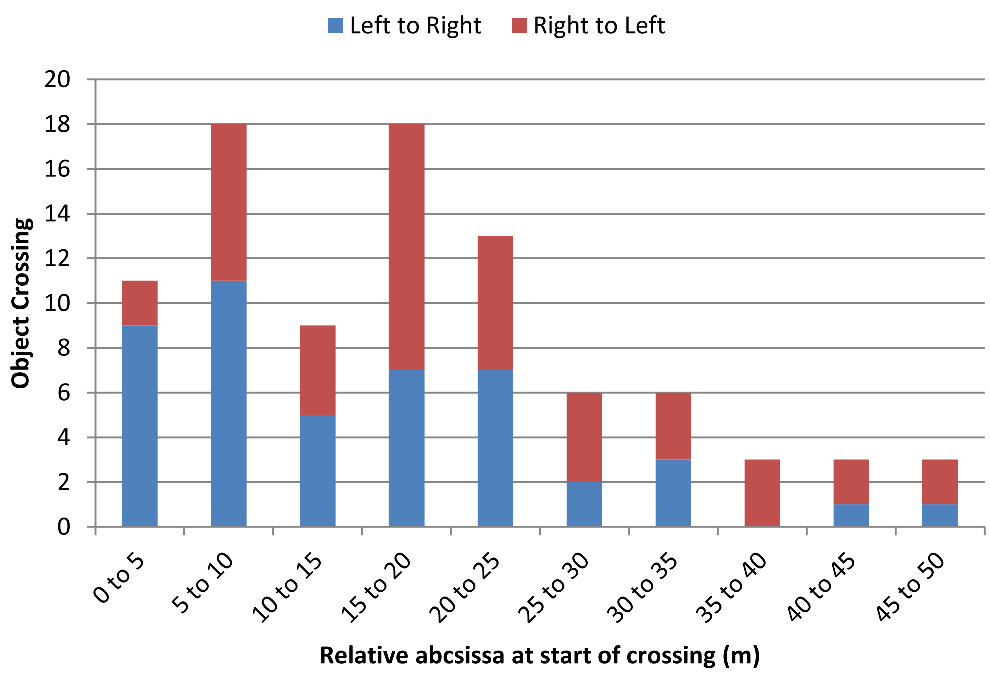


Figure 21. Distribution of relative abscissa (headway) at start of crossing

However, when taking into account the minibus’ speed, using the time headway, we observe that most crossings happen with a comfortable margin. Only 3 crossings are initiated with a time headway below 5 seconds. Those are made at a speed around 2 $m.s^{-1}$, resulting in the minibus’ lane to be crossed in less than 2 s.

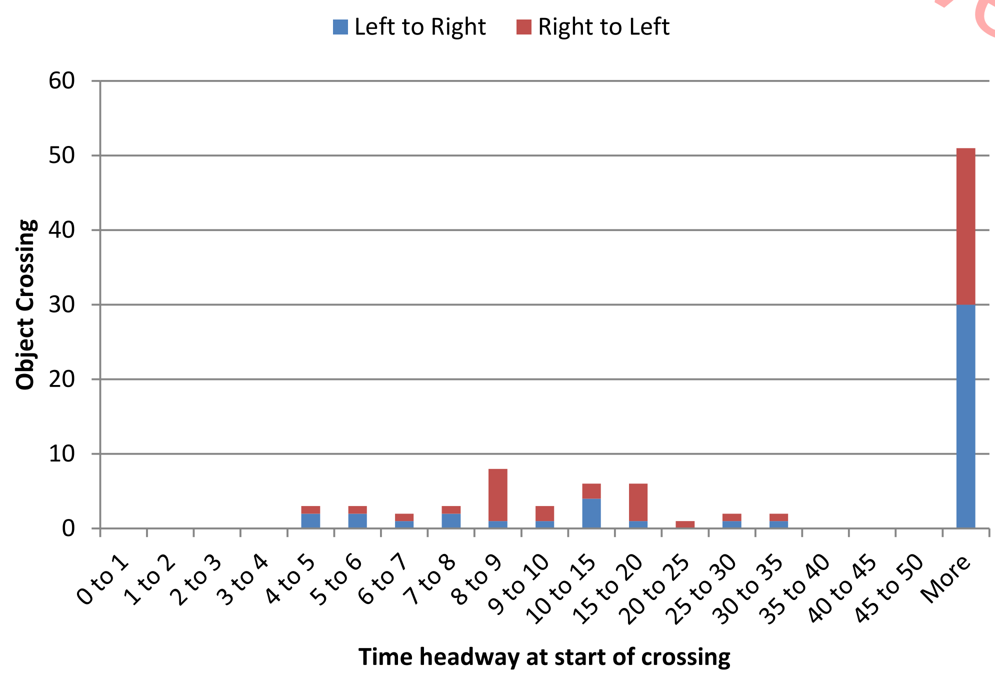


Figure 22. Distribution of time headway at start of crossing

Most objects cross the lane at speeds between 1 and 2 $m.s^{-1}$.

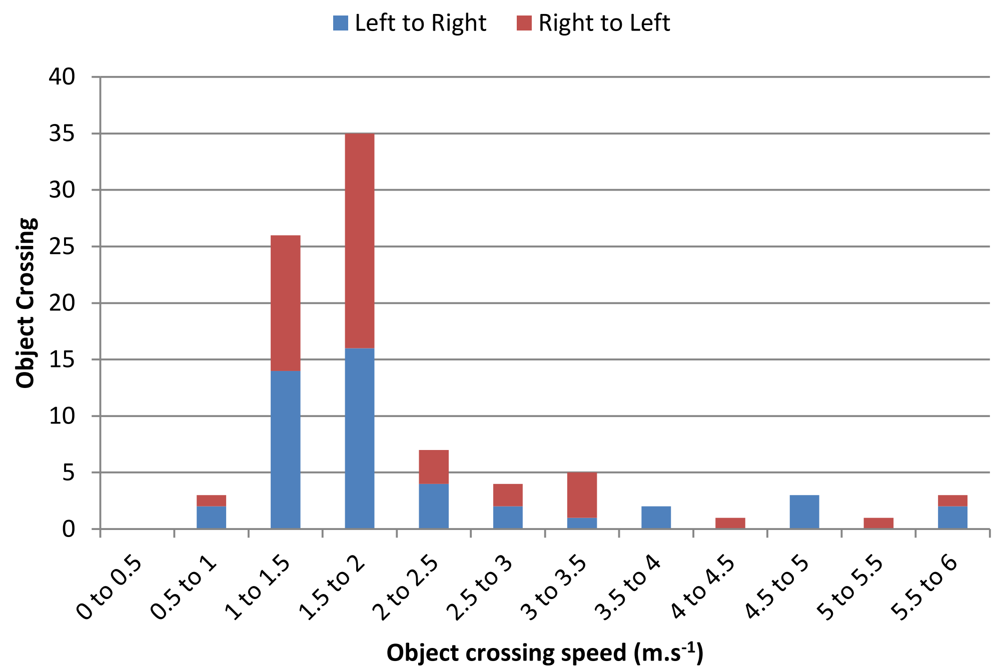


Figure 23. Distribution of crossing objects’ speed

*<u>Note:</u> these single-variable distributions are only illustrating the parameters which can be measured. Proper risk assessment requires taking into account **relationships** between parameters. This means that the observed scenarios must be summarised in the form of multivariate distributions, allowing giving the proper weight to each parameters tuple used in simulations.*

4.4.5 Other scenarios for simulation calibration

In addition to the object crossing scenario, whose instances have been automatically detected and characterised, additional scenarios have been manually extracted. These have been provided to AVL in task 6.1 to allow calibration of their vehicle model used in simulations.

Those scenarios consisted of:

- Automated stop because a static object is blocking the way (3)
- Automated stop to yield. Vehicle coming from the left (4)
- Automated stop to yield. Vehicle coming from the right (2)
- Cut-in. Minibus overtaken from the left (3)
- Minibus slows down to let pedestrian cross (9)
- Minibus slows down to let vehicle cross (1)
- Minibus slows down until pedestrian on path leaves it (2)

4.5 Conclusion on vehicle data analysis

A toolchain has been developed and tested on actual data from Copenhagen operations. Being based on SALSA and great care being taken in developing robust algorithms and efficient implementations, **this toolchain could be applied and used at a much larger scale** than what was possible given the limitations of the data collection process.

Data analysis showed that when operating prototype vehicles, harsh braking and disengagements are a somewhat disappointing way to obtain interesting or problematic interaction situations, which are buried under manifestations of technical limitations. Smart filtering of the detected instances could however greatly improve the efficiency of this kind of analysis, which will become more and more relevant as the vehicle itself improves.

Conversely, the perception of the vehicle was mature enough to allow automated detection and characterisation of instances of known scenarios, as we demonstrated with the example of the object crossing scenario. **Systematically** collecting data from pilot operations, which unfortunately wasn't possible here, should be encouraged, as it would allow building a statistical representation of the conditions met by the automated vehicle. Deriving from this, a virtual representation of challenging scenarios, used in simulation, would then allow ensuring the absence of regressions or inacceptable risk when changing the software to improve the quality of service (higher speed) or economic efficiency (removing the safety driver).

5 Injury Risk Study

Scenario simulations will provide kinematics' measures relating to the minibus and surrounding road users, depending on the circumstances. To convert those measures into actual risk estimation, one needs insights regarding risk of injury depending on kinematics.

As previously exposed in Chapter 2, section 2.4, page 15, AVENUE first concentrates on the following risks:

- Injury risk for passengers in case of harsh braking;
- Injury risk for vulnerable road users (starting with pedestrians, expanding to two-wheelers if resources allow) in case of collision.

This allows treating some of the riskiest situations, including some where multiple risks have to simultaneously be accounted for, such as realising an emergency braking to avoid or mitigate a collision with a pedestrian.

The study will span several configurations, both for passengers and pedestrians, prioritising configurations which seem the most risk-inducing (cf. Figure 24 below).

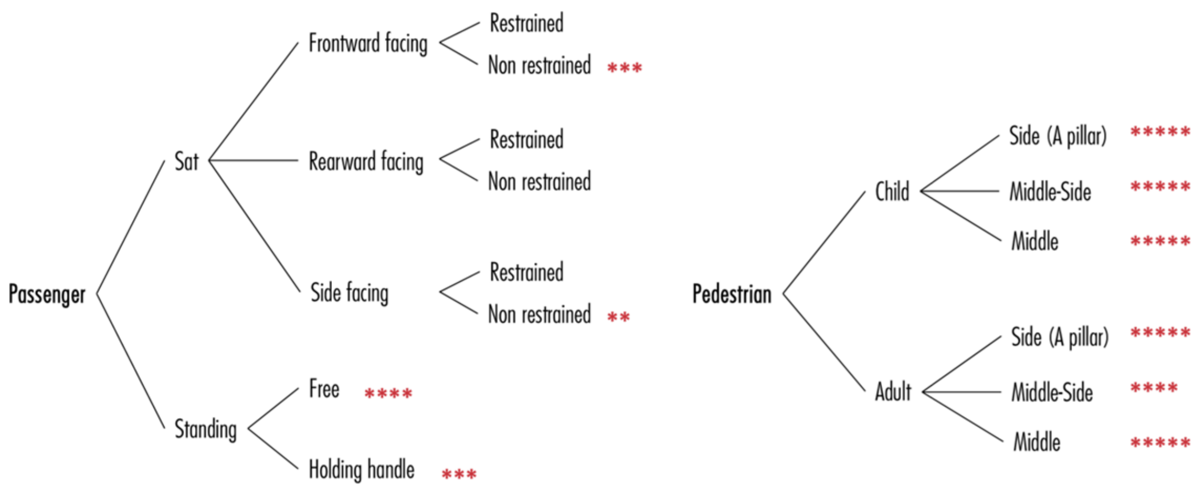


Figure 24. Configurations taken into account in injury risk study. Red stars represent most critical and therefore prioritised configurations

The current chapter presents the literature review which has been carried out, the simulation approach which has been chosen to build injury risk functions, and simulation results.

5.1 Literature Review - passenger balance and fall

An increase in the velocity and deceleration attained by an autonomous vehicle will allow travel time to be reduced and the system capability to be increased. However, higher longitudinal acceleration levels can also affect passenger safety if they cause passengers to lose their balance. During the experimental phase of the deployment of small and medium autonomous vehicles, incidents involving passengers injured during braking stop were reported (Raymond, 2019) (Shepardson, 2020). The purpose of this section is therefore to examine the effects on passengers of longitudinal accelerations found in regular operation, and the relationship to safety and injury.

Transportation security surveys (Pereira, Hecht, Segurado, Sohr, & Uettwiller, 2001) (Bjoernstig, Bylund, Albertsoon, Falkmer, Björnstig, & Petzäll, 2005) (Halpern, Siebzehner, Aladgem, Sorkine, & Bechar, 2005) report that standing passengers are the most exposed passengers in trams: even minor incidents can lead to significant balance losses, which can result in secondary impacts with other occupants or indoor equipment, resulting in injury. It can lead up to death, as in Montpellier (France) where a tramway triggered an emergency braking which caused the fall of a 73-year-old passenger who died on scene after his head violently hit the bottom of a vertical bar (tramwaydemontpellier.net, 2016). These studies also indicate that the head (25% – 33%), the arms (20–28%) and the legs are the most affected segments. Their social costs and high frequency have brought to the conclusion this may be the most critical situation to address (Pereira, Hecht, Segurado, Sohr, & Uettwiller, 2001).

5.1.1 Sense of balance - equilibrioception

Balance in humans is an unconscious proprioceptive reaction, coordinated by the brain stem, supported by the cerebellum, visual cortex and basal ganglia. Information is acquired from the somatosensory system in the feet, the vestibular system in the inner ear and visual stimuli from the eyes (Carpenter, 2003). The somatosensory system detects pressure modifications on the foot surface. If there is disequilibrium between one foot and the other, the muscles in the leg will contract so that the leg can oppose the increased pressure. The vestibular system provides the sense of balance and the information about body position that allows rapid compensatory movements in response to both self-induced and externally generated forces. The peripheral portion of the vestibular system is a part of the inner ear that acts as a miniaturized accelerometer and inertial guidance device, continually reporting information about the motions and position of the head and body to integrative centres located in the brainstem, cerebellum, and somatic sensory cortices. Finally, visual stimuli from the eyes provide an extra frame of reference to help determine position more accurately.

5.1.2 Balance recovery approaches

Three different strategies can be identified for retaining balance under the influence of an external acceleration (Vallée, 2015). Where the acceleration is small, contracting the leg muscles and bending the ankle is sufficient to react against the external acceleration and keep the body balanced; this is known as **ankle strategy** (Figure 25). If the acceleration magnitude is greater, the body must change position to prevent falling, also bending at the hip. This is known as **hip strategy** (Figure 25) and requires a longer time for the muscles to actuate. Finally, the applied acceleration may be large enough that one or more steps must be taken to avoid falling; this is the **stepping strategy** (Figure 25).

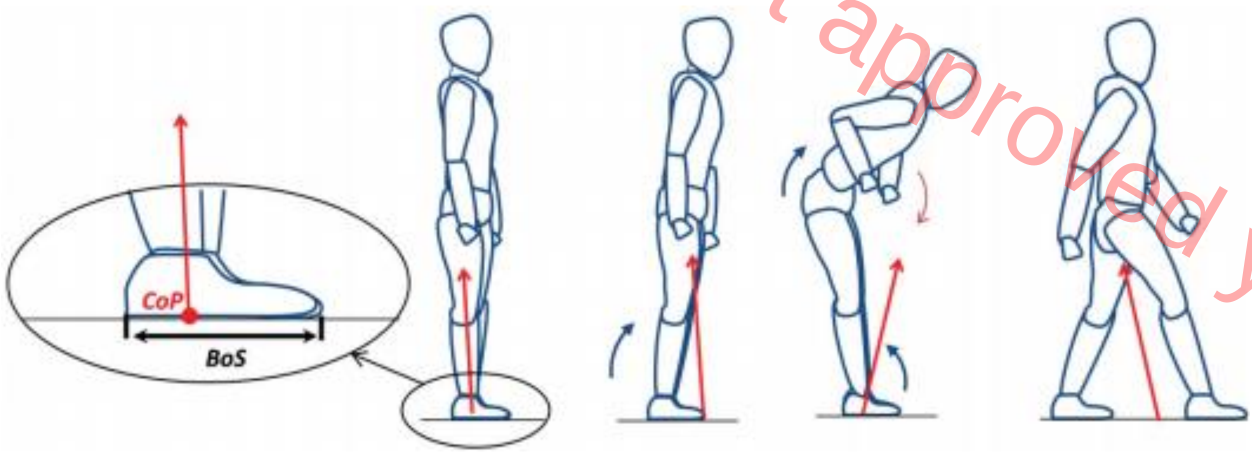


Figure 25. Different strategies for retaining balance. The neutral position; ankle strategy; hip strategy; stepping strategy (Vallée, 2015).

Muscles typically have 0.12-0.13s as a minimum time to react against external forces (Allum, 1983) (Maki & Fernie, 1988) and for the body to make larger movements to retain balance takes around 1 s (Simoneau & Corbeil, 2005). These figures may be considered to approximate the cases of the ankle and hip strategies respectively.

The peak tolerable acceleration is higher for a lower jerk level as the muscles have more time to resist the force and to act. Where the jerk is very low, the strength of the individual will be the only important human factor, as the acceleration is changing slowly enough for the body to fully react and change posture as required.

5.1.3 Balance recovery tolerance to external perturbation

Empirical research into the levels of longitudinal acceleration that passengers will tolerate can be broadly classified into subjective and objective studies.

Subjective studies typically use questionnaires and interviews with study participants in order to establish how comfortable different acceleration profiles are for different people. Passenger comfort is a subjective measure, considered quantitatively as how close an individual is to their own limit of balance. It means that they can only provide a general indication of what can be defined as acceptable or unacceptable levels, especially given the sensitivity of results to individual opinions or interpretations. Nonetheless, these studies confirmed that both jerk and acceleration influence passenger comfort and stability, and that unsupported standing passengers facing the direction of the vehicle's acceleration have the lowest tolerance.

For standing passengers, 1.0 m/s^2 was given the approximate limit that could be attained without discomfort, and around 1.2 m/s^2 was defined as uncomfortable (Loach & Maycock, 1952). Values for seated subjects were somewhat higher, and it was also noted that lower levels of jerk increased the acceleration limits.

The effect of high jerk values on the acceptability was examined of different levels of acceleration (Hiroaki, 1995). Curves for the acceptability of different levels of acceleration/jerk were produced, and an example for a group made up of regular commuters is illustrated in Figure 26.

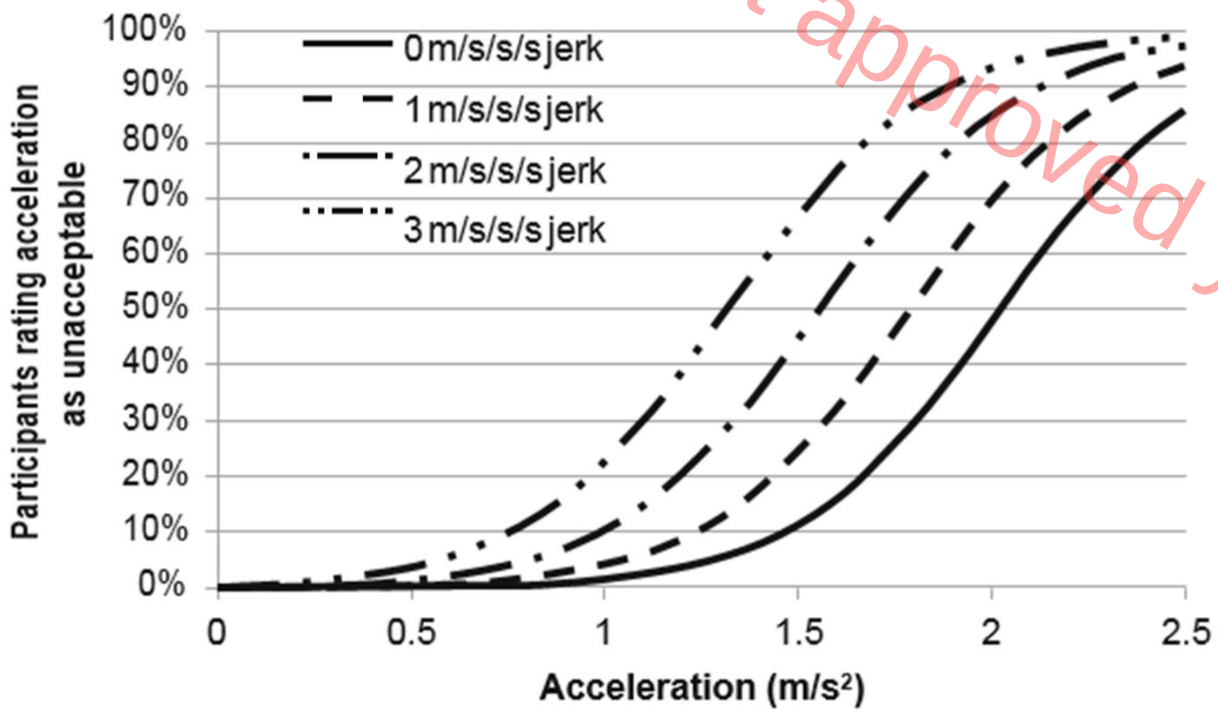


Figure 26. Acceptability of acceleration/jerk levels (Hiroaki, 1995).

Objective studies seek a quantifiable measure of people's reactions to external accelerations, rather than relying on their perception and opinion (Hoberock, 1977) (Graaf & Van Weperen, 1997). Hirchfeld (1932) confirmed that different levels of jerk (for the same acceleration) influence the retention of balance, and that unsupported passengers facing the same direction as the perturbation were least tolerant, losing their balance at an average of 1.27 m/s^2. The combined average for all unsupported standing passengers was 1.61 m/s^2, increasing to 2.25 m/s^2 with an overhead strap for support and 2.64 m/s^2 with a vertical grab rail.

Dorn (1998) included acceleration values at which seated passengers start to be dislodged from their seats, based on the results of Abernethy et al. (1980). A limit for transverse (forward- or backward-facing) seats was given as 3.0 m/s^2, well above the guidelines for standing passengers, but a lower limit of 1.4 m/s^2 was given for longitudinal (side-facing) seats.

Railway Technical Research Institute (RTRI) have also carried out further experimental studies that combine subjective and objective approaches, investigating the jerk limits required for high deceleration levels to be acceptable to passengers (Koji, Hiroharu, Hiroaki, & Hiroshi, 2007). Unfortunately, this article is not accessible anymore and the details of the perturbation used are missing which prevent its direct use for our study. The two graphs as retrieved by Powell & Palacín (2015) in Figure 27 illustrate the data points and fitted curves for acceptability (left) and the ability of passengers to retain their balance (right) with four jerk levels.

The postural stability of a small group of wheelchair users with tetraplegia or paraplegia was examined under the influence of quasi-static accelerations typically found in road vehicles (Kamper, Parnianpour, Barin, Adams, Linden, & Hemami, 1999). 95 % of the participants were able to retain balance within the wheelchair at an acceleration of 1.23 m/s^2, and the average at which balance was lost was around 2.2 m/s^2.

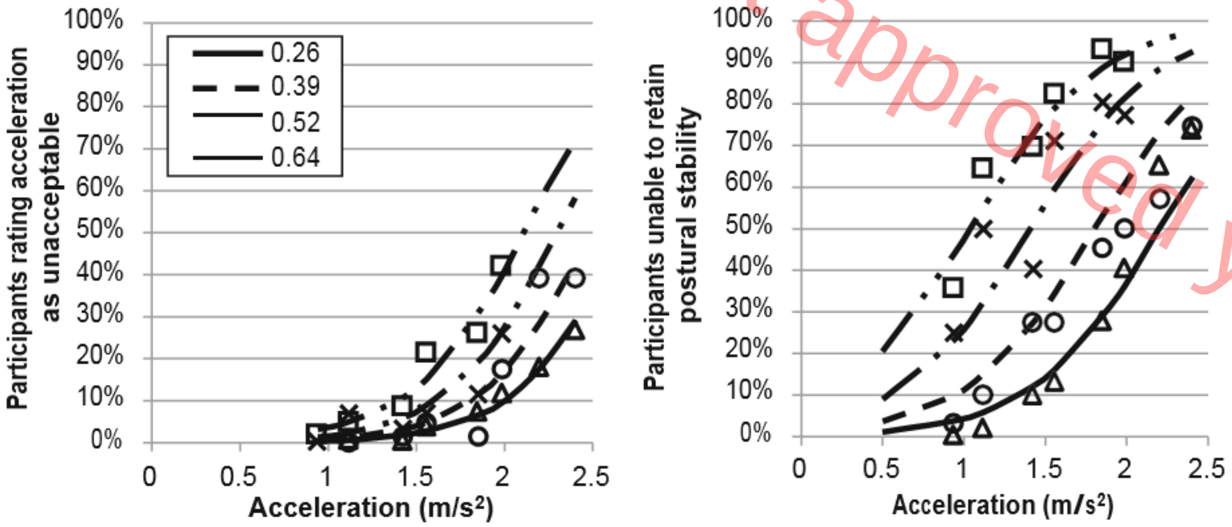


Figure 27. Subjective and objective results for forward-facing standing passengers (Koji, Hiroharu, Hiroaki, & Hiroshi, 2007). These figures were extracted from the article by Powell & Palacín (2015).

Robert, Beillas, Maupas, & Verriest (2007) studied the reaction of volunteer subjects submitted to representative situations of public transportation. They reported head kinematics of volunteer subjects in situations representative of typical transportation incidents. Two level of perturbation were tested – representing an emergency braking and a minor collision – combined with 3 different postures – free standing, using a back rest, and gripping a vertical bar. Data were obtained for (1) the three-dimensional head trajectories; (2) the maximal excursions of the head along the longitudinal axis; and (3) corridors of the head tangential velocity versus its longitudinal displacement (Figure 28). These data can be used as a first estimate to predict the risks of impact between the heads of passengers and their surrounding environment. They also provide insight into the impact velocity of this eventual collision. Furthermore, they highlight the influence of the level of perturbation and of the restraint device possibly used.

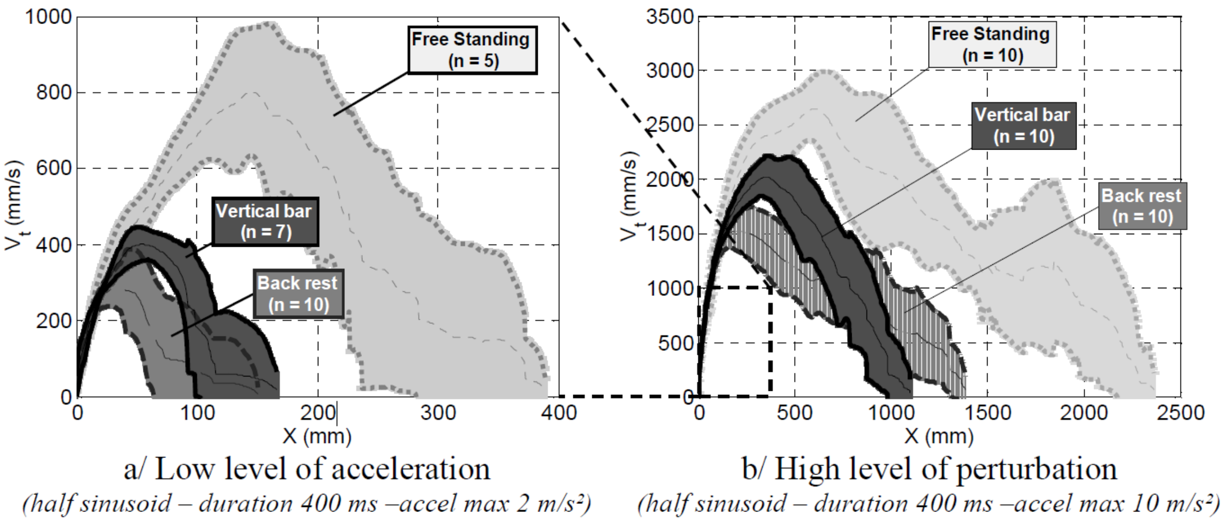


Figure 28. Experimental corridors for head tangential velocity as a function of its X-coordinate, for the 6 tests configurations (Robert, Beillas, Maupas, & Verriest, 2007).

Robert & Vallée (2014) quantified the effects of the jerk and the force on the balance recovery for a young population. Thirteen healthy young adults were instructed to try not to step in response to 20 different force/jerk combinations of forward waist-pulls. The duration of the perturbation was constant

(2 s) regardless of the test. This duration was long enough not to influence the possibility of balance recovery (Robert, et al., 2018). The discomfort caused by the perturbation was evaluated by the volunteer using the discomfort scale CP50 that was normalized. A multivariate logistic regression allowed to study the effect of the Jerk and the maximal force (F_{max}) on the discomfort value (Figure 29). For simplicity, the results are directly expressed in function of the acceleration instead of the pulling force (F_{max}= Acc*9.81). This regression was also used to assess the falling risk in cases of emergency braking defined by standard EN 13452-1 (see below). Despite the limitations due to the methodology (young population, limited range of perturbation), this regression is, to our knowledge, the only tool connecting the jerk and the acceleration with the risk of falling. By consequence, this model will be used to evaluate the risk of a standing passenger falling inside an AV using the acceleration and jerk as inputs.

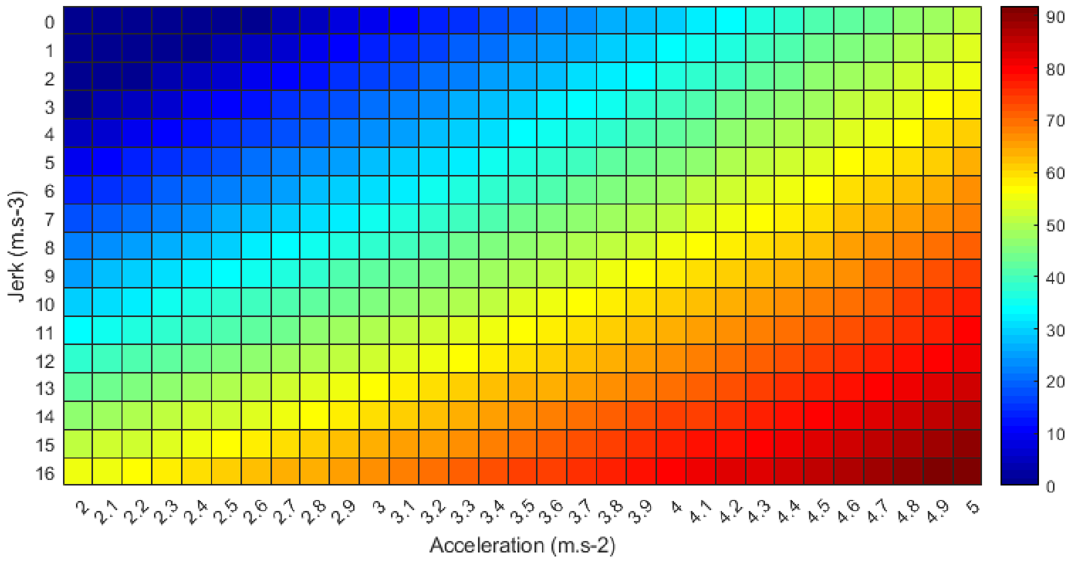


Figure 29. Passenger discomfort in function of the jerk and the acceleration (adapted from Robert & Vallée, 2014).

5.1.4 Regulation EN 13452-1

The standard EN 13452-1:2003 defines braking performance, for different braking situations and different types of public guided urban transport. Four types of emergency braking (EB) are defined: EB1 is the brake of the autopilot; EB2 is triggered by the passenger alarm; EB3 braking specific to the driver; EB4 is triggered by pressing the stop button emergency.

For each case, this standard defines two types of performance: 1 ° / Operational performance (Table 5) which define the minimum capacity of the vehicle to decelerate and whose purpose is to limit the stopping distance of the vehicle; 2 ° / The performances of comfort (Table 6) that can be seen as braking performance maximum and whose purpose is to limit discomfort and the risk of falling for standing passengers.

Table 5. Operational performances defined in standard EN 13452-1 according to braking types for a tram or a light vehicle.

	Service Brake	EB1	EB2	EB3	EB4
a_e minimal (m/s^{-2})	0-1.2	1.2	1.2	2.8	2.8
t_e maximal (s)	1.5	1.5	2	0.85	0.85

Table 6. Comfort performance defined in standard EN 13452-1 according to the types of braking for a tram or light vehicle.

	Service Brake	EB1	EB2	EB3	EB4
a_e maximal (m/s^{-2})	2	2.5	2.5	5	4
J (m/s^{-3})	1.5	4	4	8	8
% risk of falling (Vallée, 2015)	0	28.9	28.9	88	N/A

The value of t_e represents the equivalent braking time. It is calculated from the average between t_{10} (i.e. the delay time of braking demand up to 10% of maximum deceleration level) and t_{90} (i.e. the response time of the request for braking up to 90% of the maximum deceleration level). The value a_e is the equivalent deceleration: it is determined from the initial speed of the vehicle (v_0), braking distance (s_3) and t_e (Figure 30).

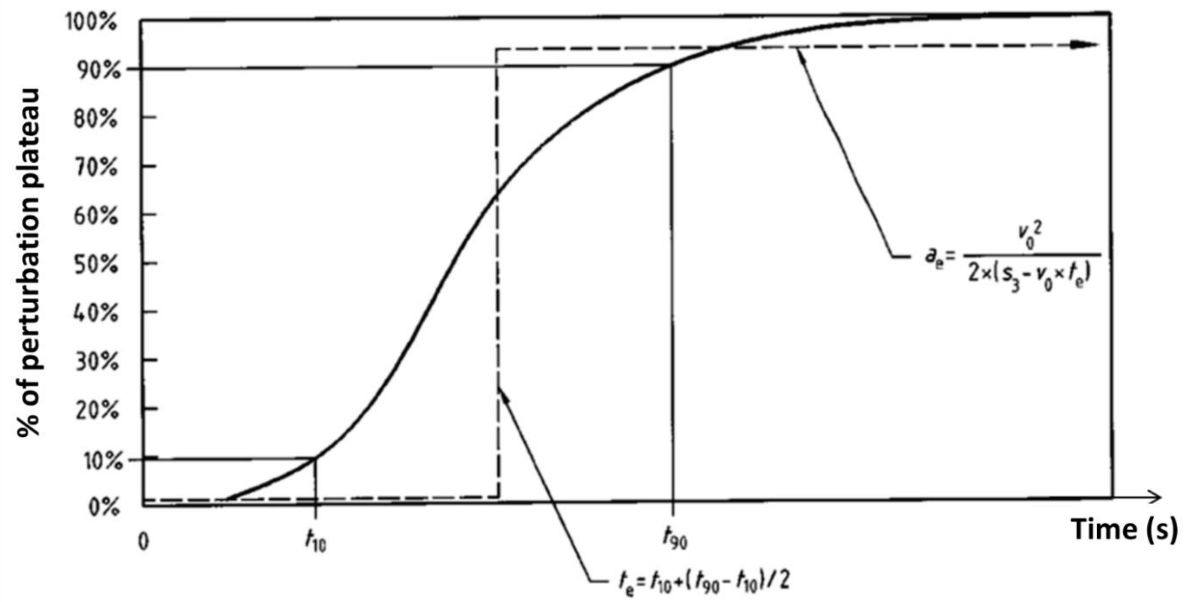


Figure 30. Illustration adapted from standard EN 13452-1 representing the braking profile and parameters used in the standard.

The choice of braking parameters, those relating to the performance of comfort, are not justified in the standard and do not seem to be based on studies published or accessible (Vallée, 2015). Considering the dynamics of a linear inverted pendulum and foot model, Vallée (2015) predicted the ability of a passenger to recover his balance after a perturbation representing the different emergency braking (EB). His analysis indicated a high risk of falling (88%) for EB3 (A_{max} = 5 m/s^{-2} and J = 8 m/s^{-3}, Table 6). He recommended a decrease of the jerk by two compared to comfort values of the standard EB3 (from 8 m/s^{-3} to 4 m/s^{-3}) allowing to pass from a high risk of falling (88%) that is to say a situation where the equilibrium is very difficult to recover in one step, to 35.6%, that is to say a situation where the equilibrium is more easily recoverable in one step.

5.1.5 Injury tolerance and criteria

Traumatic injuries occur when the mechanical tolerance limits of body structures are exceeded. Injuries are generally believed to result from excess strain induced by direct or indirect (i.e. inertial) loading.

Injury criteria relate the probability of trauma to mechanical parameters which can be measured using instrumented crash test dummies or cadavers, or evaluated in a numerical model. Injury criteria are mostly estimated from experimental tests on cadavers or animals, but tolerance thresholds are sometimes derived from human volunteer tests. Without injury criteria, the severity of trauma in a staged test or an accident reconstruction cannot be evaluated.

In this section, injury tolerance and criteria for the head are presented as the human head is the most critical body part to protect from injury as consequences can be devastating.

The main role of the head as a structure, including the skull and face, is to protect the brain against injury. It is constituted with multiple layered structures: the scalp, the skull, the meninges and the brain that represents the innermost tissue. Most important injuries to the head are those to the skull and the brain including the meninges. Soft tissue injuries to the scalp and face are commonly reported during pedestrian events but are generally regarded to be of minor importance.

There is only one head injury predictor in widespread use, the Head Injury Criterion (HIC), which is based solely on the time history of the linear acceleration of the head center of gravity (Versace, 1971). The HIC was developed from the Wayne State Tolerance Curve (WSTC) which showed that the linear acceleration required for skull fracture is inversely related to impact duration (Gurdjian, Roberts, & Thomas, 1966). Since skull fracture is correlated with moderate concussion, the WSTC was proposed as a predictor for head injury. The data derives from (1) 1-6 ms duration linear impacts of cadaver foreheads, (2) 6-10 ms duration impacts in which cadaver and animal brain pressure responses were compared and (3) longer pulse duration volunteer tests.

HIC is computed based on the following expression:

$$HIC = max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5} (t_2 - t_1)$$

where t2 and t1 are any two arbitrary time points during the acceleration time history. Acceleration is measured in multiples of the acceleration of gravity [g] and time is measured in seconds. The resultant acceleration is used for the calculation. WTSC analysis led to the proposal of a log-normal probability curve relating HIC score to skull fracture. For example, a HIC score of 1000 has an approximately 50% probability of a skull fracture. Using extrapolation, additional risk curves were generated to link HIC to the corresponding injury severity level coded using the Abbreviated Injury Scale (AIS). The AIS is an anatomically based, severity scoring system that classifies each injury in each body region assigning a score which ranges from 0 (AIS0) to 6 (AIS6) which represents a certain threat-to-life associated with an injury.

5.1.6 Summary: passenger balance and fall

Both jerk and acceleration influence passenger comfort and balance, unsupported standing passengers facing the direction of the vehicle's acceleration will have the lowest tolerance. It is difficult to set conclusive limits on acceleration and jerk, as passenger's reactions strongly depend on the individual concerned. A range was nonetheless suggested for maximum permissible accelerations of 1.0–1.5 m/s^2 as an outline guide, with jerk limited to 3 m/s^3.

Analysis of the braking performance rules as regulated in standard EN 13452-1 for public guided urban transport highlighted a risk of falling which was confirmed by modelling and accident reports.

A model estimating if balance can be recovered after a perturbation was developed and could be directly used in Section 5.3 for evaluating the risk of a standing passenger falling inside an AV after an emergency braking.

The human head is the most critical body part to protect from passenger injury as consequences can be devastating. Literature findings indicate that the most prominent criterion for the head is the HIC, which is directly related to the head kinematics (accelerations). This criterion could be used for evaluating the risk of passenger head injury inside due to falling but detailed information about the head kinematics at impact and environments are needed. To do so, numerical simulations involving a falling standing crash test dummy inside a braking minibus will be performed in Section 5.3.

5.2 Literature Review – Pedestrian Impact

The Pedestrian Crash Data Study (PCDS) database in the United States shows that injuries to the lower extremities and head are the most frequent in pedestrian accidents, with head injuries being usually the most severe (Jarrett & Saul, 1998) (Chidester & Isenberg, 2001).

In the public transport sector, pedestrians and other vulnerable road users (i.e. cyclists) suffer severe injuries from collisions as reported in trams (Weber, Muser, & Schmitt, 2015). Hence, injured pedestrians are to be expected with autonomous vehicles.

The severity of pedestrian injury depends on 5 factors: (1) the energy dissipated in the collision, which is related to the speed of the vehicle at the moment of impact; (2) the shape and stiffness of the vehicle surfaces striking the impacted body areas; (3) the post-impact kinematics of the pedestrian's body; (4) possible impact against the ground or a secondary obstacle; and (5) the pedestrian's injury tolerance to withstand the impact (Simms & Wood, 2009).

5.2.1 The importance of the vehicle speed

The idea that the faster a striking vehicle is traveling, the more damage is done to a struck pedestrian, has been documented in a number of studies (Rosén & Sander, 2009). Recently, Martin and Wu (2018) estimated pedestrians' risk of death according to the impact speed when hit by a passenger car in a frontal collision (Figure 31). Data were collected from all fatal crashes in France in 2011 and weighted to take account of police under-reporting of mild injury. A strong dependence on impact speed was observed, with the risk at 50 km/h being more than twice as high as the risk at 40 km/h and more than five times higher than the risk at 30 km/h. However, since these data are based on the car fleet of 2011 in France, they cannot be extrapolated for AV because of the different type of vehicle and situations involved.

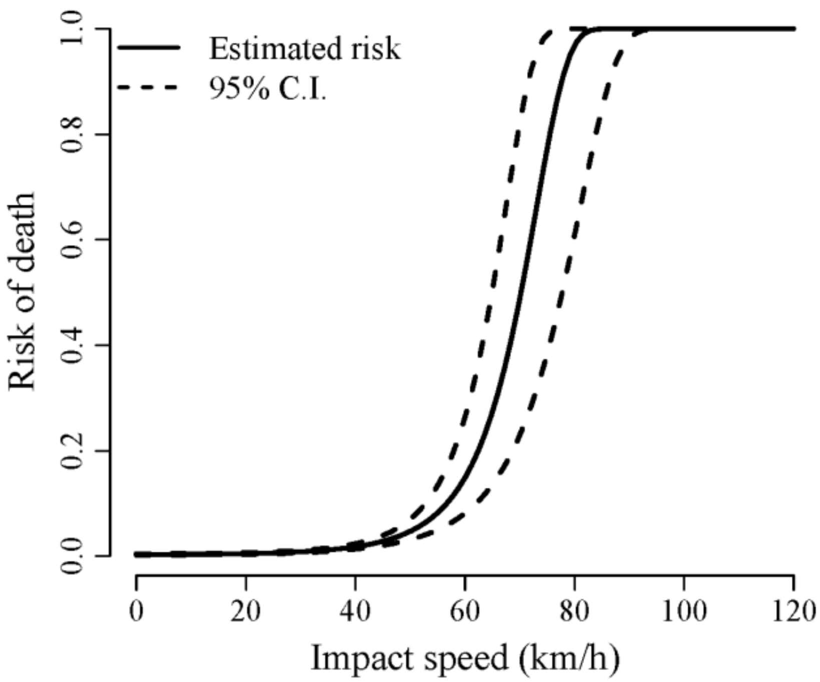


Figure 31. Probability of death according to impact speed, with 95% CI (Martin & Wu, 2018).

5.2.2 The importance of the vehicle shape and stiffness

An epidemiology study showed that pedestrians struck by an SUV are twice as likely to sustain brain injury as pedestrians struck by passenger cars (Ballesteros, Dischinger, & Langenberg, 2004). The main source of head injuries is the bonnet in SUV accidents but the windscreen dominates in passenger car accidents (Longhitano, Henary, Bhalla, Ivarsson, & Crandall, 2005).

Numerical studies, which have the advantage of being able to take body kinematics after impact into account, suggested that the importance of the aggressiveness of the shape is dependent of the speed (Crocetta, Piantini, Pierini, & Simms, 2015). Assuming no differences in stiffness between vehicle types, SUVs and vans appear to be more aggressive for head contact to adult pedestrians than cars when the impact speed is at or below 30 km/h. At 40 km/h passenger cars cause whole body rotations and higher average head impact speeds for adult pedestrians. This indicated that at 40 km/h a low front might not give any benefit in terms of reducing the severity of head impact. However, none of these previous results can be extrapolated to AV because of the different type of geometry involved.

In the context of tramway safety whose front is closer to AV, (Weber, Muser, & Schmitt, 2015) optimized the tram front-end design to reduce pedestrian injury risk and to develop practical design guidelines for public transport services and manufacturers. Typical accident scenarios were defined based on an analysis of tram-pedestrian collisions in a major Swiss city as well as on cases reported in the literature. Potentially critical areas in different tram front geometries such as the front cover, the windscreen, the a-pillars or the ground clearance were identified. Based on these findings, front-end design guidelines were established together with Swiss public transport services such as overrun protection devices and protruding parts.

(Weber, Muser, & Schmitt, 2015) identified the following front structures:

- **Front trim panel**: additional space gained by a forward 8-10 cm displacement of the front trim panel relative to the windscreen could be used for energy absorption to minimize the injury risk for the pelvis and the thorax. The use of an almost vertical contour for the lower part of the front trim panel is suggested instead of a round shape (Figure 32, A) to avoid higher body rotations and higher injury risk at the secondary impact for child pedestrians.

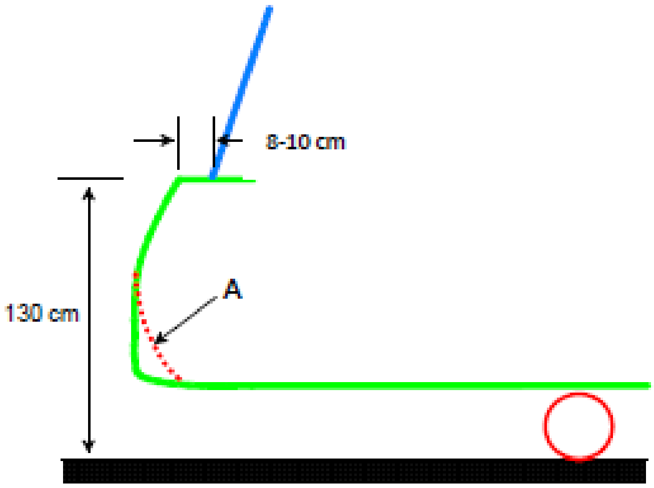


Figure 32. Potentially critical areas in tram front geometries (Weber, Muser, & Schmitt, 2015)

- **Bumpers**: often the initial contact structure in pedestrian impacts. The shape of today's bumper structures aims at transferring impact loads across a larger surface. Modern bumpers include thus soft, easily replaced layers suited for leg impact test, and stiffer structures underneath that handle the loads during the bumper standard tests.
- **Bonnet**: enough clearance between any stiff components such as the engine must be ensured. Furthermore, the bonnet and its underlying reinforcement structures need to be deformable under head impact, while at the same time ensuring enough structural stiffness, against regular car crash. To overcome this dilemma, so-called pop-up bonnets (i.e. bonnets that are lifted in case of a pedestrian/cyclist impact and thus allow for more deformation space) have been proposed.
- **Windscreen**: the windshield itself usually breaks at impact and is generally regarded as one of the 'softer' structures of a vehicle front. However, an impact to the stiff windshield frame such as the A-pillars, the area of the wipers or the roof results in significant head loading.
- **A-pillars**: the A-pillars, along with the windshield frame, represent very stiff structures as they need to carry high loads in the event of a rollover accident. Currently, A-pillars can thus be the source of serious injuries.
- **Ground clearance**: structural parts positioned above a height of about 25 cm above the ground can cause injuries if a person e.g. rotates under the tram (Figure 33, A). Structural parts located higher than 5-8 cm but lower than 25 cm above the ground (Figure 33, B) can cause injuries by direct impact, but also by e.g. trapping or crushing. Any contact with the wheels must be avoided. Thus, a movable or fixed, preferably soft-covered profile positioned about 5-8 cm above the ground (Figure 33, C) can prevent a contact with the wheels.

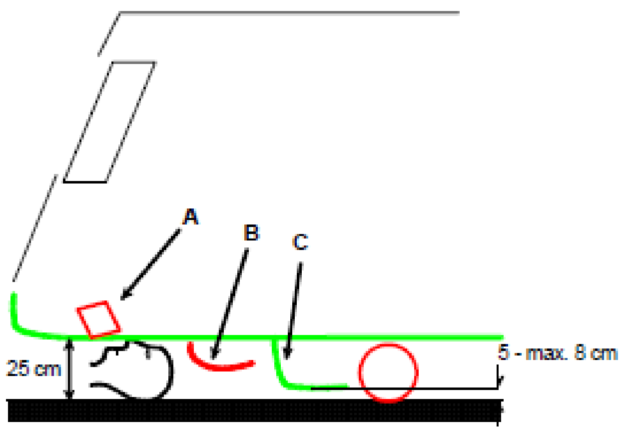


Figure 33. Potentially critical areas under the tram (Weber, Muser, & Schmitt, 2015).

5.2.3 Impact against the ground

Impact against the ground or secondary obstacles has been less studied, mainly due to lack of precise observations and the wide variety of possible obstacles (Badea-Romero & Lenard, 2013). A detailed case review of 205 accidents from the UK involving vulnerable road users with head injuries or impacts indicated that contact with the road actually outnumber impacts with the striking vehicle (Badea-Romero & Lenard, 2013). However, the vehicle accounts for a greater proportion of more serious casualties (AIS 2+ and AIS 3+ head severity). Further analysis using a multivariate classification model identified several factors that correlated with the source of injury, namely the type of interaction between the striking vehicle and vulnerable road user, the age of the vulnerable road user and the nature of injury

5.2.4 Injury tolerance and criteria

Injury to the head and the lower extremities are the focus in in pedestrian safety as these body regions are the most frequently injured in pedestrian accidents (Jarrett & Saul, 1998) (Chidester & Isenberg, 2001). These injury tolerances and criteria are a necessary foundation for the vehicle safety standards used to evaluate vehicle design for pedestrian and cyclist safety.

5.2.4.1 Head injuries

Skull fractures and brain injuries are commonly reported in pedestrian accidents (Jarrett & Saul, 1998) (Chidester & Isenberg, 2001). The associated injury mechanisms were detailed in section 5.1.5, page 54. The criterion HIC presented there is currently used to assess pedestrian safety.

5.2.4.2 Lower extremities injuries

Lower extremity injuries are frequent when pedestrians and cyclists are struck by vehicles, because this is usually the first body region struck, and many different injuries can occur.

From the bumper impact, the leg soft tissue and long bones are exposed to bending at the impact area, which can result in soft tissue injury and bone fracture. In an attempt to replicate pedestrian impact loading conditions, three points bending tests performed on femur and tibia on cadavers reported failure limits in term leg axial load and bending moment (Kerrigan, Bhalla, Madeley, Funk, Bose, & Crandall, 2003).

The knee joint is subjected to a shear force and bending moment, resulting in compressive loads on the nearest tibia and femoral condyles, and tensile forces in the knee ligaments and the joint capsule. A combination of cadaver impact tests and finite element modelling was used to derive a tolerance to lateral bending in the knee joint of 16° rotation and 15 mm shearing displacement, above which ligament injury is predicted (Arnoux, Subit, Masson, Chabrand, & Brunet, 2005).

5.2.5 Vehicle safety standards for pedestrian and cyclist safety

Pedestrian safety standards were developed by the European Enhanced Vehicle Safety Committee (EEVC), the International Organization for Standardisation (ISO) and the United Nations Economic Commission for Europe (UNECE). For Europe, the directive EC78/2009 requires motor vehicles to be tested for pedestrian safety. The test procedures are laid out in regulation UN ECE R127. Figure 34 summarizes current test procedures for impact testing according to GTR9, EC78/2009 and R127 as well as different consumer tests.

Test Method	Parameter	Euro NCAP / ANCAP U.S. NCAP[8] max. score	Euro NCAP / ANCAP U.S. NCAP[8] zero score	JNCAP max. score	JNCAP zero score	KNCAP C-NCAP max. score	KNCAP C-NCAP zero score	EU Regulations 78/2009 and 631/2009 Phase 2	UN R127 KMVSS 102-2	GTR No. 9	Japan Article 18 Attachment 99
1 Adult Headform 4.5 kg Ø 165 mm	α_A (°)	65		65		65		65	65	65	65
	V_A (km/h)	40		40		40		35	35	35	35
	WAD (mm)	1700 (1500)[1] - 2100		1700 - 2100		1700 - 2100		1700 - 2100[10]	1700 - 2100[10]	1700 - 2100[10]	1700 - 2100
	on Windscreen	yes		yes		yes		no	no	no	no
	HPC/HIC (-)	650	1700	650	1700	650	1700	1000 / 1700[3]	1000 / 1700[3]	1000 / 1700[3]	1000 / 1700[3]
2 Child Headform 3.5 kg Ø 165 mm	α_C (°)	50		50 (20[5])		50		50	50	50	50
	V_C (km/h)	40		40		40		35	35	35	35
	WAD (mm)	1000 - 1700 (1500)[1]		1000 - 1700		1000 - 1700		1000 - 1700[10]	1000[9] - 1700[10]	1000 - 1700[10]	1000 - 1700
	on Windscreen	yes		yes		yes		no	no	no	no
	HPC/HIC (-)	650	1700	650	1700	650	1700	1000 / 1700[3]	1000 / 1700[3]	1000 / 1700[3]	1000 / 1700[3]
3 Upper Legform 10.5 kg	α_U (°)	90 w.r.t. IBRL[4] - WAD 930									
	V_U (km/h)	20 - 33									
	Sum of forces (kN)	5 kN	6 kN								
	Bending Moment (Nm)	285 Nm	350 Nm								
4 Lower Legform[7]	Legform	Flex PLI		Flex PLI		Flex PLI		EEVC	Flex PLI	Flex PLI	Flex PLI
	V_L (km/h)	40		40 (44)[5]		40		40	40	40	40
	Ground clearance d (mm)	75		75		75		25	75	75	75
	Acceleration (g)							170 (250)[6]			
	Bending angle (°)							19			
	Shearing (mm)							6			
	Tibia Bending (Nm)	282	340	202	306	282	340		340 (380)[6]	340 (380)[6]	340 (380)[6]
	MCL Elongation (mm)	19	22	14.8	19,8	19	22		22	22	22
	ACL/PCL Elongation (mm)	10	10	0	13	10	10		13	13	13
5 Upper Legform[7] 9.5 kg	V_L (km/h)	40				40		40	40	40	40
	Sum of forces (kN)	5	6			5	7.5 / 6[11]	7.5	7.5	7.5	7.5
	Bending Moment (Nm)	285	350			300 / 285[11]	510 / 350[11]	510	510	510	510

[1] Points to be tested that lie between WAD 1500 and 1700 are tested with child-/small adult headform impactor, if the points are on the moveable/hinged bonnet top. Otherwise the adult headform is used.
[2] Between "Blue Line" and 1000 mm
[3] The HPC shall not exceed 1000 over one half of the child headform test area and, in addition, shall not exceed 1 000 over 2/3 of the combined child and adult headform test areas. The HPC for the remaining areas shall not exceed 1700 for both headforms.
[4] IBRL = Internal Bumper Reference Line
[5] Test velocity will be increased when leg impact is introduced in legal test.
[6] In an area no wider than 264 mm.
[7] For vehicles with a lower bumper height < 425 mm the lower legform test 4 is applied. For vehicles with a lower bumper height ≥ 500 mm the upper legform test 5 is applied. For vehicles with a lower bumper height ≥ 425 mm an < 500 mm the impactor is at the choice of the manufacturer.
[8] Proposed U.S. NCAP rating
[9] Minimum 82.5 mm rearward of Bonnet Leading Edge
[10] Maximum 82.5 mm forward of Bonnet Rear Reference Line
[11] C-NCAP

SafetyWissen by carhs.

Figure 34. Different test procedures for pedestrian impact testing (BASt / carhs).

The chosen pedestrian safety standards aimed at protecting pedestrian struck from the side by a vehicle at 40 km/h since this speed includes 80% of pedestrian accident cases. The proposed tests make use of different impactors mimicking the impact of a leg and the head to a defined area of the vehicle front (Figure 35). Headforms (adult size and child size) and a legform (tibia and femur) are used as impactors. Subsystems tests were chosen for the test procedure instead of full pedestrian dummies because of the higher number of scenarios that can be tested and their repeatability. However, the simplification of a fixed impact velocity of the subsystems test eliminates the influence of the overall vehicle shape on the head impact conditions.

The head injury criterion (HIC) is used to evaluate the head injury risk. For the tests using the child and adult headform the HIC recorded shall not exceed 1000 over two thirds of the bonnet top test area. The HIC for the remaining areas shall not exceed 1700 for both headforms.

Regarding the impact of the lower legform to the bumper (flexible lower legform impactor), the absolute value of the maximum dynamic medial collateral ligament elongation at the knee shall not exceed 22 mm, and the maximum dynamic anterior cruciate ligament and posterior cruciate ligament elongation shall not exceed 13 mm.

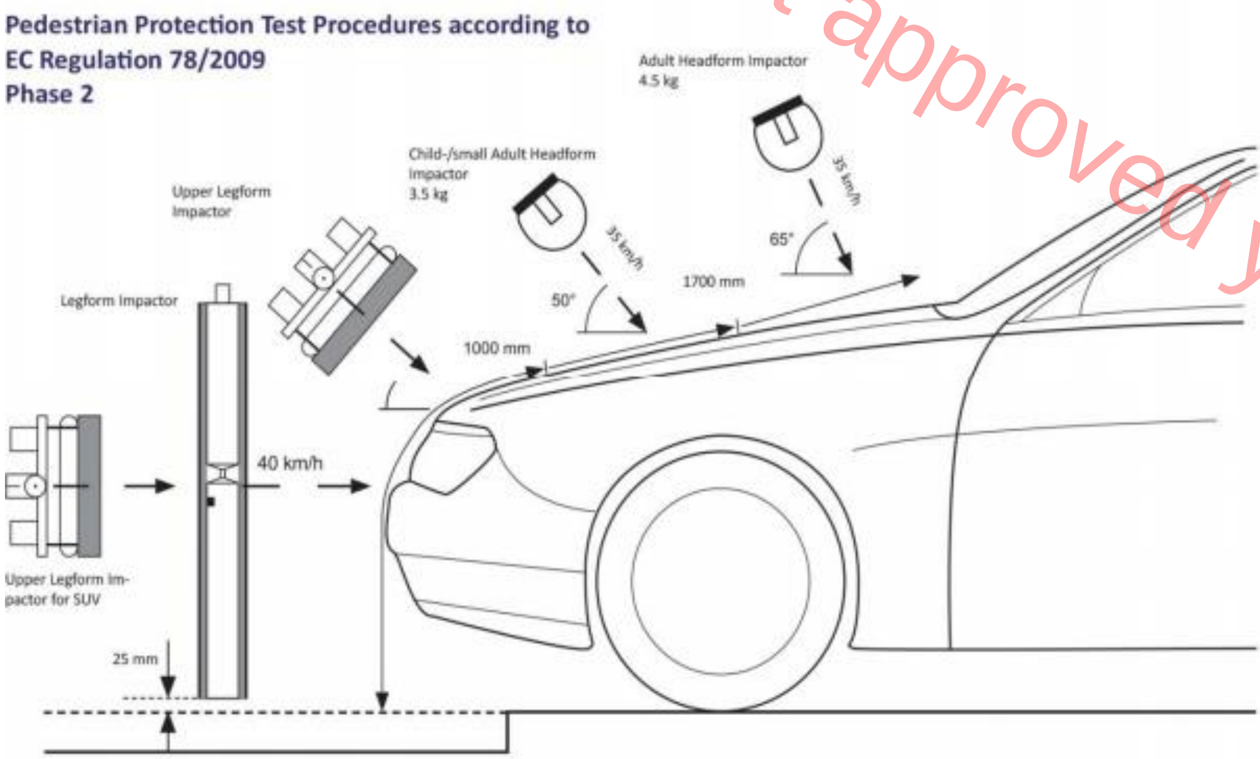


Figure 35. Pedestrian impact testing according to EC78/2009 (figure by CARHS).

It has been generally assumed that standards governing vehicle design for pedestrian safety will also improve safety for cyclists. However, adjustments are expected to account for some differences between pedestrian and cyclist impact by revisiting the impact conditions in terms of impact velocity and impact angle.

This subsystems approach could be used to implement crash safety standards for improving AV front-end design for pedestrian and cyclist impact. However, adjustments on the impact conditions (angles, velocity) will have to be made to account the specificity of an AV front-end shape and impact characteristics, especially for the head. Cadaveric tests or simulations will be necessary to ensure correct impact conditions. Numerical simulations involving the front-end of the NAVYA minibus impacting a virtual pedestrian performed in Section 5.4 will allow a better understanding of the necessary updates.

5.2.6 Summary: Pedestrian Impact

In the automotive industry, collisions of vehicles against pedestrians have been extensively addressed. Investigations have shown that the vehicle front-end design, particularly the shape and stiffness of a vehicle front-end, as well as the impact velocity have a significant influence on the injury risk of pedestrians and cyclists.

Current pedestrian safety standards aimed at protecting pedestrian struck from the side by a vehicle at 40 km/h since this speed includes 80% of pedestrian accident cases. The proposed tests make use of different impactors mimicking the impact of a leg and the head to a defined area of the vehicle front.

The human head is the most critical body part to protect from pedestrian injury as consequences can be devastating. Literature findings indicated that the most prominent criterion for the head is the HIC which is directly related to the head dummy kinematics (accelerations). This criterion could be used for evaluating the risk of pedestrian head injury but detailed information about the head kinematics at impact and environments are needed. Since these data depends on vehicle front-end design, numerical simulations involving the front of a minibus impacting a virtual pedestrian will be performed in Section 5.4.

5.3 Head injury risk for standing passengers in case of harsh braking

5.3.1 Preamble

In Section 5.3, the risk of falling due to jerk and acceleration was covered. A model estimating if balance can be recovered after a perturbation could be directly used for evaluating the risk of a standing passenger falling inside an AV after an emergency braking. In this situation, the human head was judged to be the most critical body part to protect from passenger injury.

The Head Injury Criterion could be used for evaluating the risk of passenger head injury inside due to falling, but detailed information about the head kinematics at impact and environments are needed.

Volunteer tests or simulations are usually the methods used to ensure correct kinematics. It was however beyond the budget and scope of the project to implement physical tests.

Numerical simulations involving a falling standing crash test dummy inside a braking minibus were the chosen approach. It will identify how the braking deceleration characteristics influence the head kinematics and injury risk of a standing passenger in autonomous vehicle.

5.3.2 Methods

Finite element model software will simulate the scenarios defined by braking deceleration characteristics. A pedestrian crash test dummy representing the standing passenger is placed in a vehicle interior model representing the interior of an automated minibus. The vehicle is subjected to a deceleration pulse, causing the passenger to fall and sustain injury.

The simulation was divided in two steps:

- **First step**: a pedestrian crash test dummy representing the standing passenger is placed in a vehicle interior model representing the interior of an automated minibus. The vehicle is subjected to a deceleration pulse, causing the passenger to fall.
    - Inputs: pulse characteristics, passenger orientation and position
    - Outputs: head kinematics at impact

- **Second step**: a dummy head model using the head kinematics obtained in the previous step is projected against a floor of variable stiffness covering the range of material stiffness to be expected in the minibus
    - Inputs: head kinematics at impact obtained in the first step, floor stiffness
    - Outputs: head injury risk (HIC)

In this study, it has been chosen to separate the head kinematics during the fall and impact from the head injury risk assessment to increase the number of cases covered by different material stiffness to be expected in the minibus. This allows speeding up significantly the simulation of the standing passenger falling in the vehicle model since all vehicle components can be modelled as rigid bodies.

5.3.2.1 Vehicle interior model

The vehicle model used in this study is based upon the minibus vehicle developed by NAVYA and deployed in AVENUE (Figure 36). A Finite Element model of the vehicle interior was generated based on the CAD surfaces provided by NAVYA.

Figure 36. NAVYA Minibus. Left: operating on the open road in the city of Lyon (NAVYA). Right: CAD provided by NAVYA.

The vehicle passenger compartment model included components that can be potentially in contact with the passenger: doors, floor surface, side wall, seat, windshield, handrail backrest, and electronics (Figure 37). Components were meshed with quadrilateral 2D shell elements. Automated element meshing algorithms included in Altair HyperMesh™ (Altair, 2019) were used to generate the initial mesh, but manual editing and refinement was expected on all meshes created. Ultimately, the mesh density of components was determined by automatic mesh sensitivity studies and an element size of 10 mm was chosen.

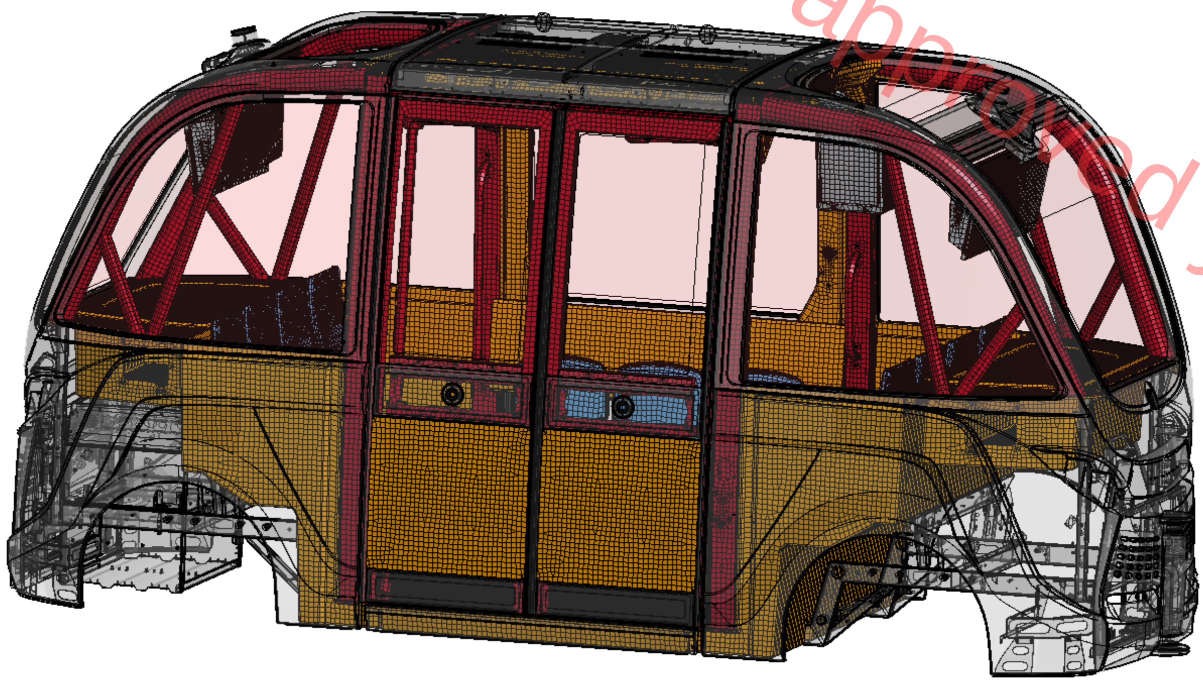


Figure 37. Vehicle interior model.

The goal of the simulation of the standing passenger falling in the vehicle model is to provide head kinematics at impact. Consequently, it was not crucial for the robustness and accuracy of the simulation that the stiffness of the vehicle components was properly implemented. Thus, all vehicle components were modelled as rigid bodies to speed up the simulation.

The vehicle will be subjected to a parametric deceleration pulse that will be in the reported range of emergency braking as in regulation EN 13452-1 (provisionally Jerk < 8 m/s^3 and A_{max} < 5 m/s^{-2}). The profile will a simplified representation of a real profile (Figure 38). It is divided into three phases: 1 °) an acceleration phase at constant jerk value (Jerk); 2 °) a constant acceleration phase at A_{max} during T seconds corresponding to the established acceleration of the actual profile and 3°) a deceleration phase at constant jerk value (-Jerk).

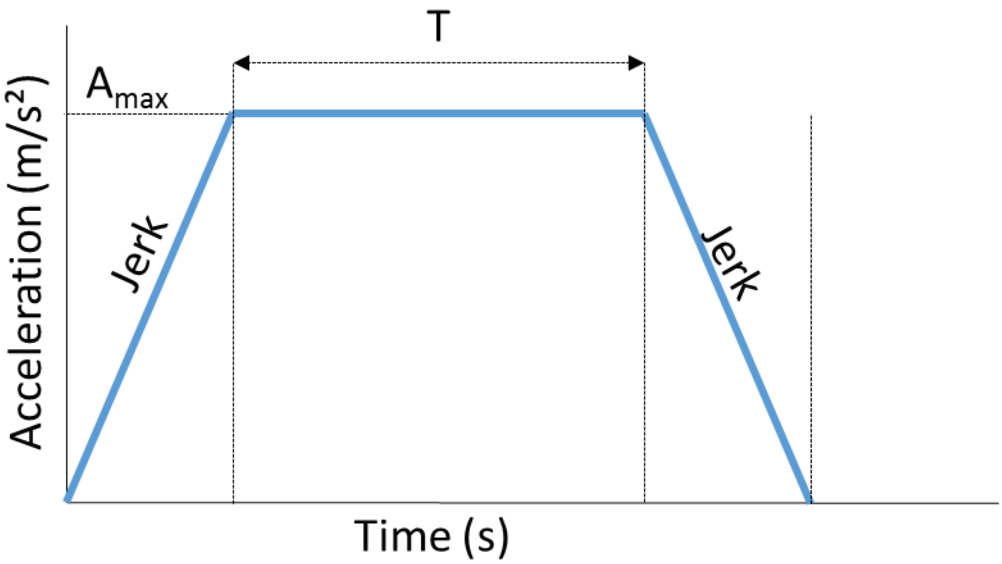


Figure 38. Parametric deceleration pulse used in this study.

5.3.2.2 Human body models

Detailed human body FE models like the GHBMC detailed 50th percentile male pedestrian model (Gayzik, Moreno, Geer, Wuertzer, Martin, & Stitzel, 2011) or the Piper child model (Peres, 2018) take approximately 8 days to complete a 2 s fall using 48 cores on a computational cluster. This runtime makes such models impractical for use in a parametric study requiring many simulations.

Therefore, the standing passenger was the Hybrid III 50th Percentile Male Standing model (1.74 m, 75.7 kg) distributed by LSTC (Figure 39). Based on the Hybrid III 50th Percentile Male Rigid-FE model, it is a semi-deformable model that is computationally inexpensive due to its low element count.

Figure 39. Hybrid III 50th Percentile Male Standing (LTSC).

The passenger model will be positioned inside the interior vehicle at different locations and orientations to cover the vehicle space. If resources allow, different standing passenger postures will be investigated to evaluate the effect of holding of a handrail on the head kinematics.

Passenger kinematics relative to the vehicle will be quantified and focus will be on the head kinematics prior to impact since these data are used as inputs in the FE Head-Ground Impact Model to quantify the head injury risk.

5.3.2.3 Parametric study

CEESAR developed a plan to investigate falling passenger kinematics during emergency braking. This plan outlines a simulation matrix for a parametric study which includes different passenger locations and pulse characteristics for the models. The simulation matrix incorporated a structured sampling of the parameter space using a fractional factorial design with two-factor interactions of the following parameters:

- *Jerk* (3 levels)
- *Acceleration* (3 levels)

- *Position* (3 levels per axis)

A total of **81 simulations** were performed.

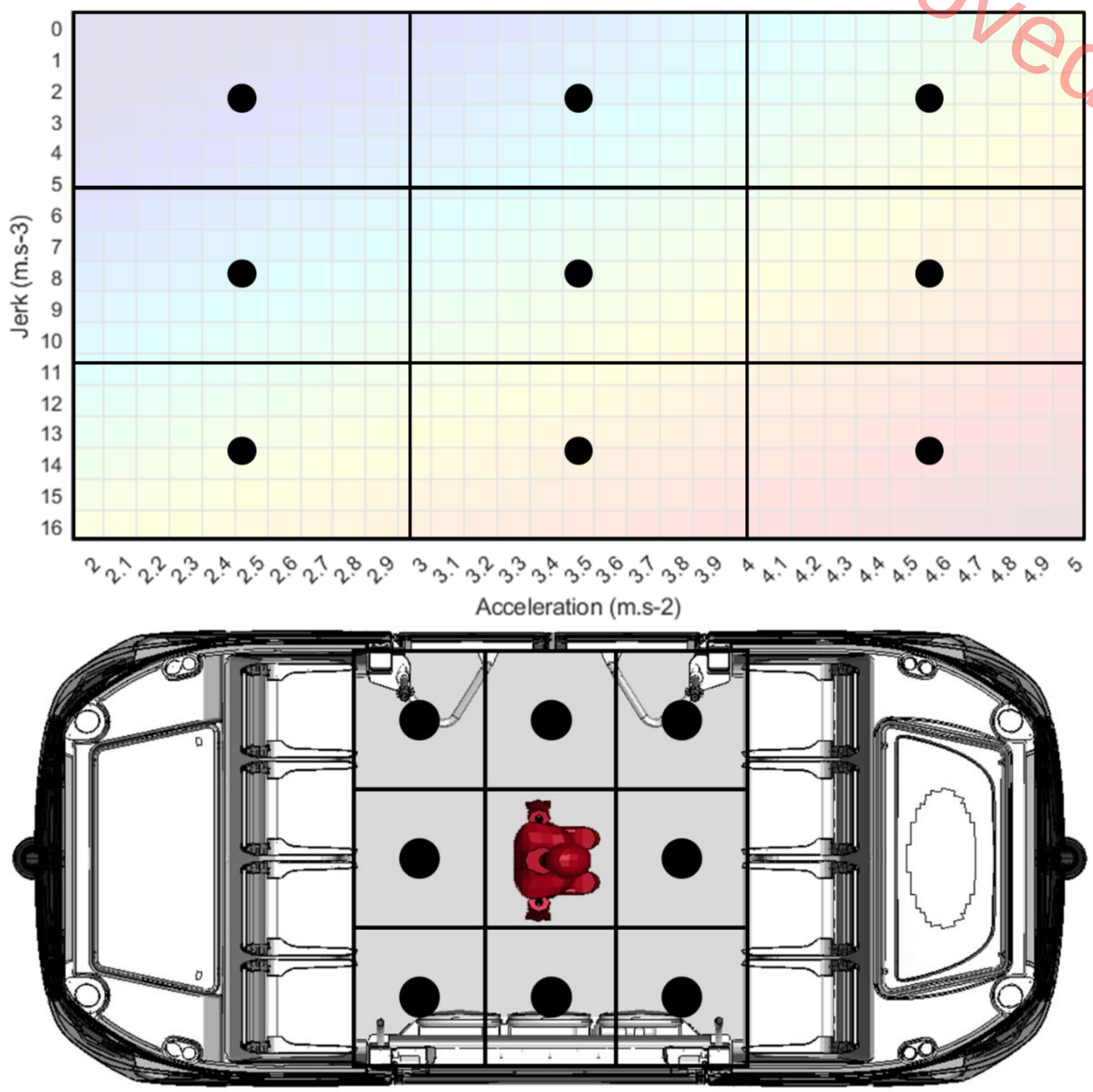


Figure 40. Sampling of the parameter space.

5.3.2.4 Finite Element (FE) Head-Ground Impact Model

In order to quantify the head injury risk, a dummy head model will be projected against a floor of variable stiffness covering the range of material stiffness to be expected in the minibus (Figure 41).

Provisionally, the head model used will be the Free Motion Headform developed and validated by LSTC and is intended for use in upper interior head impact conducted according to FMVSS 201U specifications (TRANSPORTATION, 2016).

The linear velocities, angular velocities, and linear acceleration extracted from the first simulation will be used as inputs of this more focused simulation.

From the contact forces and head accelerations obtained in the simulations, the Head Injury Criterion and the associated head injury risks will be computed.

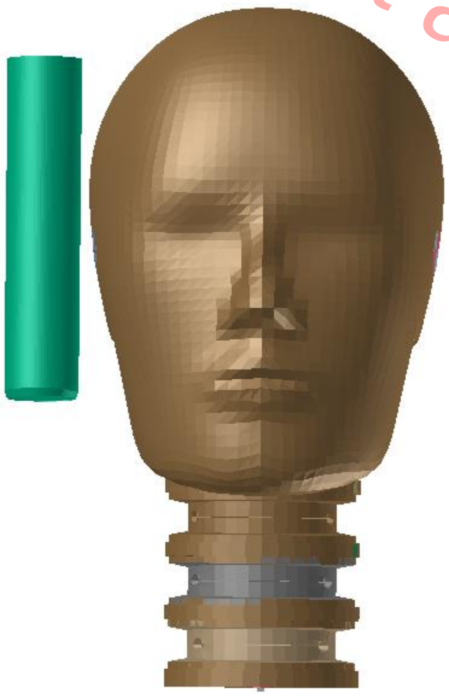


Figure 41. Free Motion Headform (LTSC).

5.3.2.5 Injury risk predictor

After completion of the simulation matrix, a statistical model estimating head injury risk as a function of jerk and deceleration of braking will be developed (Figure 42). Head injury risk will be given as probability to sustain a certain injury level, using the Abbreviated Injury Scale (AIS) (e.g. risk given as probability of AIS ≥ 3 for head injury).

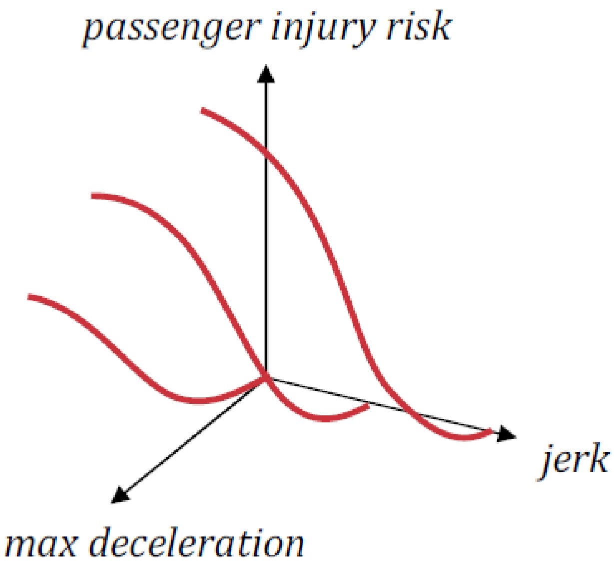


Figure 42. Risk (e.g. AIS ≥ 3 probability) as a function of dynamic parameters

5.3.3 Results

All simulations successfully terminated with no error. Across all simulations, the average head impact time was 832 ms (Figure 43). At impact, the average head impact velocity relative to the vehicle was 5.3 m/s with a maximum of 7.2 m/s obtained for the low jerk/deceleration values (Figure 44). The resulting head injury risk was 45%, with a maximum of 89% (Figure 45).

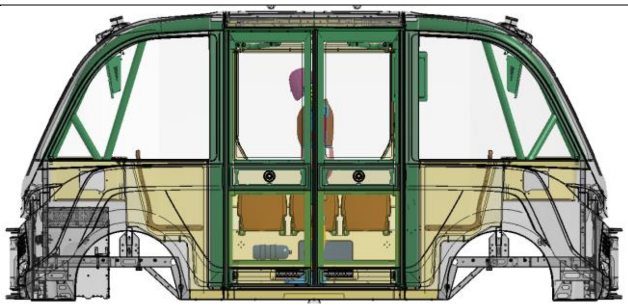
	
0 ms	Head impact (832 ± 134 ms)

Figure 43. Typical response of a standing passenger.

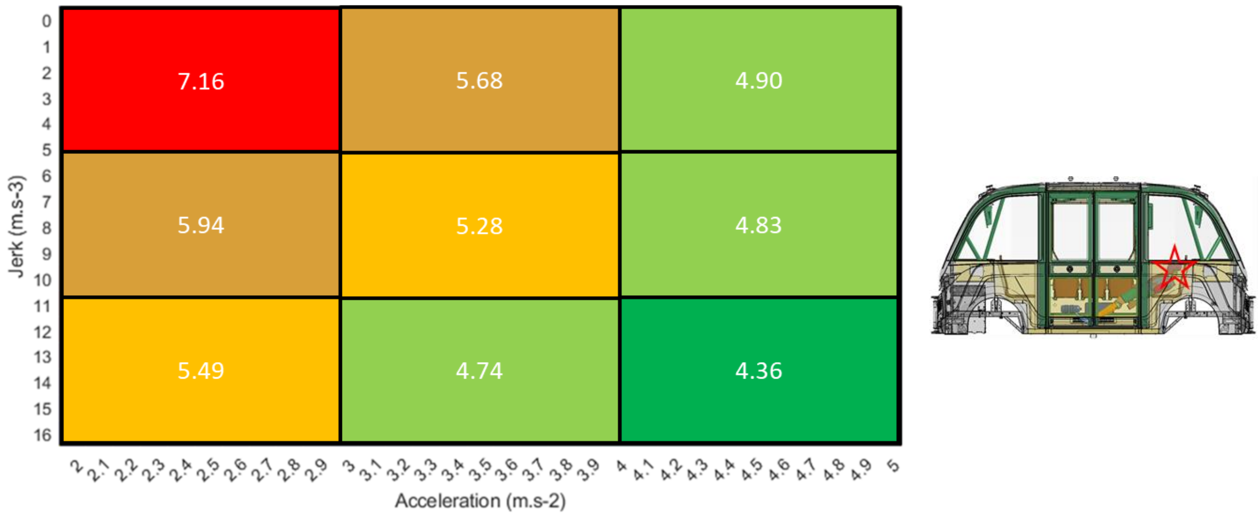


Figure 44. Maximum head speed at contact (m/s)

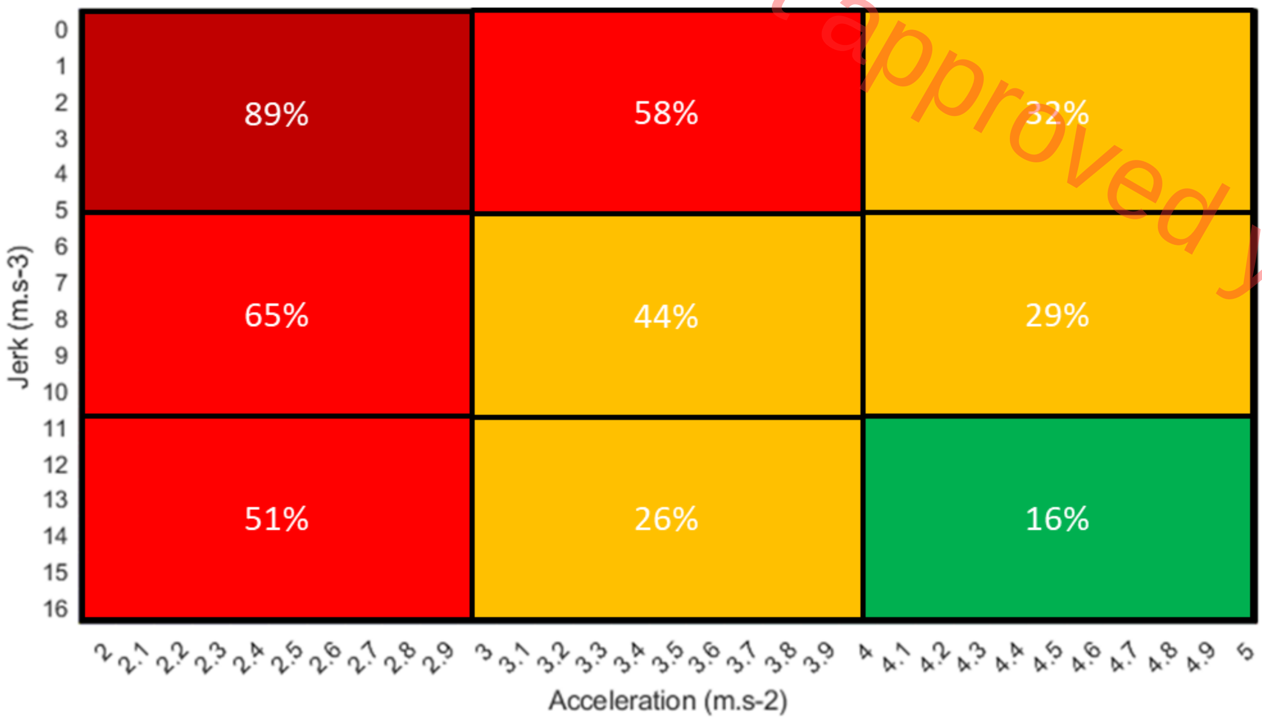


Figure 45. Head Injury Risk (%).

5.3.4 Conclusion

The analysis confirmed the concerns raised during the literature review related to the injury risk for standing passengers losing balance in case of emergency braking.

Even for low jerk/deceleration values, the speed of head at contact was important: 7.2 m/s for low intensity braking (3 m/s^2 deceleration @ 2 m/s^3 jerk) leading to certain severe head injury if impacting a rigid part of the vehicle such an handlebar.

Thus, we simply don't want standing passengers to ever lose their balance. This could be alleviated by not allowing standing passengers or ensure they maintain balance by staying in the 'safe zone' when braking:

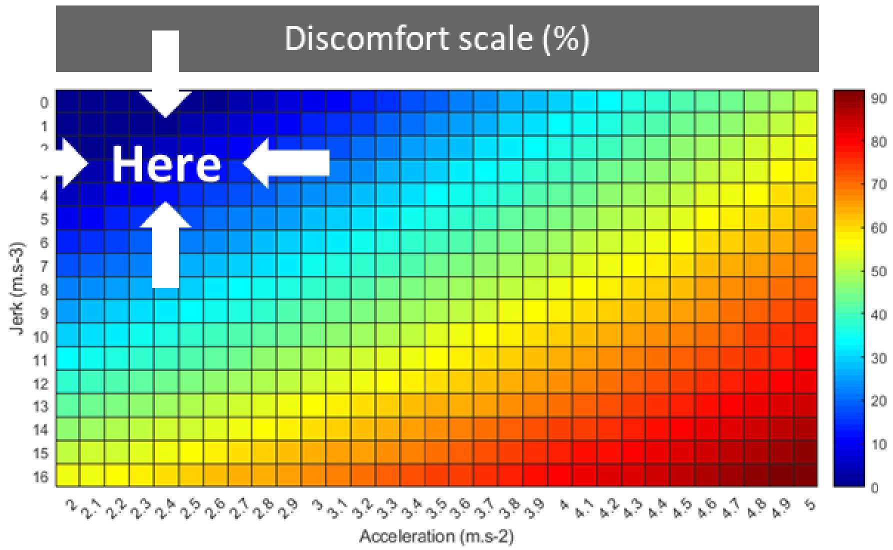


Figure 46. Safe zone based on the passenger discomfort scale (adapted from Robert & Vallée, 2014).

The risk predictor is composed of the falling risk regression defined by Robert & Vallée (2014) which associates the jerk and the acceleration with the risk of falling. It was provided to the partners as an Excel file.

5.4 Head injury risk for pedestrians in case of collision

5.4.1 Preamble

In Section 5.2, collisions of vehicles against pedestrians have been extensively addressed. Investigations have shown that the vehicle front-end design and the impact velocity have a significant influence on the injury risk of pedestrians and cyclists. The human head is the most critical body part to protect from pedestrian injury as consequences can be devastating. The Head Injury Criterion (HIC) which is directly related to the head dummy kinematics (accelerations could be used for evaluating the risk of pedestrian head injury with the front-end of an AV but detailed information about the head kinematics at impact and environments are needed. Physical tests using cadavers or simulations are usually used to extract correct impact conditions. It was beyond the budget and scope of the project to implement such physical tests.

Numerical simulations involving the front-end of the NAVYA minibus impacting a virtual pedestrian were the chosen approach. It will identify the relationship of pedestrian injury to collision speed, impact location on an autonomous vehicle.

5.4.2 Methods

A finite element model software was used to simulate impact. In the simulation, a crash test dummy and child model representing a crossing pedestrian were placed in front of a vehicle model representing an impacting automated minibus. The vehicle is subjected to an initial velocity, impacting the pedestrian to the front of the vehicle. It should be noted that due to data availability, the materials used when developing the vehicle model were assumed, referring to common forms in existing vehicle models. Therefore, the model used can't be considered to be an actual model of the vehicle used during AVENUE, whose materials' mechanical properties could well be different.

5.4.2.1 Vehicle model

The geometry of the vehicle model used in this study is based upon the minibus vehicle developed by NAVYA (Figure 36). A Finite Element model of the front vehicle was generated based on the CAD surfaces provided by NAVYA. The vehicle model included the front-end of the vehicle: panel, LIDAR, grill, and window (Figure 47). Other components were not modelled but their equivalent mass and inertia properties were included in the model.

Components were meshed with 300 000 quadrilateral 2D shell elements. Automated element meshing algorithms included in Altair Hypermesh™ (Altair, 2019) were used to generate the initial mesh, but manual editing and refinement was expected on all meshes created. Ultimately, the mesh density of components was determined by automatic mesh sensitivity studies and an element size of 10 mm was chosen.

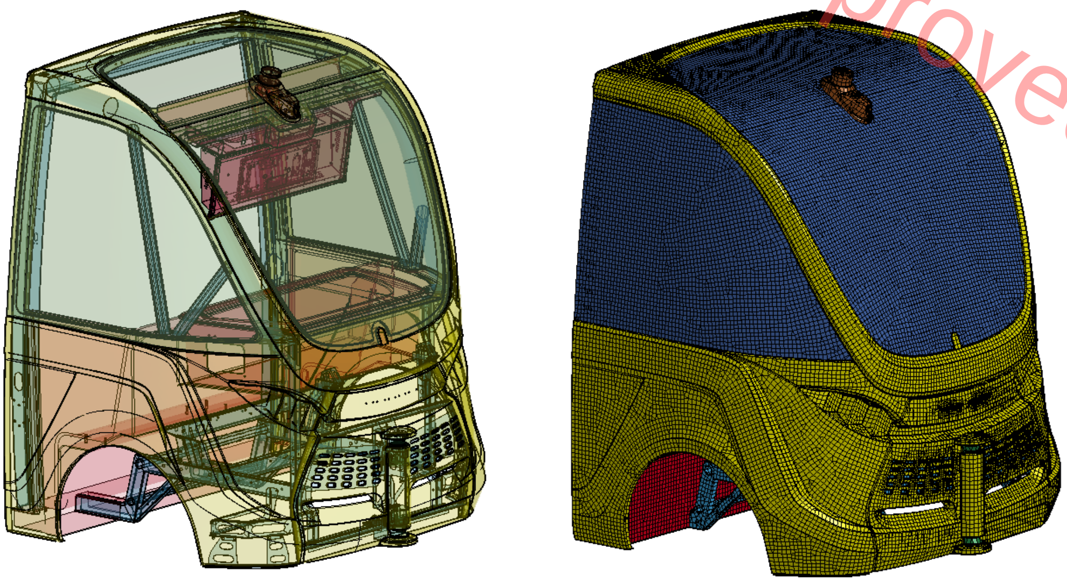


Figure 47. Vehicle front-end model.

It was crucial for the robustness and accuracy of the simulation that the stiffness of the vehicle components in contact with the pedestrian was properly implemented. However, such information which involved material and failure characterization through impact testing was not provided for the NAVYA vehicle. As it was beyond the scope of this project to perform such characterization, such materials were assumed referring to common forms in existing vehicle models. For example, the panel material which initially was a 4 mm thickness ABS was replaced with a mild steel panel with a thickness of 1.0 mm (commonly used for mid-size sedan) and a three-layered laminated glass was assumed for the windshield. Components that will never be in contact with the human were modelled as rigid bodies.

The vehicle was subjected to an initial velocity that provisionally will be varied from 3 m/s (10.8 km/h) to 13 m/s (46.8 km/h).

5.4.2.2 Human body models

The standing pedestrian models were the Hybrid III 50th Percentile Male Standing model distributed by LSTC and the pedestrian version of the open-source Piper child model (Figure 48Figure 39).

The Hybrid III 50th Percentile Male Standing model (1.74 m, 75.7 kg) is a semi-deformable model that is computationally inexpensive due to its low element count. It is designed to allow output measurements like those that would be recorded by the instrumentation of a physical dummy.

The Piper child model (1.14 m, 23 kg) is a detailed human body model representing a 6 years old child (Beillas, et al., 2016) (Peres, 2018). Validated in kinematics (Peres, 2018) (Klug, Feist, Schneider, Sinz, Ellway, & Ratingen, 2018), the pedestrian model is not intended yet to predict crash induced injuries based on tissue-level criterion, but virtual instrumentation (load cell, accelerometer) is included, similar to a crash test dummy, for injury risk assessment.

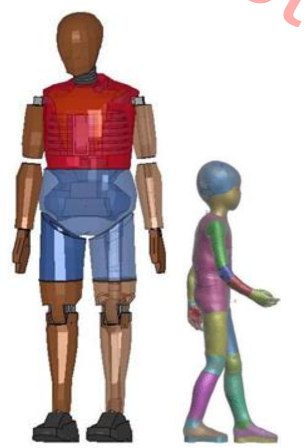


Figure 48. Hybrid III 50th Percentile Male Standing (LTSC) and Piper pedestrian model.

The pedestrian model will be positioned in front of the vehicle at different locations and orientations to cover the vehicle space (Figure 49).

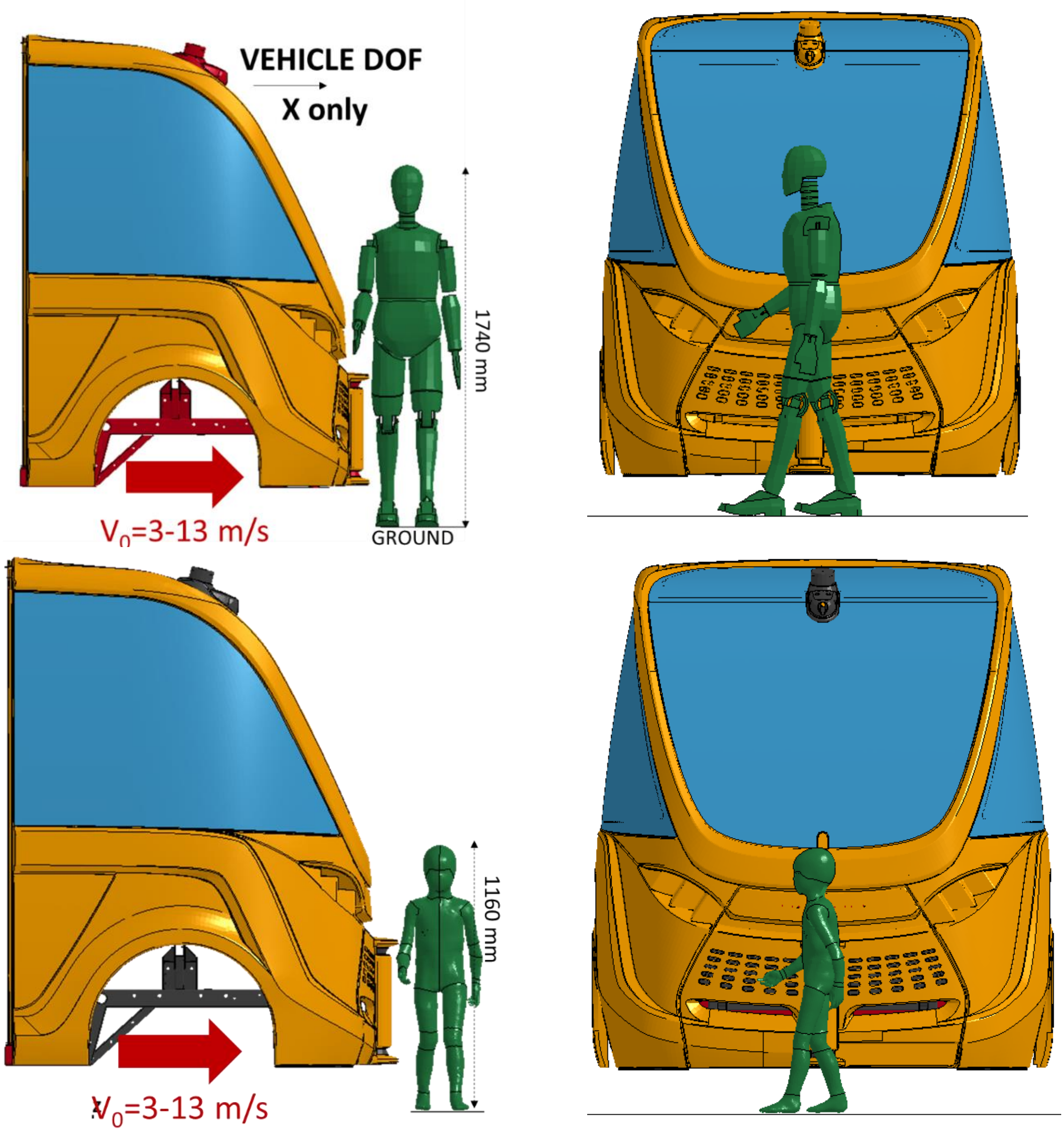


Figure 49. Model integration with vehicle.

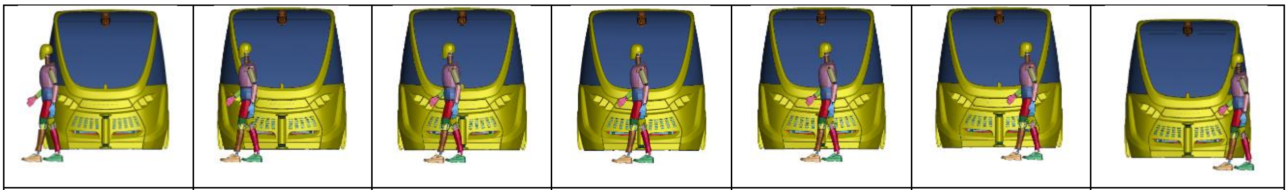
Pedestrian kinematics relative to the vehicle will be quantified and focus will be on the head kinematics at impact. From the contact forces and head accelerations obtained in the simulations, the Head Injury Criterion and the associated head injury risks will be computed.

5.4.2.3 Simulation matrix

The simulation matrix incorporated a structured sampling of the parameter space using a full factorial design of the following parameters:

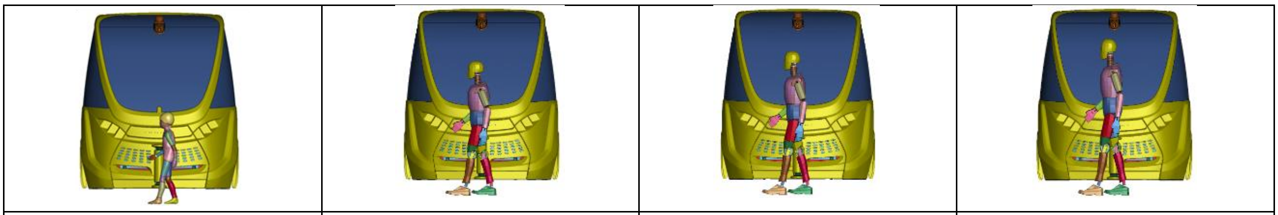
- *Position along front-end* (7 levels)
- *Height* (4 levels)
- *Vehicle speed* (4 levels)

A total of 112 simulations was performed.



-866 mm	-500 mm	-133 mm	0 mm	133 mm	500 mm	866 mm

Figure 50. Position along front-end.



114 cm	162 cm	174 cm	189 cm

Figure 51. 3 adults heights and 1 child.

2 m/s	5 m/s	8 m/s	12 m/s

Figure 52. 4 vehicle speeds.

5.4.2.4 Injury risk predictor

After completion of the simulation matrix, a statistical model estimating head injury risk as a function of the collision speed will be developed (Figure 53). Head injury risk will be given as probability to sustain a certain injury level, using the Abbreviated Injury Scale (AIS) (e.g. risk given as probability of AIS ≥ 3 for head injury).

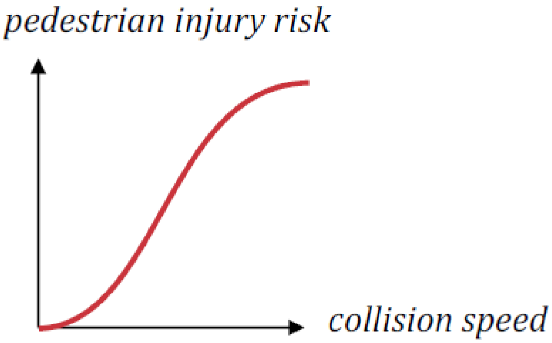
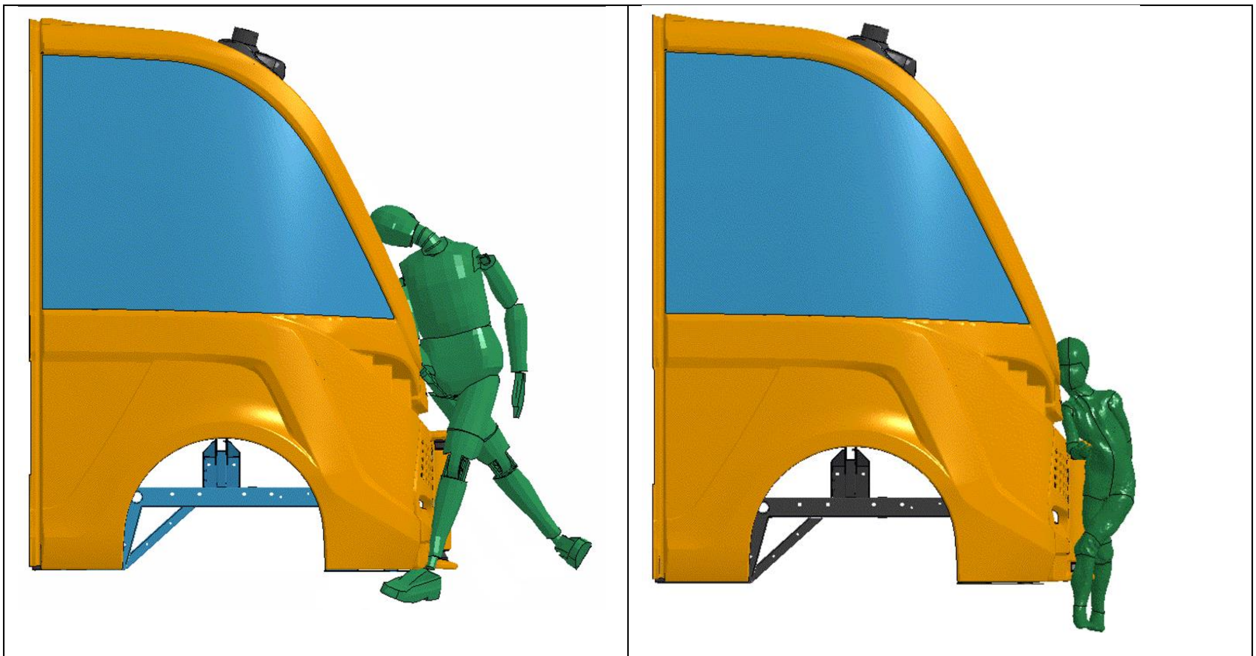


Figure 53. Risk (e.g. AIS ≥ 3 probability) as a function of dynamic parameters

5.4.3 Results

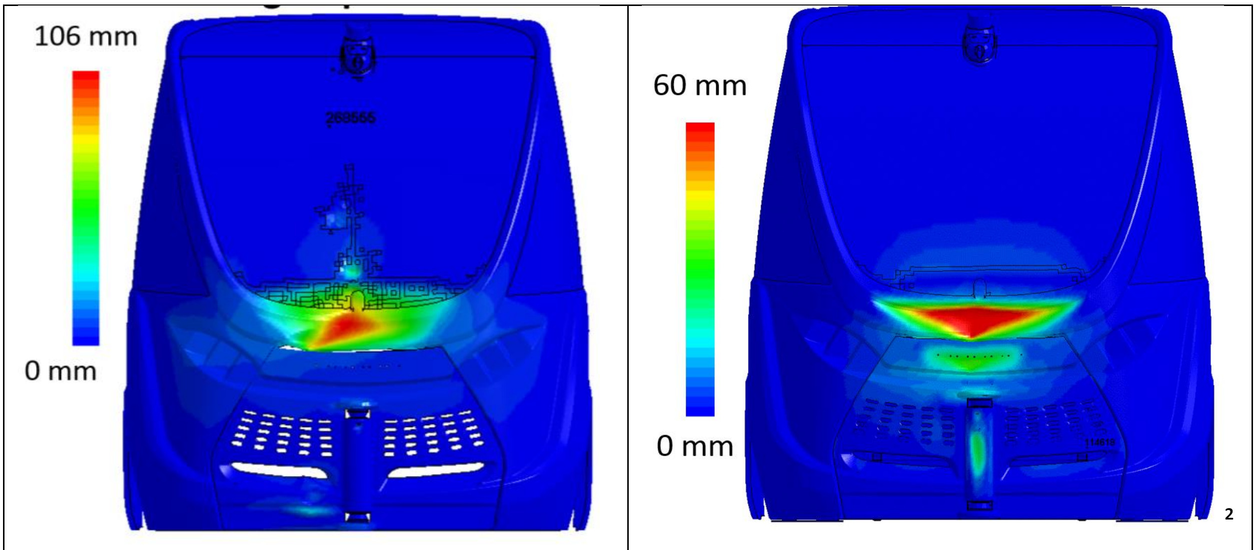
5.4.3.1 Impact sequence

Key differences between the trajectories of the dummy and the child model were observed due to the difference of stature (Figure 54). The adult model wraps around the front panel and its head hits the centre of the windshield, which cracked under the impact (Figure 55). The child model was struck by an almost flat and vertical surface due to its lower centre of gravity. As a result, very little rotation is observed which lead to its head hitting the bonnet leading edge.



Adult model | Child model

Figure 54. Pedestrian impact locations.



Hybrid III 50th Percentile Male Standing model | Piper child model

Figure 55. Front vehicle deformation after impact.

5.4.3.2 Head impact velocity

The head impact velocity V_{Head} relative to the vehicle is available in Figure 56. It was determined that a head impact speed of 40 km/h (Euro-NCAP conditions) against a minibus represented a pedestrian impact at 38 km/h (Figure 37). The average difference in velocity ΔV between the vehicle $V_{Vehicle}$ and the head V_{Head} was 2.09 ± 0.30 km/h. The linear regression performed between V_{Head} and $V_{Vehicle}$ could be used to adjust vehicle pedestrian evaluation protocols to account the specificity of an AV front-end shape.

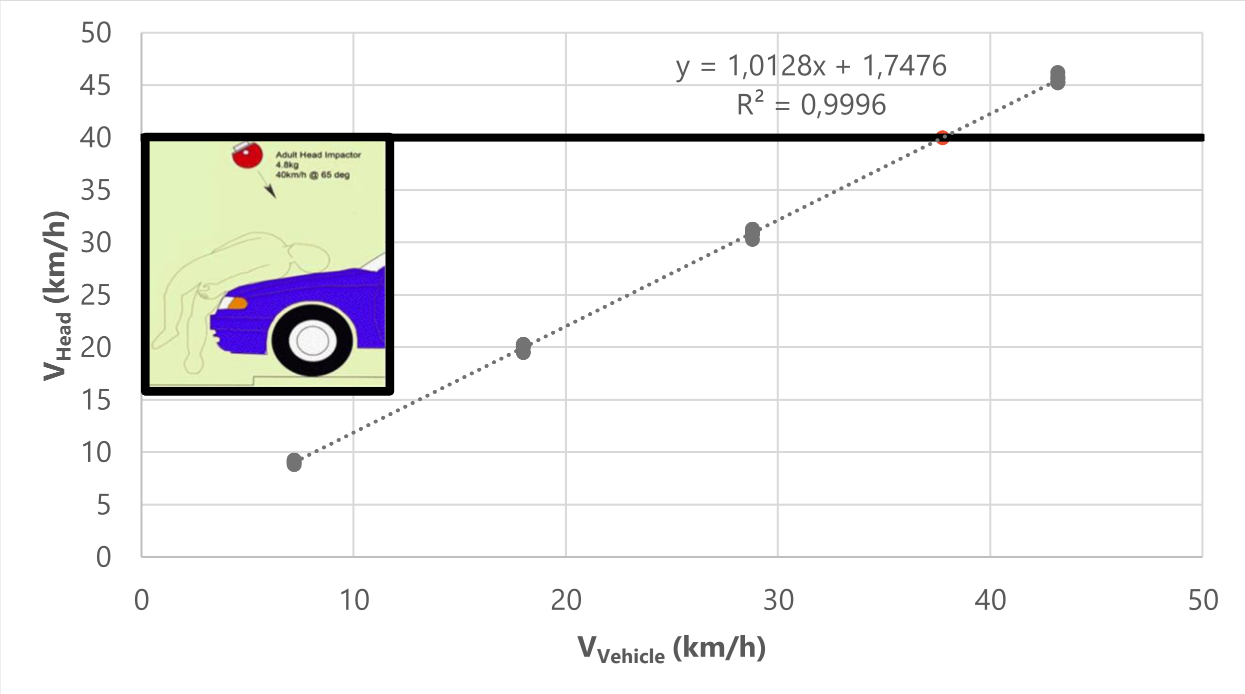


Figure 56. Determination of the equivalent speed in consumerist tests for the AV.

5.4.3.3 Head Injury Criterion

Figure 57 summarizes the results obtained for each simulation regarding the HIC. The child model was associated with a significantly higher HIC than the adult models. This can be explained because the impacted component by the child, bonnet leading edge represents a very stiff structure and can lead to serious head injuries. The height of the adult was not a significant parameter influencing the HIC and was therefore excluded.

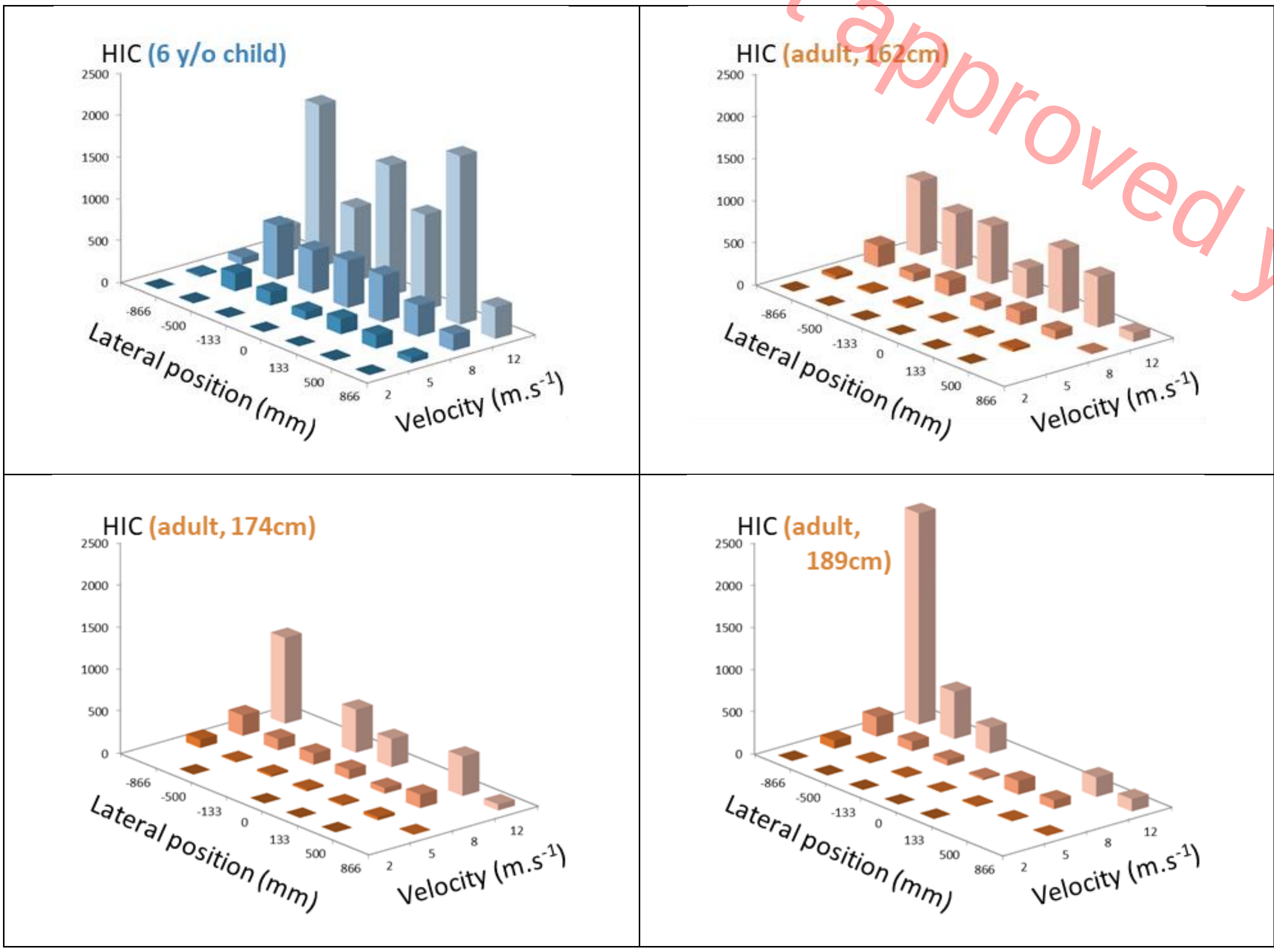
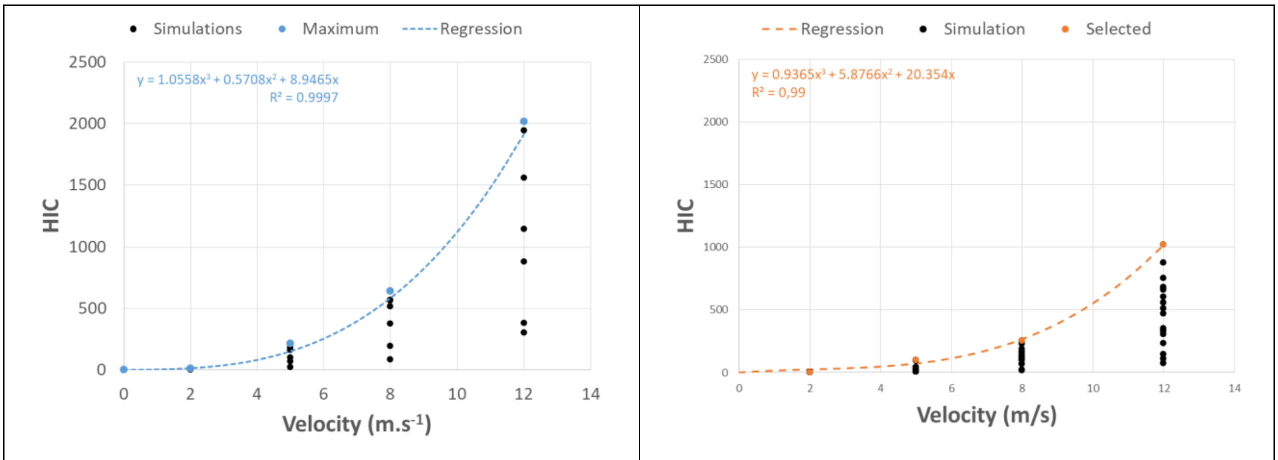


Figure 57. HIC results.

5.4.3.4 Injury risk predictor

A statistical model estimating HIC as a function of the collision speed (the most dominant factor) was developed from the highest HIC value for the child and the adult (Figure 58). The resulting probability of skull fracture was then computed from these HIC regressions (Figure 59). Relevant injury risk levels and their associate velocities are provided in



(6 y/o child)	(Adult)

Figure 58. Regression on worst HIC value for each speed step.

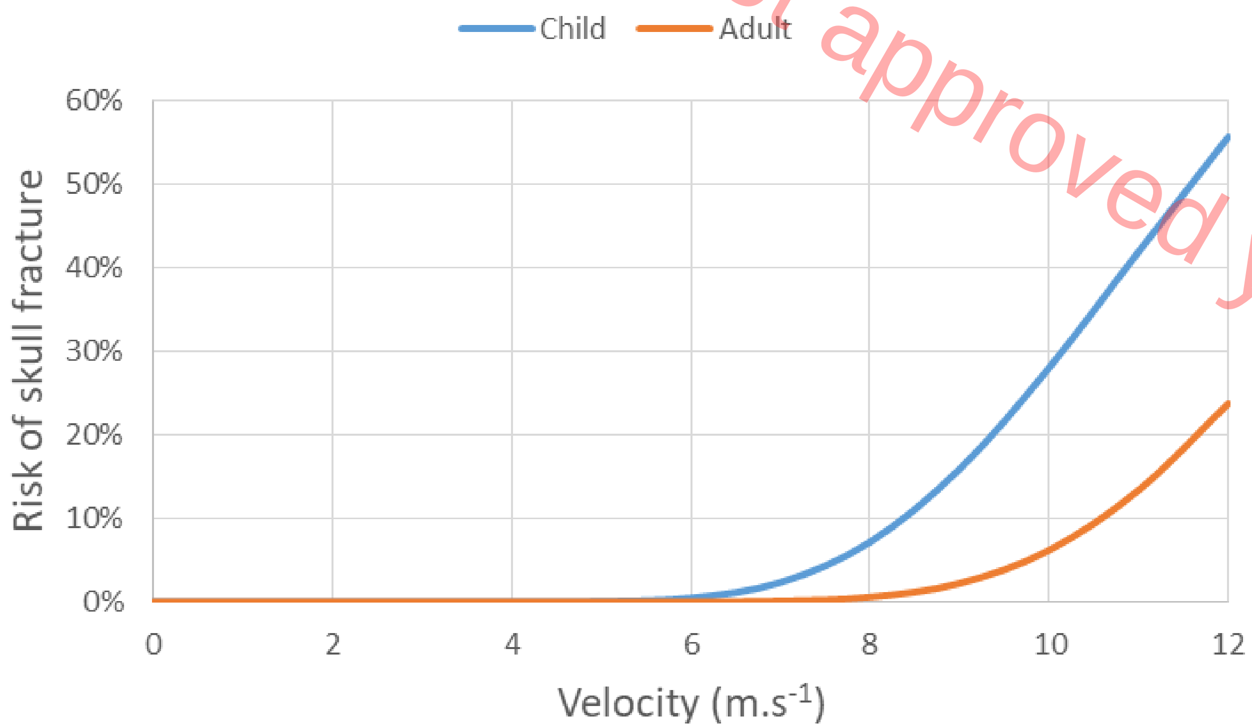


Figure 59. Resulting risk of skull fracture.

	Collision speed			
Risk of skull fracture	**Child**		**Adult**	
1%	6.4 m/s	23.0 km/h	8.4 m/s	30.1 km/h
5%	7.6 m/s	27.4 km/h	9.8 m/s	35.2 km/h
10%	8.4 m/s	30.2 km/h	10.6 m/s	38.1 km/h
25%	9.8 m/s	35.3 km/h	12.1 m/s	43.6 km/h
50%	11.6 m/s	41.8 km/h	14.1 m/s	50.6 km/h

Figure 60. Head injury risk levels.

The injury risk predictor is composed of the child HIC regression from the collision velocity and the injury risk curve linking HIC to the risk of skull fracture. It was provided to the partners as an Excel file.

5.4.3.5 Limitations

Only severe head injury (skull fracture) was covered, and only during the first impact with the minibus.

Pedestrians can have complex kinematics after initial impact and could sustain even more severe injuries when impacting the pavement.

Less critical, but still serious injuries (e.g. concussion) can also happen at lower HIC / speed values.

Only static pedestrians were tested. For e.g. cyclists, their own speed may directly be added (depending on trajectories) to the minibus speed.

6 Scenarios simulations

Simulations aim at **confronting the automated minibus – and its characteristics – to specific situations**, and measure the resulting kinematics (position, speed, acceleration). Those kinematics properties are then used to assess whether the simulated situations are handled by the vehicle in a safe way.

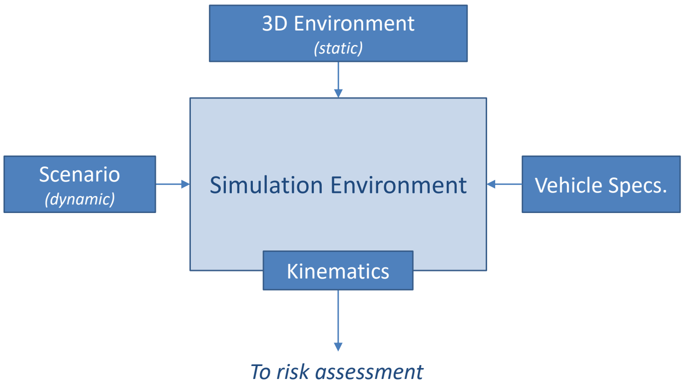


Figure 61. Scenarios simulation scope

6.1 Simulation environment architecture

A simulation environment had to be created. Its generic architecture is presented here. Actual implementations made within tasks 6.1 will then be succinctly presented. Further details are available in deliverables D6.3 and D6.4.

6.1.1 Simulation inputs

The inputs of a simulation are:

- **The vehicle specifications**, which include sensors location and performance, perception and control software behaviour, but also physical characteristics such as weight and braking performance;
- **A scenario**, which describes the intended manoeuver of the autonomous vehicle, but also the behaviour of surrounding actors (e.g. other vehicles, pedestrians) or more generally, the dynamic content of the simulation which is not under the autonomous vehicle's direct control. This may also include, for instance, traffic lights states and weather. Scenarios are provided to task 6.1 as *logical scenarios.* Those consist in high level descriptions of vehicle and other surrounding actors manoeuvers, identification of parameters contributing to the scenario outcome (i.e. initial positions, manoeuvers characteristics, static obstacles or visual occlusions), and possible values or distributions of those parameters. As one simulation corresponds to one specific set of parameters values, i.e. to a *concrete scenario*, sampling from logical scenarios and translation to a concrete scenario description file format must be performed prior to simulation.
- **A virtual environment**, which describes the static properties (e.g. geometry) of surroundings.

All those inputs have important impact on the simulation outcome and may be independently changed and combined to study the contribution of various factors to the resulting performance.

6.1.2 Internals

The simulation environment itself consists of various components:

- A **3D environment simulation tool**, which places and moves the different actors of the scenario in the chosen virtual environment. It includes **virtual sensors** which generate streams of data based on the relative positions of objects and sensors' own properties. Those virtual sensors may simulate complex physical phenomena to generate realistic raw data, relying on fine simulation of external conditions such as e.g. weather. In such case, perception algorithms themselves can be included in the simulation and tested. They may also and otherwise generate higher level data, bypassing the fine simulation of perception to directly provide detected objects based on simpler properties (field of view, range…).
- A **controller**, which generates steering, acceleration and braking commands based on the sensors' streams. This controller may be the actual software embedded in a specific vehicle under study, in which case we will describe the process as a "*Software-in-the-Loop"* simulation. It may also be a simplified version with a simpler parameter set to ease wide range parametric studies. The later was the approach favoured in AVENUE.
- A **dynamic model of the vehicle**, which models the way that the vehicle reacts to the commands provided by the controller, depending on its mechanical characteristics (e.g. weight). This model therefore takes the controller commands as inputs and returns the motion characteristics (i.e. kinematics) of the vehicle under study. These kinematics are the desired output of the whole simulation, but are also fed back to the 3D environment simulation tool to properly move the vehicle in the environment. This continuously changes its perspective of the simulated world, and the resulting sensors streams, as the simulation goes on.
- Finally, as this architecture requires various software modules to communicate together as a closed-loop system, some kind of **communication framework** is usually required.

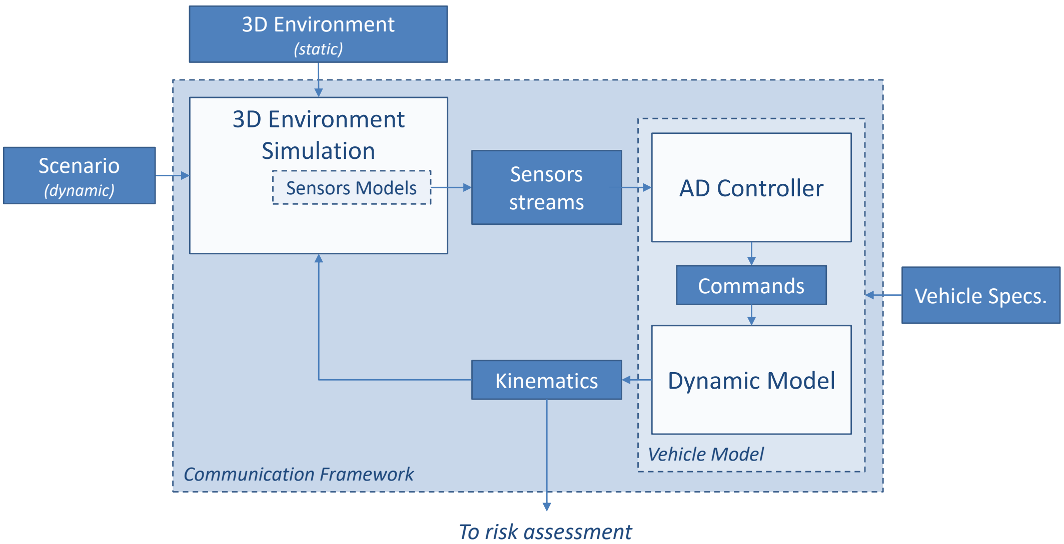


Figure 62. Simulation environment components

As the aim in AVENUE isn't to provide fine-tuned simulations reproducing very specific vehicle behaviour under very specific conditions, but rather to identify the sensitivity of safety to the main characteristics (e.g. sensors amount and location, detection latency) of a potentially not-yet-created vehicle, "ideal sensors" providing high level detected objects and simplified controller logic were favoured.

Two successive approaches to implement a toolchain corresponding to the aforementioned architecture were experimented. The first one was built around the CARLA simulation tool, an open source tool under continuous development, and the other one around VTD, an established commercial package.

6.1.3 Simulation outputs and risk assessment

The outputs of the simulations consist of **kinematics**, i.e. position, speed and acceleration profiles of the minibus and other interacting actors. Those were used to assess the risk associated with each simulation, based on criteria obtained from the injury risk study (chapter 5, page 47).

Principal criteria used in the assessment were:

- External users safety:
  - Minimum distance between the minibus and the closest interacting user[3].
- Minibus passengers:
  - Maximum deceleration,
  - Discomfort scale, i.e. a combination of deceleration and jerk (as seen page 52).

Those criteria were implemented in AVL DRIVE ADAS, which allows computing them on each simulation run, but would also allow real-time assessment if that software and accompanying hardware was installed in running minibuses.

6.2 Implementation

6.2.1 Tool selection

The first step was to select a tool which would be both sufficiently affordable for the AVENUE project, and meet our principal requirements:

- Support for a physical model of the autonomous vehicle to be simulated (e.g. break behaviour depends on weight and grip),
- Support for modelling sensors (i.e. provide real-time sensor output from the simulated scene),
- Ability to interface perception and decision software,
- Support for vulnerable road users, notably pedestrians,
- Ability to control and finely define other actors' behaviour, in the form of scenarios which can be run in a reproducible way.

Following comparison of multiple tools (Pilz, 2019), **CARLA** (Dosovitskiy, Ros, Codevilla, Lopez, & Koltun, 2017) appeared to be an excellent candidate, and has been initially selected. CARLA is free and open source software benefiting from an active community and continuous improvement. It integrates

[3] Although the injury risk study provided insights about skull fracture risk for pedestrians depending on an eventual collision's relative speed, it was decided that no collision, i.e. no null distance between the minibus and an external user could be considered acceptable.

physical models of vehicles, can model sensors, interfaces with perception/decision software notably through a bridge to ROS (Robot Operating System, ros.org), supports pedestrians, and can run scenarios, notably scenarios defined following the OpenSCENARIO standard (ASAM, 2017).

As implementation of scenarios started, however, some limitations which would have negatively impacted AVENUE appeared:

- Support for OpenSCENARIO is currently limited, excluding pedestrians until CARLA developers and VIF implemented such support;
- The included virtual environments do not provide all necessary infrastructure, particularly roundabouts, and CARLA does not support the OpenDRIVE standard to implement road networks;
- Tooling is reduced: creating and controlling simulations and models rely exclusively on users' programming through, at best, CARLA's Python API at runtime, or at worst using the Unreal Engine tools and editors, on which CARLA is based, but which would generally require recompiling the complete tool;
- Most notably, as questions arose concerning vehicle model development, using Vires Virtual Test Drive (VTD), which is a commercial alternative, started to make more sense (see below).

6.2.2 Vehicle model development approach

As previously stated, a model representing the automated minibus must also be integrated in the virtual environment. This model must include physics, geometry (sensors position), sensors themselves, and perception and decision software. Our goal at project start was never to perfectly mimic NAVYA's own minibus, but rather to develop a much-simplified model. This model could be tuned to *reasonably* match NAVYA's Arma performance, but also to easily allow testing other hypothesis regarding vehicle specifications. Such a simple model could then be used in a later parametric study, to identify what vehicle performances *should be,* in order to address such and such use cases.

However, even such a simple model requires extensive development work which would have been too much given AVENUE's resources. Two possibilities for this vehicle model have been considered:

- **Using NAVYA's actual embedded software**. For its own needs, NAVYA has already integrated their vehicles' embedded software with CARLA, meaning that scenarios developed in WP6 could have been tested with the actual software being used in currently operated minibuses. This would have consolidated the choice of CARLA for running simulations.
- **Using AVL's Model.CONNECT and vehicle simulation tool AVL Vehicle Simulation Model (VSM) to describe the vehicle's behaviour.** Those tools facilitate development and allow reaching our initial goal of a generic model. However, they run with VTD, which is commercial and rather expensive software.

Both approaches had pros and cons which are summarised in Table 7 below.

Table 7. Approaches for vehicle simulation

CARLA and NAVYA's software	**Custom model in VSM/Model.CONNECT/VTD**
+ Actual Software used in production + Reduced development effort, meaning WP6 can develop more/better scenarios + Already implemented in CARLA	+ WP6 retains control of its own vehicle model + WP6 can perform an unlimited number of simulations, as and when needed + The model can be simple and hence flexible, allowing testing multiple hypotheses, then defining what performance of a vehicle *should* be.
- Unknown mechanical /dynamics model - Simulations must run at NAVYA to protect their intellectual property, making project rely on more complex, likely less efficient interactions - Model is not flexible: only actual/current software and sensors can be used	- Significant development work - Relies on expensive Vires VTD.

In the end, the second option was favoured, as VTD could be obtained for a very favourable "academic" cost within the context of AVENUE. A toolchain relying on VTD and AVL software was therefore implemented (see below), and a simplified but representative vehicle model was developed.

However, a large amount of scenarios from the scenario catalogue were still implemented in CARLA, using its supported subset of OpenScenario, allowing later reuse.

6.2.3 The AVENUE simulation toolchain

A modular toolchain, built around the proprietary Vires VTD (Virtual Test Drive) simulation tool has been developed.

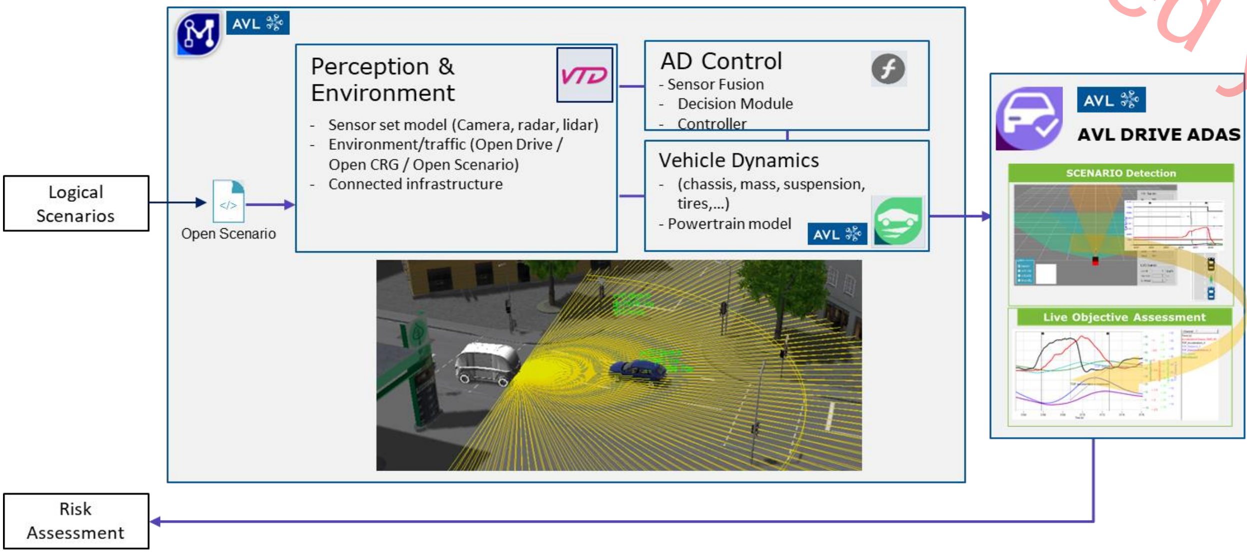


Figure 63. Schematic representation of the toolchain

The toolchain is composed by many modules, each performing a specific role in the simulation context, and communicating based on an open co-simulation platform, **AVL Model.CONNECT**:

- The **virtual environments** used in the simulation were created using **Road Designer ROD**, which provides an interactive road network editor with extensive libraries of 3d objects, textures etc. that can be used to create a realistic 3D environment.
- The **3D Simulation Tool** is **Vires VTD**. It models the environment (roads, weather, etc.) and the other actors of the simulation (vehicles, pedestrians, etc.), as well as the vehicle's sensors. It also generates the 3D image visualization of the simulation.
- The **Controller**, i.e. the algorithm responsible for computing the vehicle's actions, reading sensor information, running decision-making and control algorithms, and outputting the required signals for the actuators, is an AVL made software consisting of a longitudinal controller and a lateral controller, and is described further below.
- The **dynamic model of the vehicle** is implemented in **AVL VSM**. It models the vehicle and its dynamics, calculates the response to the actuators and outputs the vehicle state (speed, position, etc.).

Model.CONNECT couples all the aforementioned tools into one single environment and manages the interaction between them. It provides an interface for configuring the simulation settings and parameters, and for visualizing the results.

AVL-DRIVE ADAS monitors the various simulation variables generated by the other programs in order to evaluate the driving performance (in terms of safety, comfort, etc.) and attribute a score to the events during simulation.

The aim of this toolchain is first to allow virtual testing of a wide range of situations, but it can also be used with real data measurement. As a matter of fact, the safety evaluation tool can also be connected to the real vehicle to allow performing “Model-in-the-Loop (MiL)”, as shown on Figure 63, or Vehicle-in-the-Loop (ViL) testing, as seen below.

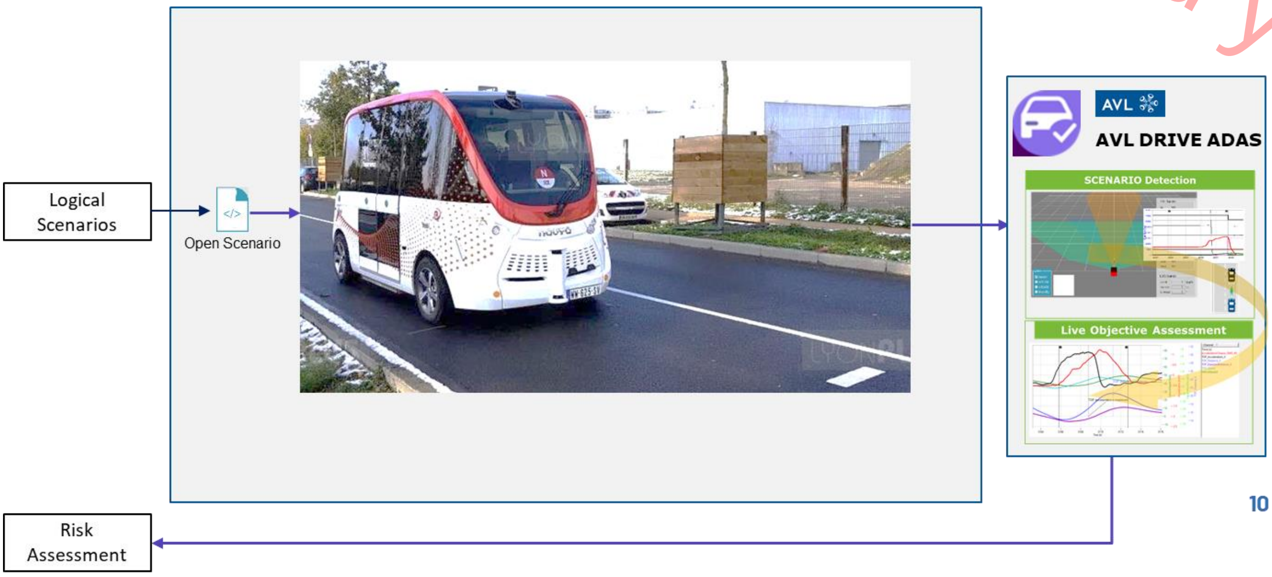


Figure 64. Vehicle-in-the-Loop assessment

6.2.4 The AVENUE vehicle model

As previously written, the model includes physics, geometry (sensors position), sensors themselves, and perception and decision software. When developing such a model, the favoured approach was to create a “generic” model which could be tuned to reasonably match the minibus used in AVENUE, while allowing exploring possible variations.

For the **physics**, i.e. chassis geometry, actuators characteristics, weight etc., a model was created using **AVL VSM.** It was parametrised by either directly entering Navya Arma’s known characteristics, or by deducing parameters from known properties of the vehicle (for instance, the wheels’ maximum steer angle was derived from the minimum turning radius).

For **sensors**, although VTD allows creating realistic sensors modelling actual physical characteristics and providing a simulated raw data flow, *PerfectSensors* were favoured. Those provide accurate information about objects which are detectable in their field of view, while still simulating said field of view and masking effects. This implies that although simpler, those are still sensitive to sensor location, and hence properly model blind spots. This also means that **perception** is a non-issue and notably, makes sensors’ fusion trivial.

For the decision software, simple **lateral and longitudinal controllers** were created. Both implement servo loops minimising, respectively, the lateral distance to a ‘virtual’ lane, and either the difference between the actual speed and the desired speed on each road section (when free driving), or the difference between the actual timegap and a desired timegap when a target is on the path. Those controllers were calibrated using actual vehicle data:

- For 'normal' driving: the same data from Copenhagen used in chapter 4 (page 34),
- For emergency braking: test track data provided by Keolis.

Further details about simulation environment creation are given in deliverables 6.3 & 6.4.

6.3 Simulations

Several scenarios were simulated while varying their relevant parameters (resulting in hundreds of simulation runs for each scenario). At first, task 6.1 created a complex environment reproducing the geometry of an existing intersection at the Lyon's test site, which allowed testing the complete toolchain on multiple scenarios. It then focused on the challenge of a pedestrian crossing while being initially masked by parked vehicles, as this was identified as a major concern during scenarios ranking. The latter is succinctly presented here, while much more details are available in deliverables 6.3 & 6.4.

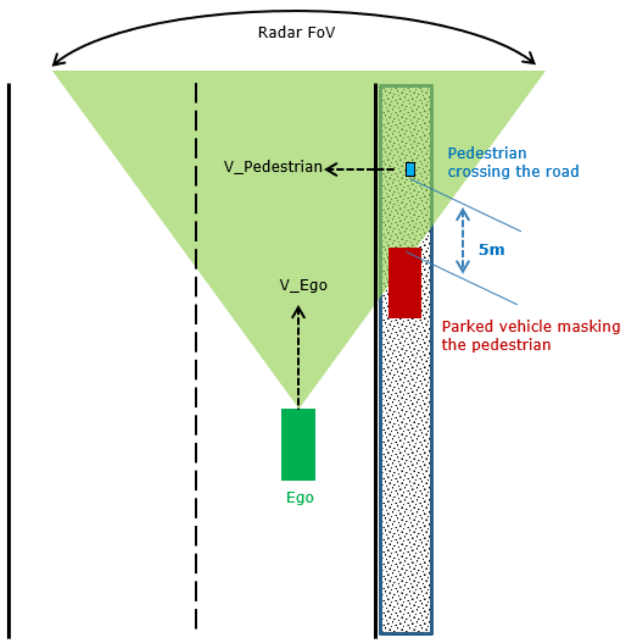


Figure 65. Pedestrian crossing with masking scenario

This example scenario consists of a pedestrian crossing from near side to far side, perpendicular to the road, 5 meters after a parked vehicle masking the pavement. Many parameters could be varied (minibus position when pedestrian starts crossing, pedestrian trajectory and starting position in relation to the masking obstacle, road geometry…). For the sake of the example, only 3 are varied in a parametric study: the speed of the ego (i.e. the minibus) from 10km/h to 20km/h in 2.5km/h increments, the speed of the crossing pedestrian from 1km/h to 10km/h in 1 km/h increments, and one vehicle characteristic: the front sensor's field of view, from 60° to 100° in 20° increments. Two main key performance indicators are considered: minimum *relative distance between the minibus and the pedestrian*, which is an indicator of the pedestrian's safety, and *discomfort scale* (as seen page 52), which is an indicator of passenger's safety. For this simple example, a set of 150 simulations were therefore run and their results aggregated. Those are presented in below.

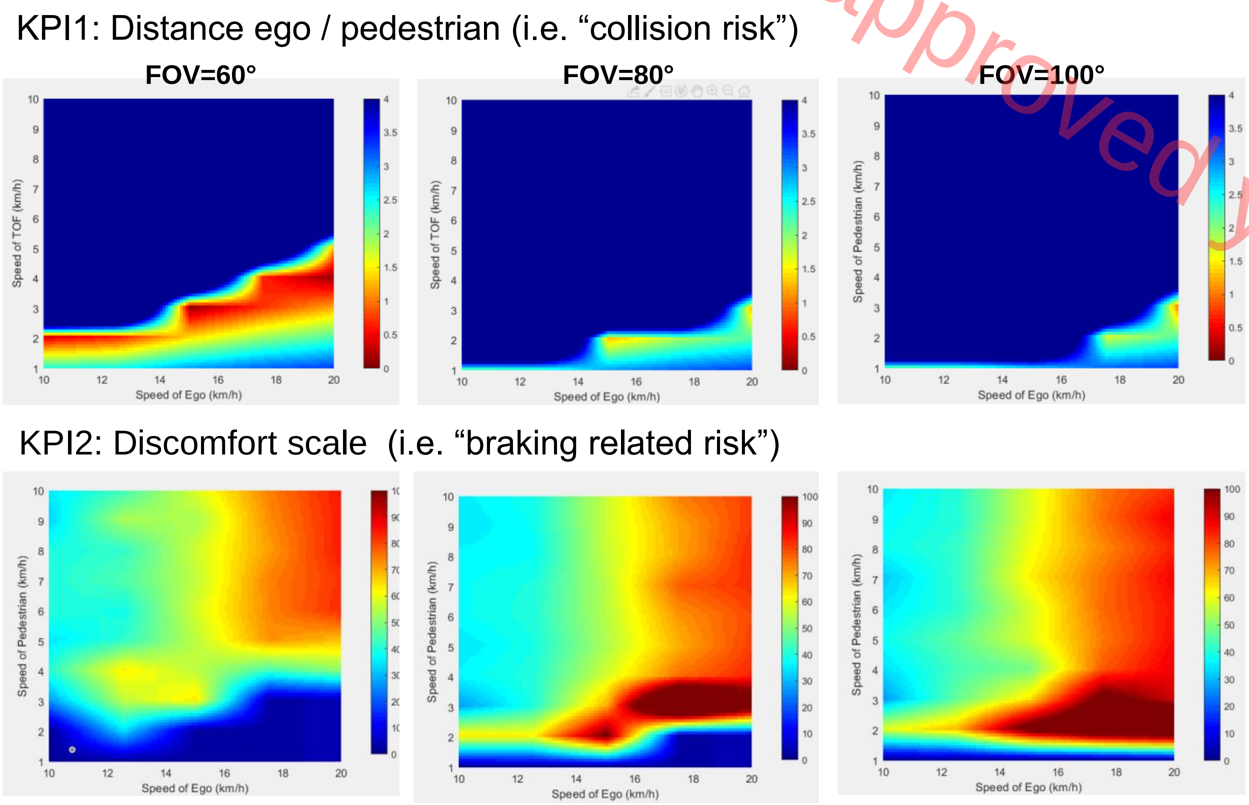


Figure 66. Pedestrian crossing simulations results

These results illustrate the kind of **trade-offs** that appear when studying such issue: although widening the field of view can drastically reduce the risk for the pedestrian to be hit by the minibus, this would be at the expense of passengers' safety, as a very late braking, made possible by the widened field of view, has to be much harsher to have any positive effect.

In such case, enhancing the vehicle's perception would only really be beneficial if passengers' safety can also be ensured, i.e. if no passenger can be found standing in the minibus. This is currently enforced by safety stewards, but would require some kind of apparatus in their absence. This is not entirely inconceivable: the project has also demonstrated that passengers' postures and attitudes could be successfully and automatically detected and analysed from video feeds using artificial intelligence. The vehicle could rely on such technology to adapt its speed to the passengers' postures, while informing them that should they all sit down, the minibus could ride faster.

Other possibilities to address such scenario could be both "high" and "low" tech: the vehicle already relies on **V2X** systems to handle traffic lights. Such technology could be used, associated with sensors located on the infrastructure, to "see" behind static obstacles and corners. The cost and functional safety risk of such system are not negligible, though. Particularly conspicuous Vehicle Audio Alert System (**VAAS**) could also prevent pedestrians crossing just in front of the vehicle in the first place, at least if they're not using headphones while doing so. Finally, although we certainly won't advocate cutting roadside trees, **infrastructure choices** can also help minimise risk: parking spots directly on the near side of an automated minibus path should, for instance, be avoided whenever possible.

7 Conclusions

A methodology has been developed, and the corresponding tools have been implemented, resulting in a practical toolchain that can be used to assess safety of automated minibus in a virtual environment. This methodology relies on actual data, collected from test sites, to characterise the operating environment in terms of a succession of scenarios, defined by their parameters. This results in a virtual representation of the challenges that an automated urban vehicle has to address, which can then be used in numerical simulations. Key performance indicators, to assess the criticality of each individual simulation have been selected and/or developed.

The methodology relies on several steps, as described on Figure 67 below.

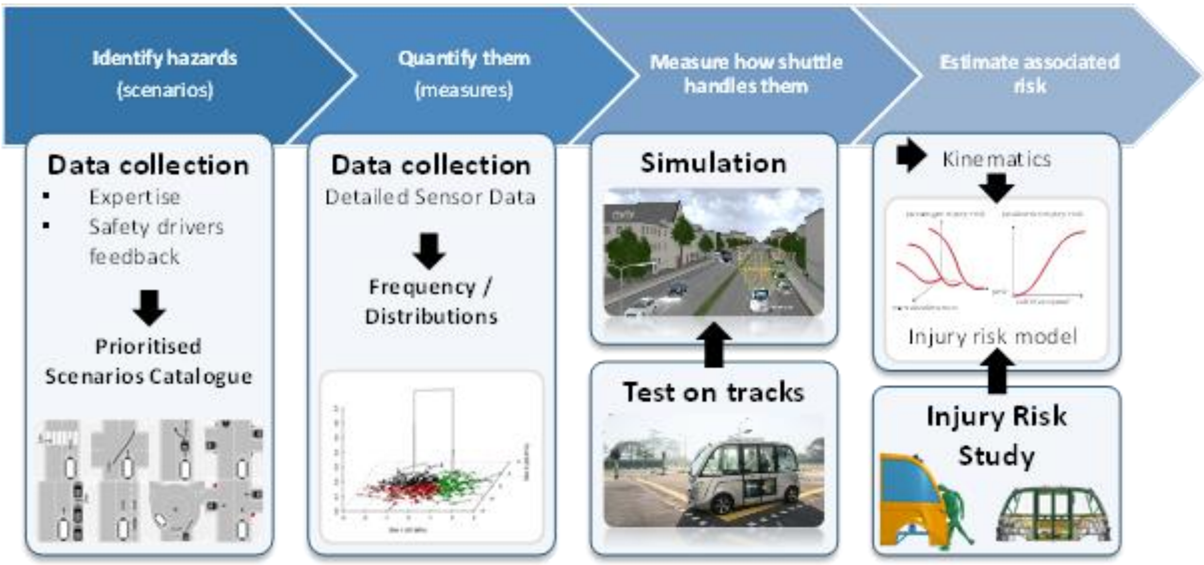


Figure 67. Methodology overview

- The first step consists in <u>identifying hazards</u>, in the form of relevant scenarios. As automated minibuses follow a predefined path at a predefined speed, we defined relevant scenarios as ***any circumstances which mandated significant alteration of either path or speed (e.g. braking) to avoid a collision***. A scenario catalogue was constituted, based on pre-existing knowledge on urban accident scenarios, examination of test sites' infrastructure to deduce possibly problematic interactions, and operator feedbacks during interviews and a focus group. It was then ranked / prioritised by the operators and their safety drivers using an innovative approach.

- The second step consists in <u>quantifying those hazards</u>. This steps allows giving a weight -a probability- for each scenario to be met, not only in broad terms (occurrence of a scenario of a certain category, i.e. a *functional scenario* as per (Menzel, Bagschik, G., & Maurer, A. M., 2018)), but also taking into account the parameters describing it which might have an impact on the outcome. Such parameters as initial speeds, relative positions etc. are summarised in the form of multivariate distributions. This relies on detailed sensor data collection and processing.

- The third step consists in assessing how the vehicle would handle each possible situation (i.e. each parameters' tuple), depending on its own characteristics (e.g. sensors location) relying on massive simulations. Behaviour of the automated minibus is simulated in a virtual environment, which provides kinematics (positions and speeds for the minibus and other relevant traffic participants). Parameters which impact the vehicle's behaviour, such as sensors' type and position, can safely be explored through that approach.

- The final step consists in estimating actual risk, by computing performance indicators for passengers and other traffic participants' safety. This requires injury risk models which take the relevant kinematics parameters as inputs: relative speed and position at collision for vulnerable road users; braking characteristics for passengers. An injury risk study was carried out to develop such injury risk models.

Figure 68 below summarises how, for one specific scenario, data collection and processing, injury risk models and simulations contribute to estimating the associated risk.

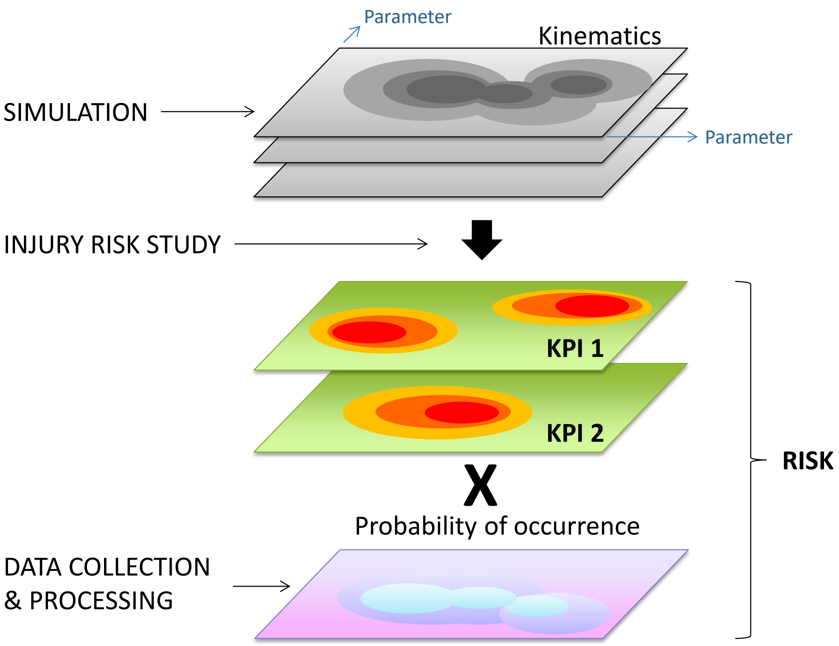


Figure 68. Application of the methodology to one scenario

Each step of the methodology has been implemented and applied at its own scale, depending on feasibility and resources constrains. Scenarios identification and ranking as well as injury risk criteria development have been done in an extensive way, while vehicle data collection and scenarios simulation were demonstrated at a smaller scale.

This allowed drawing useful observations, identifying limits in the approach, and making recommendations.

In terms of observations, the most salient probably was that, although approaches currently developed for passenger cars' ADAS and ADS validation can be used, **direct knowledge doesn't apply**. In some respects, addressing safety issues of a vehicle that 'simply' follows a pre-mapped path at a predefined speed is simpler. However, automated minibuses present their own specific challenges. Most notably, whereas passenger cars' occupants are sat and restrained, meaning that harsh braking and/or steering dynamics are not, inherently, a threat to passengers' safety and can be used to avoid hurting an external vulnerable road user; this is not the case for minibuses. In the absence of specific enforcement ensuring that every passenger is also sat and restrained in a minibus (which would likely cause capacity issues); passenger safety is a much higher concern there. This immediately leads to dilemmas where improving passengers' safety would be at the expanse of external vulnerable road users, and vice versa. This is an obvious illustration of the "trolley problem" (Thomson, 1976) and raises question about **who should decide on acceptable risks and trade-offs**. Less concerning but still significant, whereas pedestrians' protection norms and rules exist for passenger cars, those have no validity on urban minibuses, which have vastly different front shapes and rely on stiff and protruding sensors to operate. An extensive study was carried out in AVENUE to gain adapted and applicable knowledge in that respect.

Another observation was that, independent from potential data sharing issues within a collaborative project, **large scale, extensive and continuous data collection** of vehicles' operation was not performed, even for the vehicle's manufacturer's own internal needs. This surprised us as from our perspective, deployment projects are exactly the circumstances where everything should constantly be recorded and analysed, for safety concerns among others.

In terms of limits in the proposed approach, the following can be said:

- Although parameters for one simulated scenario can be varied in an automated way, the initial scenario creation is a manual and labour intensive process, which does not scale well. A massive automation effort would be welcome but not trivial, notably to model infrastructure variants. In that respect, site-specific simulation before deployment would be possible, profiting from initial site mapping to model the infrastructure.

- Although an important effort resulted in a vast amount of identified functional scenarios, comprehensiveness cannot entirely be assured. Comprehensiveness of the *parameter space* identified as relevant for each scenario also cannot be assured either. Only extensive data collection and analysis following the proposed approach, relying on multiple sources, can improve confidence in the completeness of scenarios used in vehicle validation.

- The approach corresponds to the state of the art, allowing getting close to *actually demonstrate* safety. It is however a long and costly one, which is problematic in a domain where fast-paced innovation and limited funding are the norm.

Finally, the following recommendations can be made:

- Ensuring that passengers are properly sat and possibly restrained would drastically change the envelope of acceptable braking, for the benefit of both operation speed and external vulnerable road users' safety. Means to enforce that or adapt the vehicle speed if passengers are standing need to be implemented.

- Public transport operators should also be made conscious that deploying automated minibuses is nothing like using "minibuses without drivers". It is developing a completely new transportation **system**, under their responsibility, where:

1. The infrastructure is as least as important as the vehicle, and likely to require adaptations to augment the vehicle's capabilities (addition of V2I systems…) or reduce occurrence of problematic scenarios (avoid parking spaces directly at near side),

2. The vehicle's *actual* capabilities should be carefully confronted to the specific challenges imposed by each site's specificities in terms of road users, traffic and interactions.

- Public transport operators should require **methodical demonstration** of the vehicle's safety from its manufacturer, prominently in terms of **SOTIF**, as discussed in this report, but also in all dimensions relevant to safety, notably **crashworthiness and passengers protection** as well as **functional safety**.

- In terms of SOTIF, they should identify potentially difficult scenarios in their own site, and challenge the manufacturer with them.

- When pilot deployments such as those initiated in AVENUE are made **detailed sensor data should be continuously collected and analysed**:

1. Each disengagement and harsh braking should be treated as a 'bug' and strategies to progressively eliminate them put into motion,

2. Each incident, even minor, should be considered as an accident waiting to happen, and treated accordingly,

3. Each interaction with another road user should be identified, processed, summarised as a collection of relevant parameters, and contribute to a comprehensive digital representation of the environment in which the vehicle operates, allowing proper safety validation in large scale simulations.

Acknowledgement

The methodology has been refined by CEESAR, AVL and VIF, notably thanks to a joint workshop involving Philipp Quinz, Jerôme Ehrhardt, Jean-Charles Fuerxer, Johannes Jany-Luig, Omar Veledar (AVL), Michael Karner (VIF), Clément Val and Karla Quintero (CEESAR).

The scenarios catalogue was developed and maintained by Karla Quintero and Jacques Saadé (CEESAR), with help from Reakka Krishnakumar and Patrick Moro (CEESAR). The web plateform for incident collection, scenarios management and scenarios ranking has been developed by Fabien Croes (CEESAR).

The data collection and processing toolchain has been developed by Clément Val, with support from Romain Gallard (CEESAR).

The injury risk study was carried out by David Poulard (CEESAR) with support from Joris Tricaud (CEESAR).

Peter Lorenz (VIF) developed scenario simulations in CARLA, contributing to that tool's management of OpenScenario files in the process. Sehrizada Sahinovic (VIF) developed dozen of scenarios in the OpenScenario format, validating them in CARLA.

Larbi Jabine (AVL) implemented the final simulation framework using VTD, VSM and Model.Connect, and ran large scale simulations on a subset of most relevant scenarios.

References

The International Organization for Standardization (ISO). (2018, 12). ISO 26262: Road Vehicles – Functional Safety.

AAAM. (2015). Récupéré sur https://www.aaam.org/abbreviated-injury-scale-ais/

Abernethy, C. N., Jacobs, H. H., Plank, G. R., Stoklosa, J. H., & Sussman, E. D. (1980). Maximum deceleration and jerk levels that allow retention of unrestrained, seated transit passengers. *Transportation research record, 774*, 45-51.

Allum, J. H. (1983). Organization of stabilizing reflex responses in tibialis anterior muscles following ankle flexion perturbations of standing man. *Brain research, 264*, 297-301.

Altair. (2019). *Altair HypermeshTM*. Récupéré sur https://www.altair.com/: https://www.altair.com/hypermesh/

Arnoux, P.-J., Subit, D., Masson, C., Chabrand, P., & Brunet, C. (2005). Knee ligaments mechanics: From experiments to FE simulations. *Revue Européenne des Eléments, 14*, 577-600.

ASAM. (2017). OpenSCENARIO. *https://www.asam.net/standards/detail/openscenario/*.

Badea-Romero, A., & Lenard, J. (2013). Source of head injury for pedestrians and pedal cyclists: striking vehicle or road? *Accident Analysis & Prevention, 50*, 1140-1150.

Ballesteros, M. F., Dischinger, P. C., & Langenberg, P. (2004). Pedestrian injuries and vehicle type in Maryland, 1995–1999. *Accident Analysis & Prevention, 36*, 73-81.

Beillas, P., Giordano, C., Alvarez, V., Li, X., Ying, X., Chevalier, M.-C., et al. (2016). Development and performance of the PIPER scalable child human body models. *14th International Conference on the Protection of Children in Cars*, (pp. 19-25).

Bjoernstig, U. L., Bylund, P. O., Albertsoon, P., Falkmer, T., Björnstig, J., & Petzäll, J. (2005). Injury events among bus and coach occupants: Non-crash injuries as important as crash injuries. *IATSS research, 29*, 79-87.

Carpenter, R. (2003). *Neurophysiology, 4th edition.* London (UK): Arnold.

Chidester, A. B., & Isenberg, R. A. (2001). Final report - the pedestrian crash data study. *Proceedings: International Technical Conference on the Enhanced Safety of Vehicles. 2001*, p. 12. National Highway Traffic Safety Administration.

Crocetta, G., Piantini, S., Pierini, M., & Simms, C. (2015). The influence of vehicle front-end design on pedestrian ground impact. *Accident Analysis & Prevention, 79*, 56-69.

Dorn, M. R. (1998). Jerk, acceleration and the safety of passengers. *Technology for Business Needs. Birmingham, 24th–26th November*.

Dosovitskiy, A., Ros, G., Codevilla, F., Lopez, A., & Koltun, V. (2017, 11). CARLA: An Open Urban Driving Simulator. *Proceedings of Machine Learning Research, 78*, pp. 1-16.

Gayzik, S., Moreno, D., Geer, C., Wuertzer, S., Martin, R., & Stitzel, J. (2011). Development of a full body CAD dataset for computational modeling: a multi-modality approach. *Ann. Biomed Eng.*, 2568–2583.

Graaf, B. D., & Van Weperen, W. (1997). The retention of balance: an exploratory study into the limits of acceleration the human body Can withstand without losing equilibrium. *Human factors, 39*, 111-118.

Gurdjian, E. S., Roberts, V. L., & Thomas, L. M. (1966, 9). Tolerance curves of accelerations and intracrianial pressure and protective index in experimental head injury. *Journal of Trauma and Acute Care Surgery, 6*, 600.

Halpern, P., Siebzehner, M. I., Aladgem, D., Sorkine, P., & Bechar, R. (2005). Non-collision injuries in public buses: a national survey of a neglected problem. *Emergency medicine journal, 22*, 108-110.

Herbrich, R. a. (2007, January). TrueSkill(TM): A Bayesian Skill Rating System. *Advances in Neural Information Processing Systems 20*, pp. 569-576.

Hiroaki, S. (1995). Ability to withstand sudden braking. *Railw Res Rev, 52*, 18-21.

Hirshfeld, C. F. (1932). *Disturbing effects of horizontal acceleration.* Electric Railway Presidents' Conference Committee.

Hoberock, L. L. (1977). A survey of longitudinal acceleration comfort studies in ground transportation vehicles. *Journal of Dynamic Systems, Measurement, and Control, 99*, 76-84.

IGLAD Project. (2018). Retrieved 2019, from http://www.iglad.net/web/page.aspx?refid=10

Jarrett, K. L., & Saul, R. (1998). Pedestrian injury-analysis of the PCDS field collision data. *16th International Technical Conference on the Enhanced Safety of Vehicles*, *2.*

Kalra, N., & Paddock, S. M. (2016, September 23). Driving to safety: How many miles of driving would it take to demonstrate autonomous vehicle reliability? *Transportation Research*, pp. 182-193.

Kamper, D., Parnianpour, M., Barin, K., Adams, T., Linden, M., & Hemami, H. (1999). Postural stability of wheelchair users exposed to sustained, external perturbations. *Journal of rehabilitation research and development, 36*, 121-132.

Kerrigan, J. R., Bhalla, K. S., Madeley, N. J., Funk, J. R., Bose, D., & Crandall, J. R. (2003). *Experiments for establishing pedestrian-impact lower limb injury criteria.* Tech. rep., SAE Technical Paper.

Klug, C., Feist, F., Schneider, B., Sinz, W., Ellway, J., & Ratingen, M. (2018, 9). Development Of a certification procedure for numerical pedestrian models. *Ircobi 2018 Conference.* Athens (Greece).

Koji, O., Hiroharu, E., Hiroaki, S., & Hiroshi, S. (2007). Ride evaluation during high deceleration braking. *Railw Res Rev, 64*, 26-29.

Loach, J. C., & Maycock, M. G. (1952). Recent developments in railway curve designs. *Proceedings of the Institution of Civil Engineers, 1*, 503-541.

Longhitano, D., Henary, B., Bhalla, K., Ivarsson, J., & Crandall, J. (2005). Influence of vehicle body type on pedestrian injury distribution. *SAE transactions*, 2283-2288.

Maki, B. E., & Fernie, G. R. (1988). A system identification approach to balance testing. Dans *Progress in brain research* (Vol. 76, pp. 297-306). Elsevier.

Martin, J.-L., & Wu, D. (2018). Pedestrian fatality and impact speed squared: Cloglog modeling from French national data. *Traffic injury prevention, 19*, 94-101.

Menzel, T., Bagschik, G., & Maurer, A. M. (2018). Scenarios for Development, Test and Validation of Automated Vehicles. *IEEE Intelligent Vehicles Symposium, Proceedings.*

Pereira, M. S., Hecht, M., Segurado, V., Sohr, S., & Uettwiller, M. (2001). LRV statistics, passive safety in urban railway systems, Light Rail Vehicle (LRV)–accident statistics. *Final report, SAFETRAM project, Technical University of Berlin, Berlin*.

Peres, J. (2018, 9). A Pedestrian Version of the Piper 6 Year Old Child Model. *2018 IRCOBI Conference Proceedings.* Athens (Greece).

Pilz, C. (2019). Development of a scenario simulation platform to support autonomous driving verification. Master’s thesis at Graz university of technology.

Powell, J. P., & Palacín, R. (2015). Passenger stability within moving railway vehicles: limits on maximum longitudinal acceleration. *Urban Rail Transit, 1*, 95-103.

Raymond, A. (2019, July 19). *Utah driverless shuttle mishap doesn't slow 76-year-old state employee*. Récupéré sur DeseretNews: https://www.deseret.com/2019/7/19/8937032/utah-driverless-shuttle-mishap-doesn-t-slow-76-year-old-state-employee

Robert, T., & Vallee, P. (2014). Assessment of a numerical model of balance recovery by stepping. *Computer methods in biomechanics and biomedical engineering, 17*, 176-177.

Robert, T., Beillas, P., Maupas, A., & Verriest, J.-P. (2007). Conditions of possible head impacts for standing passengers in public transportation: an experimental study. *International journal of crashworthiness, 12*, 319-327.

Robert, T., Vallée, P., Tisserand, R., Buloup, F., Bariatinsky, D., Vercher, J. L., et al. (2018). Stepping boundary of external force-controlled perturbations of varying durations: Comparison of experimental data and model simulations. *Journal of biomechanics, 75*, 89-95.

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

Shepardson, D. (2020, February 25). *U.S. agency slams brakes on self-driving EasyMile shuttles after passenger injury*. Récupéré sur Reuters: https://www.reuters.com/article/us-autos-selfdriving/u-s-agency-suspends-self-driving-shuttle-easymile-use-in-10-u-s-states-idUSKBN20J2N6

Simms, C., & Wood, D. (2009). *Pedestrian and cyclist impact: a biomechanical perspective* (Vol. 166). Springer Science & Business Media.

Simoneau, M., & Corbeil, P. (2005). The effect of time to peak ankle torque on balance stability boundary: experimental validation of a biomechanical model. *Experimental brain research, 165*, 217-228.

The International Organization for Standardization (ISO). (2019). ISO/PAS 21448:2019(E). *Road vehicles - Safety of the intended functionaity*. ISO.

Thomson, J. J. (1976, April). Killing, letting die and the trolley problem. *The Monist, Vol. 59, No. 2*, pp. 204-217.

tramwaydemontpellier.net. (2016, Septembre 3). Récupéré sur tramwaydemontpellier.net: https://tramwaydemontpellier.net/2016/09/03/3-septembre-2016-il-y-a-quatre-ans-exactement-un-voyageur-decede-a-la-suite-dune-chute-a-bord-de-la-rame-2095-citadis-402-alstom/

TRANSPORTATION, U. D. (2016). *FMVSS No. 201U - Occupant Protection in Interior Impact.* U.S. DEPARTMENT OF TRANSPORTATION.

UDRIVE Project. (2017). Retrieved from http://www.udrive.eu/

Vallée, P. (2015). *Estimation du risque de chute suite à une perturbation d'équilibre.* PhD Thesis, Université Claude Bernard-Lyon I.

Versace, J. (1971). *A review of the severity index.* Tech. rep., SAE Technical Paper.

WAYMO. (2018). *Waymo Safety Report, on the road to fully self-driving.* Récupéré sur https://waymo.com/safety/

Weber, T., Muser, M., & Schmitt, K.-U. (2015). Optimising the design of tramways to mitigate injury risk in pedestrian impacts. *IRCOBI Conference Proceedings.*

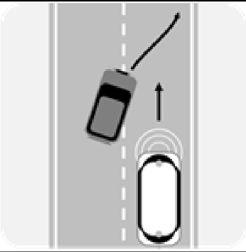
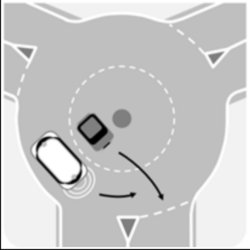
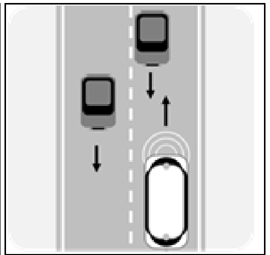
Appendix A: Focus groups outline

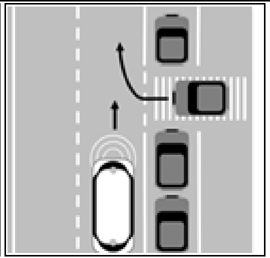
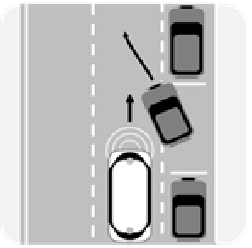
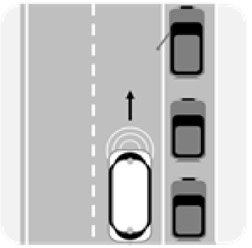
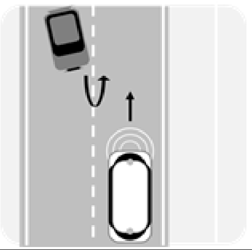
- Welcome, brief introduction of moderators and agenda
- Reminder to participants: participation is anonymous, employer will only get summarised results, but audio needs to be recorded for further analysis.
- Consent form signing
- Participants briefly introduce themselves
- **Guided but open discussion around safety (list of questions below)**
- Summary by assistant moderator
- **Workshop**:
  - Identify 'hot-spots' on the map (i.e. specific updated itinerary for each PTO)
  - Try to find corresponding scenarios pictograms
  - Identify scenarios that are missing in the catalogue

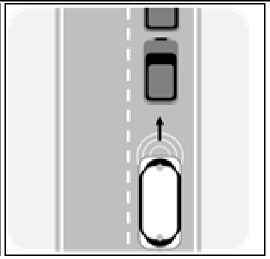
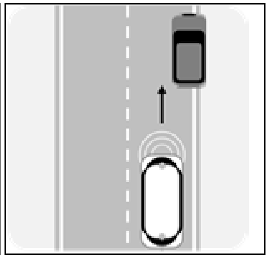
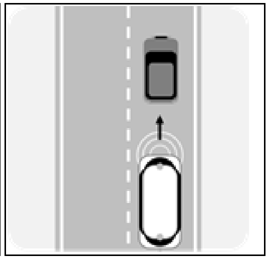
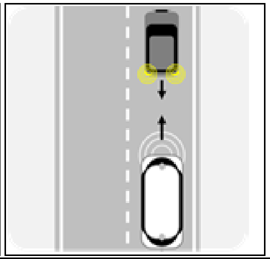
Questions to be addressed during the discussion:

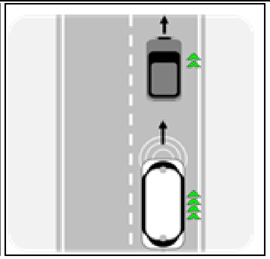
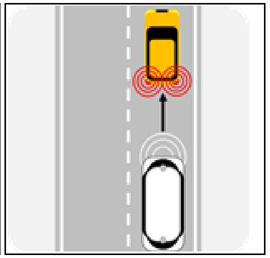
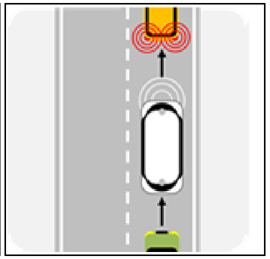
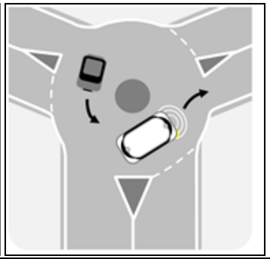
- **General** *(does safety come up naturally?)*
  - How do you describe your job to friends?
  - Which were your biggest surprises when you started this job?
  - What do you feel is the most important part of your job?
  - Once you're in the minibus, what do you enjoy about your job?
  - What do you dislike?
  - What are the difficulties of your job?
- **Safety**
  - Are you concerned about autonomous minibus' safety?
  - Whom are you concerned the most about? (Passengers? pedestrians? others?)
  - Do you often have to intervene in order to preserve safety? In which circumstances?
  - Were you already truly afraid? In which circumstances? Is that frequent?
- **Future: higher speed**
  - Could we operate at a higher speed?
  - Would a higher speed improve safety in some cases? Which?
  - Could a higher speed be more dangerous? In which circumstances in particular?
  - What currently prevents us from safely operating at a higher speed?
- **Future: remote monitoring**
  - Could you remotely monitor the operation of several minibuses? *(PTOs : is that relevant?)*
  - What would likely be the problems?
  - Which kind of situations do you think will require your presence for the foreseeable future?

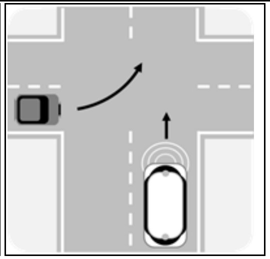
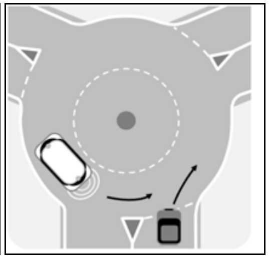
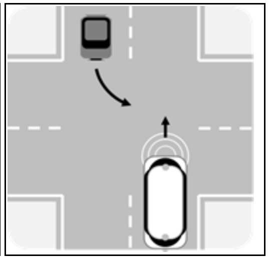
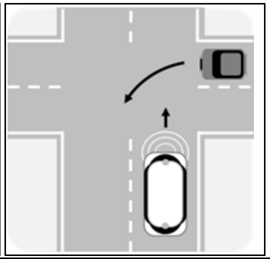
Appendix B: Scenario catalogue

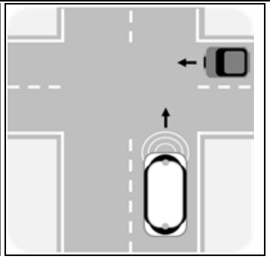
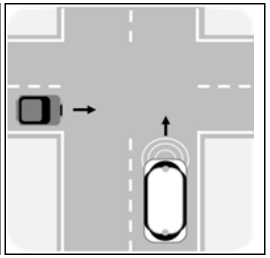
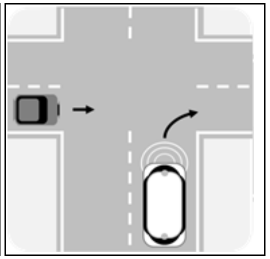
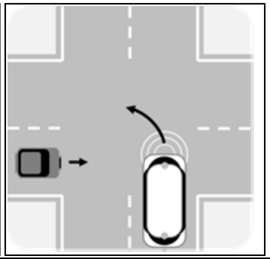
Scenario	Pictogram	Category(ies)	Other road user(s)	Infrastructure	Trajectory other road user	Trajectory AV
Cut-in by another vehicle		• Detect and respond to lane changes • Detect and respond to other vehicles	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway	• Same direction as AV • Not in the same lane as AV • In front of AV • Lane change to the right	• Going forward
Cut-in by another vehicle exiting roundabout		• Detect and respond to lane changes • Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Roundabout	• At intersection • Not in the same lane as AV • In front of AV • Lane change to the right	• Going forward • At intersection
An oncoming vehicle is encroaching on the AV lane while overtaking		• Detect and respond to other vehicles	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Bidirectional roadway	• Same direction as AV • Not in the same lane as AV • In front of AV • Lane change to the left	• Going forward

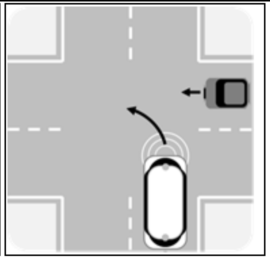
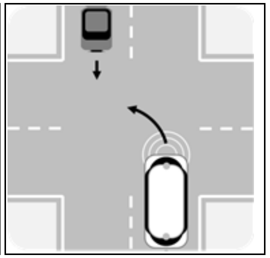
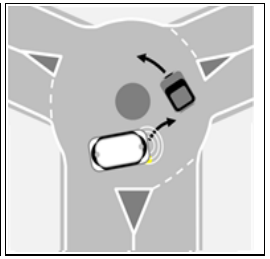
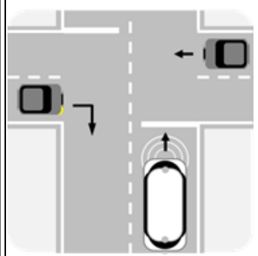
Vehicle leaving an underground car park, a private parking		• Detect and respond to other vehicles	• Cyclist • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway	• Not in the same lane as AV • In front of AV • Coming from the right side	• Going forward
Vehicle leaving a parking place		• Detect and respond to other vehicles	• Car • Light Goods Vehicle • Heavy Goods Vehicle	• Unidirectional roadway • Bidirectional roadway	• In front of AV • Accelerating while leaving a parking • On the right lane	• Going forward
Door opening by a parked vehicle		• Detect and respond to other vehicles	• Car • Light Goods Vehicle • Heavy Goods Vehicle	• Unidirectional roadway • Bidirectional roadway	• In front of AV • On the right lane • Parked	• Going forward
U turn from the opposite vehicle		• Detect and respond to other vehicles	• Cyclist • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle	• Bidirectional roadway	• On the opposite lane • Turning into path • Lane change to the left	• Going forward

Vehicle stopped fully and momentarily in AV's lane due to traffic		• Detect and respond to other vehicles	• Cyclist • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway	• In same lane as AV • Stopped • In front of AV	• Going forward
Vehicle stopped partly and durably in AV's lane		• Detect and respond to other vehicles	• Cyclist • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway	• In same lane as AV • Stopped • In front of AV	• Going forward
Vehicle stopped fully and durably in AV's lane		• Detect and respond to other vehicles	• Cyclist • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway	• In same lane as AV • Stopped • In front of AV	• Going forward
AV follows a vehicle which starts going in reverse		• Detect and respond to other vehicles	• Cyclist • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway	• In same lane as AV • In front of AV • Going in reverse	• Going in reverse

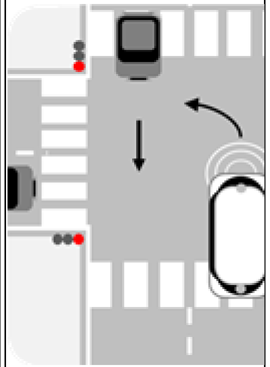
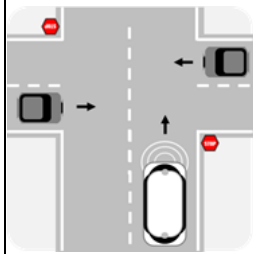
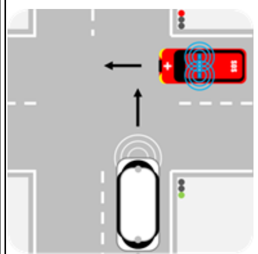
AV follows vehicle going slower than the target speed		• Detect and respond to other vehicles	• Cyclist • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway	• Going forward • In same lane as AV • Same direction as AV • In front of AV	• Going forward
AV follows a vehicle performing a harsh braking		• Detect and respond to other vehicles	• Cyclist • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway	• Going forward • In same lane as AV • In front of AV	• Going forward
AV follows a vehicle performing a harsh braking while being followed by another vehicle		• Detect and respond to other vehicles	• Cyclist • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway	• Going forward • In same lane as AV • In front of AV	• Going forward
AV exits a roundabout		• Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Roundabout	• At intersection • Behind AV	• Exiting intersection

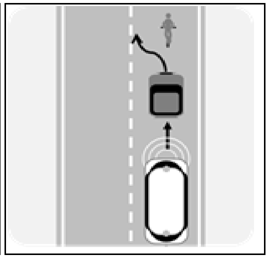
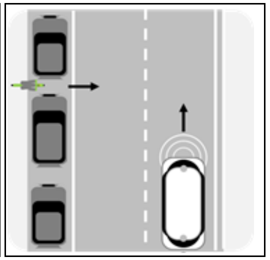
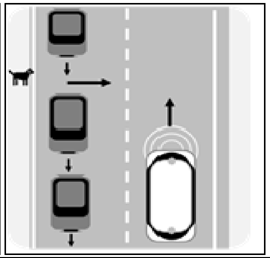
AV going straight while another vehicle turning into path from farside to nearside		• Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• From farside to nearside • At intersection • Turning into path	• Going forward • At intersection
Cut-in by a vehicle entering into roundabout		• Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Roundabout	• At intersection • In front of AV • Inserting into intersection	• Going forward • At intersection
AV going straight while another vehicle turning across path from farside to nearside		• Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Bidirectional roadway • X intersection • Y intersection • T intersection	• From farside to nearside • At intersection • Turning across path	• Going forward • At intersection
AV going straight while another vehicle turning across path from nearside to farside		• Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Bidirectional roadway • X intersection • Y intersection • T intersection	• At intersection • From nearside to farside • Turning across path	• Going forward • At intersection

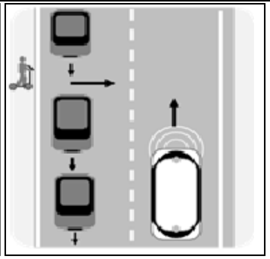
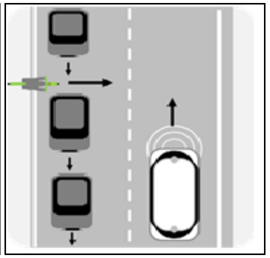
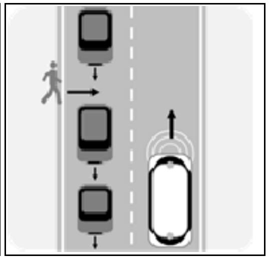
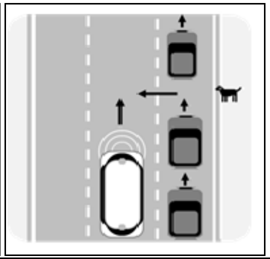
AV crossing path of another vehicle going from nearside to farside		• Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • At intersection • From nearside to farside	• Going forward • At intersection
AV crossing path of another vehicle going from farside to nearside		• Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • At intersection	• Going forward • At intersection
AV turning nearside into path of another vehicle which is going straight from farside to nearside		• Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • At intersection	• Turning nearside • At intersection • Turning into path
AV turning farside across path of another vehicle who is going straight from farside to nearside		• Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • At intersection	• Turning farside • At intersection • Turning across path

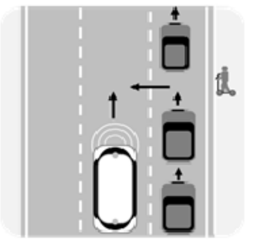
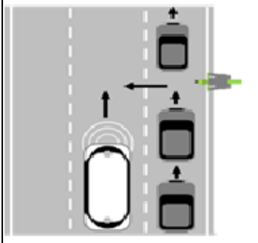
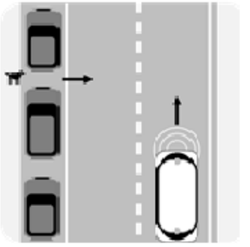
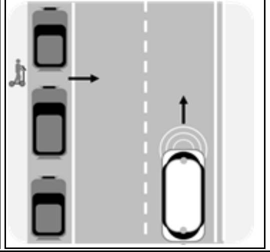
AV turning farside into path of another vehicle which is going straight from nearside to farside		• Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • At intersection • From nearside to farside	• Turning farside • At intersection • Turning into path
AV turning farside across path of another vehicle which is going straight in opposite direction		• Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • At intersection • Opposite direction of AV	• Turning farside • At intersection • Turning across path
AV wants to exit a roundabout while being preceeded by a vehicle		• Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Roundabout	• At intersection • In front of AV	• Exiting intersection
AV stops or gives way to other vehicles at stop/yield markings on the pavement		• Detect and respond to other vehicles at intersections • Detect and respond to Traffic Signals and Stop/Yield Signs	• Cyclist • PMD user • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • Turning farside • Turning nearside • At intersection • Opposite direction of AV • From nearside to farside • On the opposite lane • Turning across path • Turning into path	• At intersection • Stopped • Decelerating

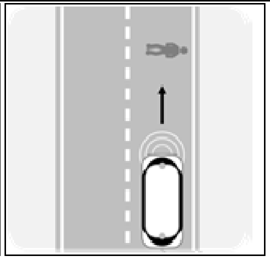
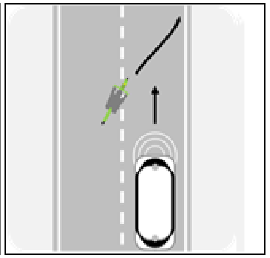
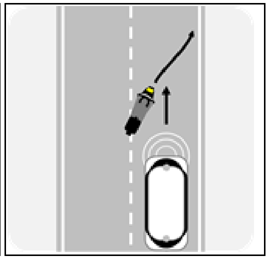
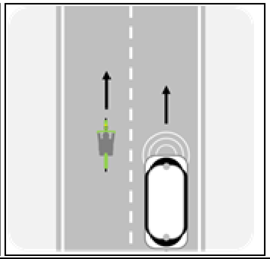
AV stops or gives way to another vehicle which has right-of-way at intersections without signs or markings		• Detect and respond to other vehicles at intersections • Detect and respond to Traffic Signals and Stop/Yield Signs	• Cyclist • PMD user • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • Turning farside • Turning nearside • At intersection • Opposite direction of AV • From nearside to farside • On the opposite lane • Turning across path • Turning into path	• Going forward • Turning farside • Turning nearside • At intersection • Stopped • Turning across path • Turning into path
AV has to follow the instructions of the police officer instead of the traffic lights		• Detect and respond to other vehicles at intersections • Detect and respond to Traffic Signals and Stop/Yield Signs	• Cyclist • PMD user • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • Turning farside • Turning nearside • At intersection • Opposite direction of AV • From nearside to farside • On the opposite lane • Turning across path • Turning into path	• Going forward • Turning farside • Turning nearside • At intersection • Turning across path • Turning into path
AV is in roundabout and a prioritary vehicle inserts in front of it		• Detect and respond to other vehicles at intersections • Detect and respond to Traffic Signals and Stop/Yield Signs	• Prioritary vehicle	• Roundabout	• Going forward • In front of AV • Inserting into intersection	• Going forward • At intersection

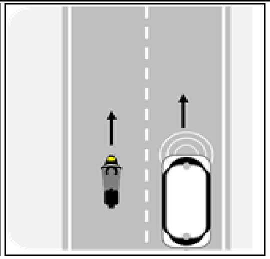
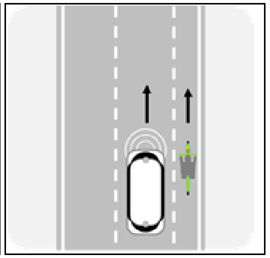
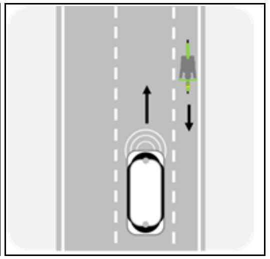
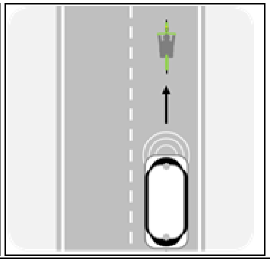
A vehicle crosses AV path after violating AV priority		• Detect and respond to other vehicles at intersections • Detect and respond to Traffic Signals and Stop/Yield Signs	• Cyclist • PMD user • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • Turning farside • Turning nearside • At intersection • Opposite direction of AV • From nearside to farside • On the opposite lane • Turning across path • Turning into path	• Going forward • Turning farside • Turning nearside • At intersection • Stopped • Turning across path • Turning into path
AV stops or gives way to other vehicles at stop/yield signs		• Detect and respond to other vehicles at intersections • Detect and respond to Traffic Signals and Stop/Yield Signs	• Cyclist • PMD user • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • Turning farside • Turning nearside • At intersection • Opposite direction of AV • From nearside to farside • On the opposite lane • Turning across path • Turning into path	• At intersection • Stopped • Decelerating
Emergency vehicle overrules AV's priority at intersection		• Detect and respond to other vehicles at intersections • Detect and respond to Traffic Signals and Stop/Yield Signs	• Prioritary vehicle	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • Turning farside • Turning nearside • At intersection • Opposite direction of AV • From nearside to farside • On the opposite lane • Turning across path	• Going forward • Turning farside • Turning nearside • At intersection • Turning across path • Turning into path

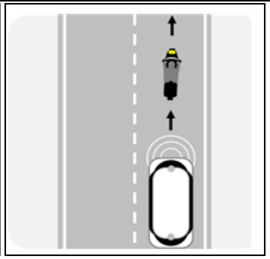
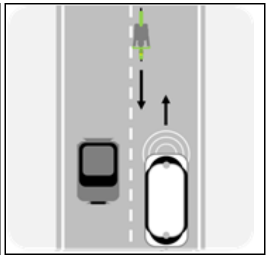
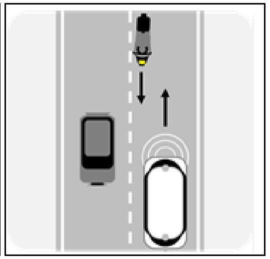
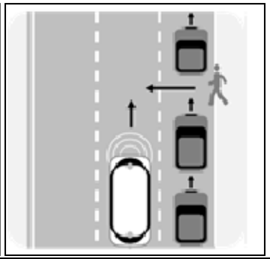
					• Turning into path	
AV inserts into a roundabout while a vehicle is in the roundabout		• Detect and respond to other vehicles • Detect and respond to other vehicles at intersections	• Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Roundabout	• At intersection	• Inserting into intersection
PMD user stopped in the same lane as AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Bidirectional roadway	• In same lane as AV • Back facing AV • Front facing AV • Stopped	• Going forward
Cyclist crosses outside of crosswalk from farside to nearside and is masked by static obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • From farside to nearside	• Going forward
Animal crosses outside of crosswalk from farside to nearside and is masked by moving obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Bidirectional roadway	• Going forward • From farside to nearside	• Going forward

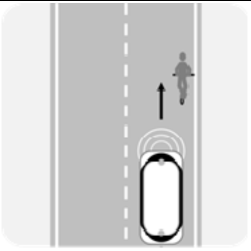
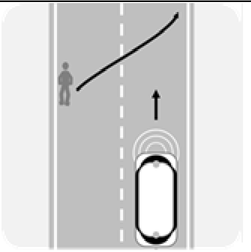
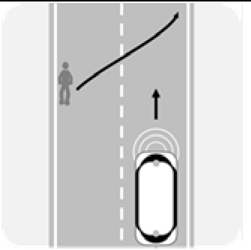
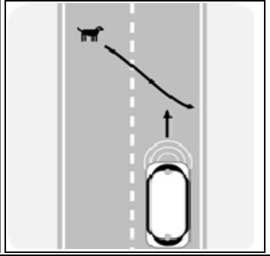
PMD user crosses outside of crosswalk from farside to nearside and is masked by moving obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Bidirectional roadway	• Going forward • From farside to nearside	• Going forward
Cyclist crosses outside of crosswalk from farside to nearside and is masked by moving obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Bidirectional roadway	• Going forward • From farside to nearside	• Going forward
Pedestrian crosses outside of crosswalk from farside to nearside and is masked by moving obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Bidirectional roadway	• Going forward • From farside to nearside	• Going forward
Animal crosses outside of crosswalk from nearside to farside and is masked by moving obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Unidirectional roadway • Bidirectional roadway	• Going forward • From nearside to farside	• Going forward

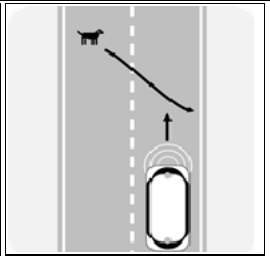
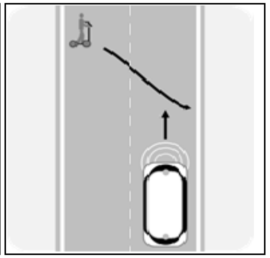
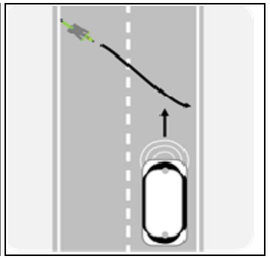
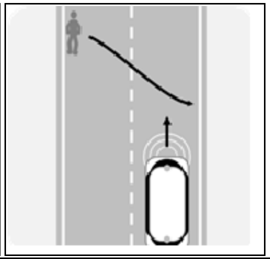
PMD user crosses outside of crosswalk from nearside to farside and is masked by moving obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Unidirectional roadway • Bidirectional roadway	• Going forward • From nearside to farside	• Going forward
Cyclist crosses outside of crosswalk from nearside to farside and is masked by moving obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • From nearside to farside	• Going forward
Animal crosses outside of crosswalk from farside to nearside and is masked by static obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Unidirectional roadway • Bidirectional roadway	• Going forward • From farside to nearside	• Going forward
PMD user crosses outside of crosswalk from farside to nearside and is masked by static obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Unidirectional roadway • Bidirectional roadway	• Going forward • From farside to nearside	• Going forward

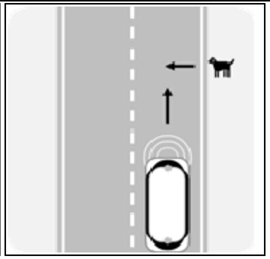
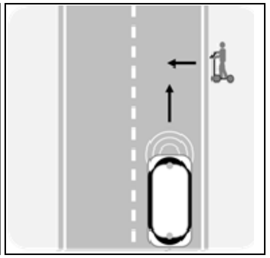
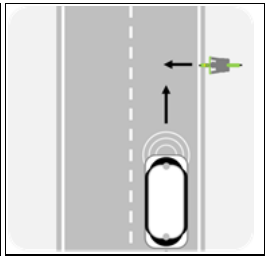
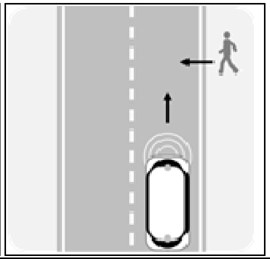
Pedestrian lying on the road in same lane as AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• In same lane as AV • Stopped	• Going forward
Cyclist crosses in front of AV		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• Same direction as AV • Not in the same lane as AV • In front of AV • Lane change to the right	• Going forward
Motorcyclist crosses in front of AV		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Motorcyclist	• Unidirectional roadway • Bidirectional roadway	• Same direction as AV • Not in the same lane as AV • In front of AV • Lane change to the right	• Going forward
Cyclist overtakes the AV without merging		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • Same direction as AV • Not in the same lane as AV • In protected lane	• Going forward

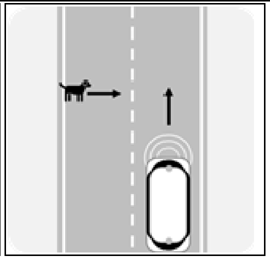
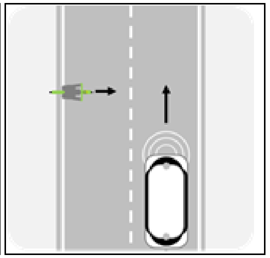
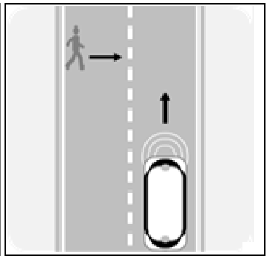
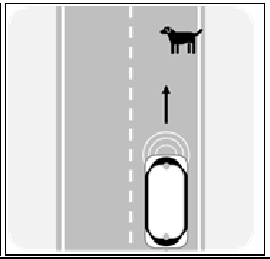
Motorcyclist overtakes the AV without merging		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Motorcyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • Same direction as AV • Not in the same lane as AV • In protected lane	• Going forward
Cyclist is on the road on bike lane in the same direction as AV		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • Same direction as AV • Not in the same lane as AV • In protected lane	• Going forward
Cyclist is on the road on bike lane in the opposite direction as AV		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • Opposite direction of AV • Not in the same lane as AV • In protected lane	• Going forward
Cyclist is on the road in same direction and same lane as AV - no bike lane		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • In same lane as AV • Same direction as AV • In front of AV	• Going forward

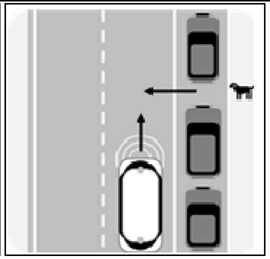
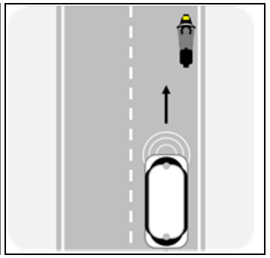
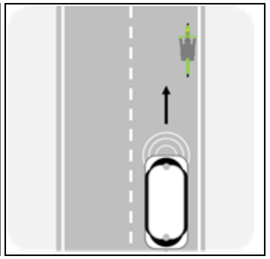
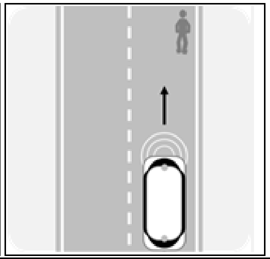
Motocyclist is on the road in same direction and same lane as AV - no bike lane		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Motorcyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • In same lane as AV • Same direction as AV • In front of AV	• Going forward
Cyclist is on the road in opposite direction and same lane as AV - no bike lane		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Bidirectional roadway	• Going forward • Opposite direction of AV • In same lane as AV • In front of AV	• Going forward
Motocyclist is on the road in opposite direction and same lane as AV - no bike lane		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Motorcyclist	• Bidirectional roadway	• Going forward • Opposite direction of AV • In same lane as AV • In front of AV	• Going forward
Pedestrian crosses outside of crosswalk from nearside to farside and is masked by moving obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• Going forward • From nearside to farside	• Going forward

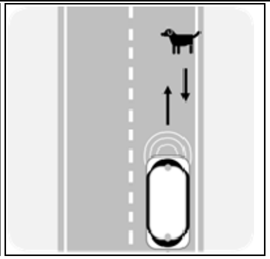
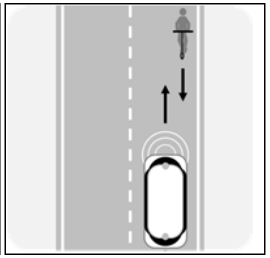
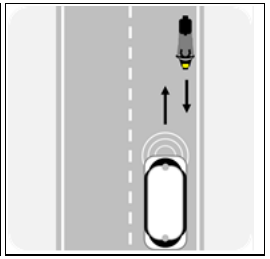
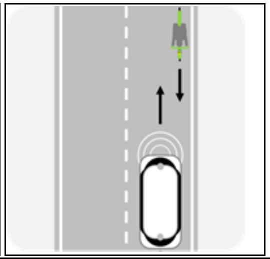
PMD user is stopped in the same lane as AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Unidirectional roadway • Bidirectional roadway	• In same lane as AV • Back facing AV • Front facing AV • Stopped	• Going forward
Pedestrian crosses diagonally the road outside an intersection or crosswalk from farside to nearside, back facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• From farside to nearside • Back facing AV • Diagonally	• Going forward
Pedestrian crosses diagonally the road outside an intersection or crosswalk from farside to nearside, back facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• From farside to nearside • Back facing AV • Diagonally	• Going forward
Animal crosses diagonally the road outside an intersection or crosswalk from farside to nearside, front facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Unidirectional roadway • Bidirectional roadway	• From farside to nearside • Front facing AV • Diagonally	• Going forward

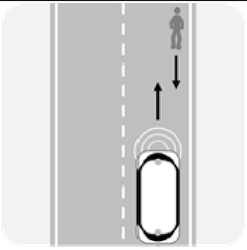
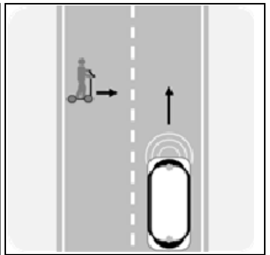
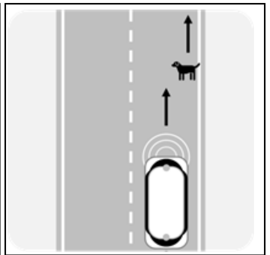
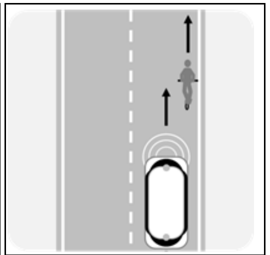
Animal crosses diagonally the road outside an intersection or crosswalk from farside to nearside, front facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Unidirectional roadway • Bidirectional roadway	• From farside to nearside • Front facing AV • Diagonally	• Going forward
PMD user crosses diagonally the road outside an intersection or crosswalk from farside to nearside, front facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Unidirectional roadway • Bidirectional roadway	• From farside to nearside • Front facing AV • Diagonally	• Going forward
Cyclist crosses diagonally the road outside an intersection or crosswalk from farside to nearside, front facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• From farside to nearside • Front facing AV • Diagonally	• Going forward
Pedestrian crosses diagonally the road outside an intersection or crosswalk from farside to nearside, front facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• From farside to nearside • Front facing AV • Diagonally	• Going forward

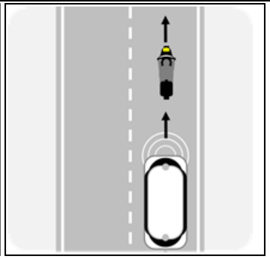
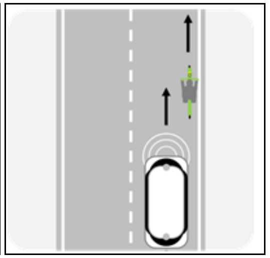
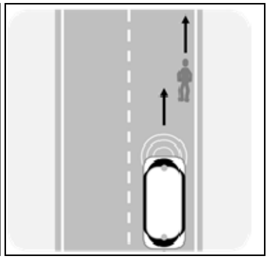
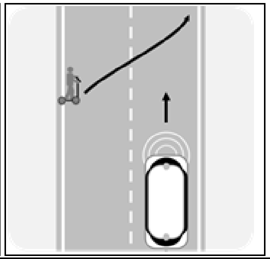
Animal crosses the road outside an intersection or crosswalk from nearside to farside - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Unidirectional roadway • Bidirectional roadway	• Going forward • From nearside to farside	• Going forward
PMD user crosses the road outside an intersection or crosswalk from nearside to farside - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Unidirectional roadway • Bidirectional roadway	• Going forward • From nearside to farside	• Going forward
Cyclist crosses the road outside an intersection or crosswalk from nearside to farside - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • From nearside to farside	• Going forward
Pedestrian crosses the road outside an intersection or crosswalk from nearside to farside - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• Going forward • From nearside to farside	• Going forward

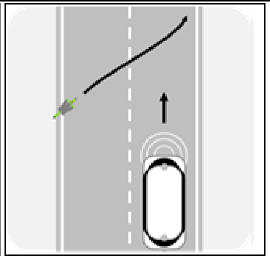
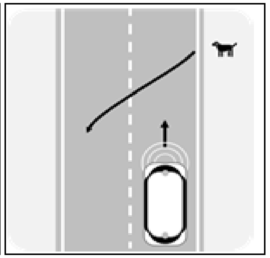
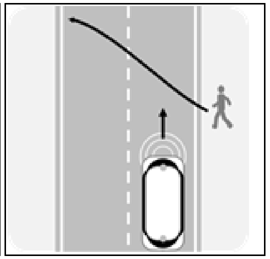
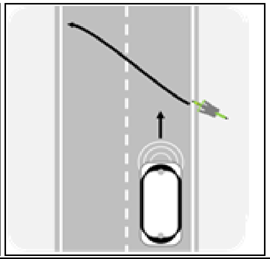
Animal crosses the road outside an intersection or crosswalk from farside to nearside - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Unidirectional roadway • Bidirectional roadway	• Going forward • From farside to nearside	• Going forward
Cyclist crosses the road outside an intersection or crosswalk from farside to nearside - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • From farside to nearside	• Going forward
Pedestrian crosses the road outside an intersection or crosswalk from farside to nearside - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• Going forward • From farside to nearside	• Going forward
Animal is stopped in the same lane as AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Unidirectional roadway • Bidirectional roadway	• In same lane as AV • Back facing AV • Front facing AV • Stopped	• Going forward

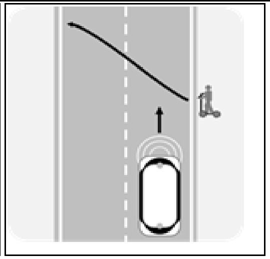
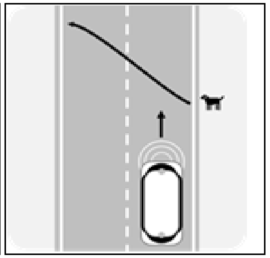
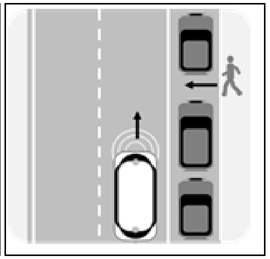
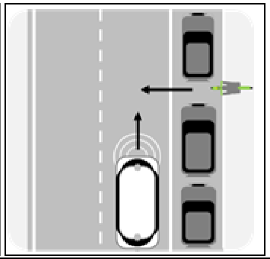
Animal crosses outside of crosswalk from nearside to farside and is masked by static obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Unidirectional roadway • Bidirectional roadway	• Going forward • From nearside to farside	• Going forward
Motorcyclist is stopped in the same lane as AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Motorcyclist	• Unidirectional roadway • Bidirectional roadway	• In same lane as AV • Back facing AV • Front facing AV • Stopped	• Going forward
Cyclist is stopped in the same lane as AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• In same lane as AV • Back facing AV • Front facing AV • Stopped	• Going forward
Pedestrian is stopped in the same lane as AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• In same lane as AV • Back facing AV • Front facing AV • Stopped	• Going forward

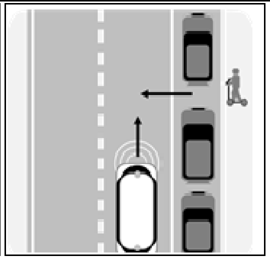
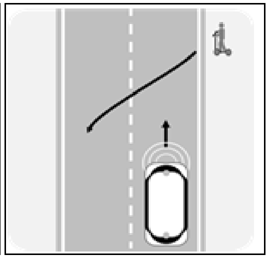
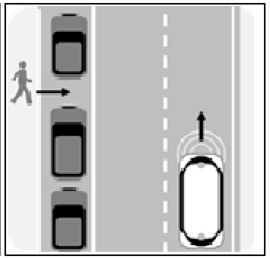
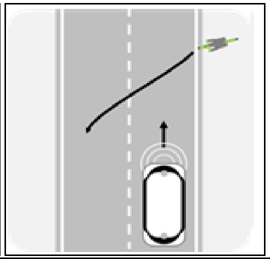
Animal is in the same lane as AV walking towards AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Unidirectional roadway • Bidirectional roadway	• Going forward • Opposite direction of AV • In same lane as AV • Front facing AV	• Going forward
PMD user is in the same lane as AV walking towards AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Unidirectional roadway • Bidirectional roadway	• Going forward • Opposite direction of AV • In same lane as AV • Front facing AV	• Going forward
Motorcycle is in the same lane as AV going towards AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Motorcyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • Opposite direction of AV • In same lane as AV • Front facing AV	• Going forward
Cyclist is in the same lane as AV riding towards AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian • Cyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • Opposite direction of AV • In same lane as AV • Front facing AV	• Going forward

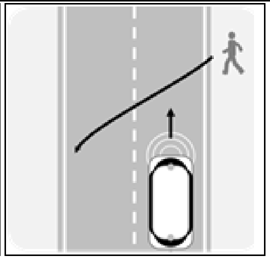
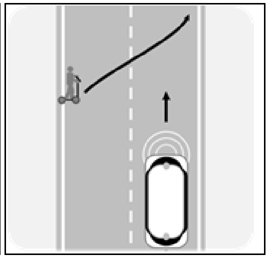
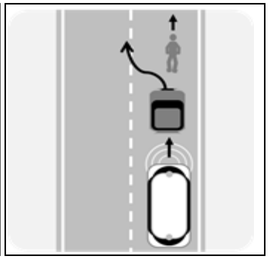
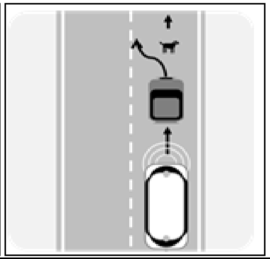
Pedestrian is in the same lane as AV walking towards AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• Going forward • Opposite direction of AV • In same lane as AV • Front facing AV	• Going forward
PMD user crosses the road outside an intersection or crosswalk from farside to nearside - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Unidirectional roadway • Bidirectional roadway	• Going forward • From farside to nearside	• Going forward
Animal is in the same lane as AV walking away from AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Unidirectional roadway • Bidirectional roadway	• Going forward • In same lane as AV • Same direction as AV • Back facing AV	• Going forward
PMD user is in the same lane as AV riding away from AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Unidirectional roadway • Bidirectional roadway	• Going forward • In same lane as AV • Same direction as AV • Back facing AV	• Going forward

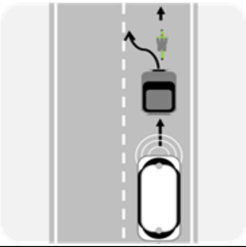
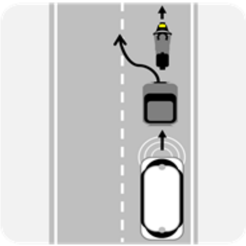
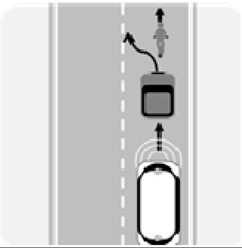
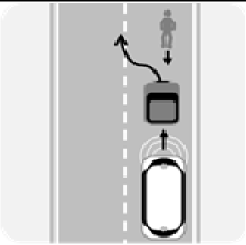
Motorcyclist is in the same lane as AV riding away from AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Motorcyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • In same lane as AV • Same direction as AV • Back facing AV	• Going forward
Cyclist is in the same lane as AV riding away from AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • In same lane as AV • Same direction as AV • Back facing AV	• Going forward
Pedestrian is in the same lane as AV walking away from AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• Going forward • In same lane as AV • Same direction as AV • Back facing AV	• Going forward
Animal crosses diagonally the road outside an intersection or crosswalk from farside to nearside, back facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Unidirectional roadway • Bidirectional roadway	• From farside to nearside • Back facing AV • Diagonally	• Going forward

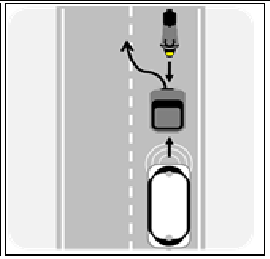
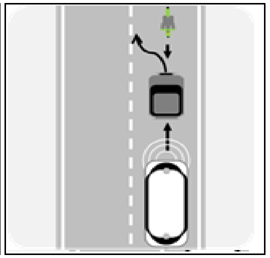
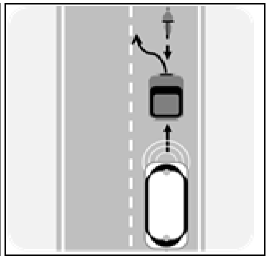
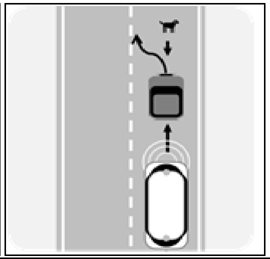
Cyclist crosses diagonally the road outside an intersection or crosswalk from farside to nearside, back facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• From farside to nearside • Back facing AV • Diagonally	• Going forward
Animal crosses diagonally the road outside an intersection or crosswalk from nearside to farside, front facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Unidirectional roadway • Bidirectional roadway	• From nearside to farside • Front facing AV • Diagonally	• Going forward
Pedestrian crosses diagonally the road outside an intersection or crosswalk from nearside to farside, back facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• From nearside to farside • Back facing AV • Diagonally	• Going forward
Cyclist crosses diagonally the road outside an intersection or crosswalk from nearside to farside, back facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• From nearside to farside • Back facing AV • Diagonally	• Going forward

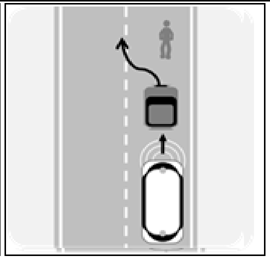
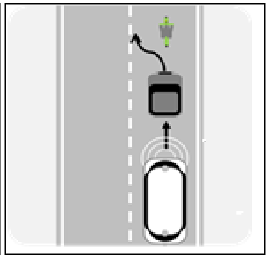
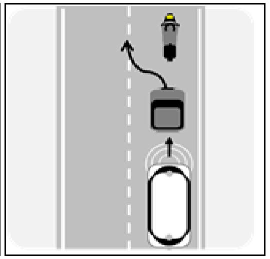
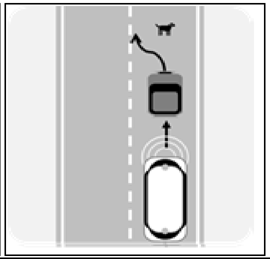
PMD user crosses diagonally the road outside an intersection or crosswalk from nearside to farside, back facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Unidirectional roadway • Bidirectional roadway	• From nearside to farside • Back facing AV • Diagonally	• Going forward
Animal crosses diagonally the road outside an intersection or crosswalk from nearside to farside, back facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Animal	• Unidirectional roadway • Bidirectional roadway	• From nearside to farside • Back facing AV • Diagonally	• Going forward
Pedestrian crosses outside of crosswalk from nearside to farside and is masked by static obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• Going forward • From nearside to farside	• Going forward
Cyclist crosses outside of crosswalk from nearside to farside and is masked by static obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • From nearside to farside	• Going forward

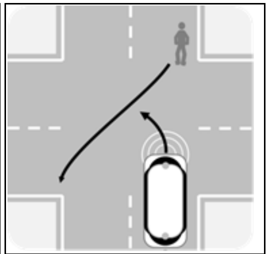
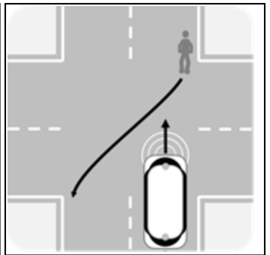
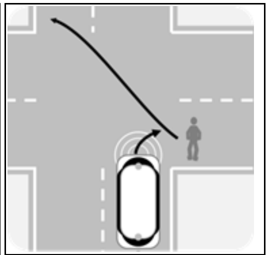
PMD user crosses outside of crosswalk from nearside to farside and is masked by static obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Unidirectional roadway • Bidirectional roadway	• Going forward • From nearside to farside	• Going forward
PMD user crosses diagonally the road outside an intersection or crosswalk from nearside to farside, front facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Unidirectional roadway • Bidirectional roadway	• From nearside to farside • Front facing AV • Diagonally	• Going forward
Pedestrian crosses outside of crosswalk from farside to nearside and is masked by static obstacle(s) - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• Going forward • From farside to nearside	• Going forward
Cyclist crosses diagonally the road outside an intersection or crosswalk from nearside to farside, front facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• From nearside to farside • Front facing AV • Diagonally	• Going forward

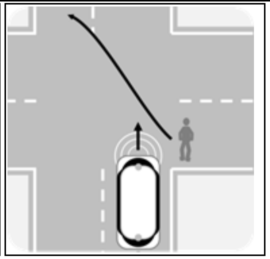
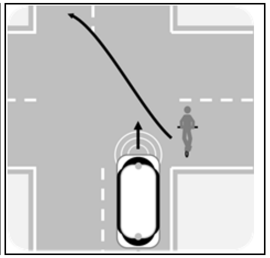
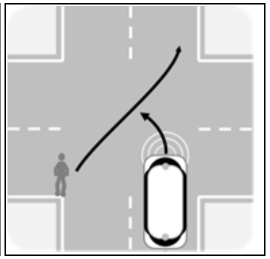
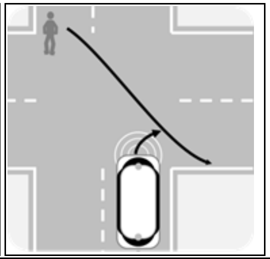
Pedestrian crosses diagonally the road outside an intersection or crosswalk from nearside to farside, front facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• From nearside to farside • Front facing AV • Diagonally	• Going forward
PMD user crosses diagonally the road outside an intersection or crosswalk from farside to nearside, back facing AV - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk)	• PMD user	• Unidirectional roadway • Bidirectional roadway	• From farside to nearside • Back facing AV • Diagonally	• Going forward
Pedestrian in the same lane as AV walking away from AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• Pedestrian	• Bidirectional roadway	• Going forward • In same lane as AV • Same direction as AV	• Going forward
Animal in the same lane as AV walking away from AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• Animal	• Bidirectional roadway	• Going forward • In same lane as AV • Same direction as AV	• Going forward

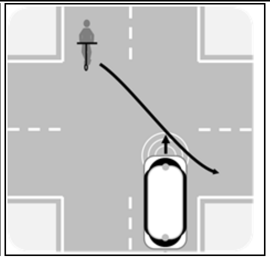
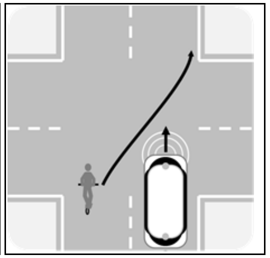
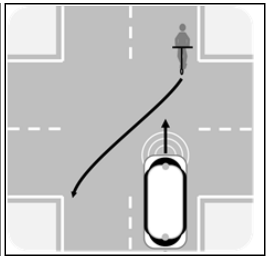
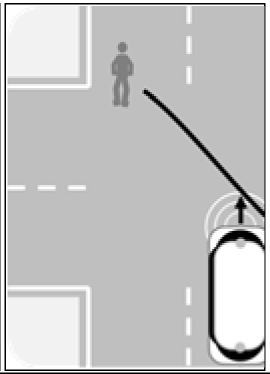
Cyclist in the same lane as AV riding away from AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• Cyclist	• Bidirectional roadway	• Going forward • In same lane as AV • Same direction as AV	• Going forward
Motorcyclist in the same lane as AV riding away from AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• Motorcyclist	• Bidirectional roadway	• Going forward • In same lane as AV • Same direction as AV	• Going forward
PMD user in the same lane as AV riding away from AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• PMD user	• Bidirectional roadway	• Going forward • In same lane as AV • Same direction as AV	• Going forward
Pedestrian in the same lane as AV walking towards AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• Pedestrian	• Bidirectional roadway	• Going forward • Opposite direction of AV • In same lane as AV	• Going forward

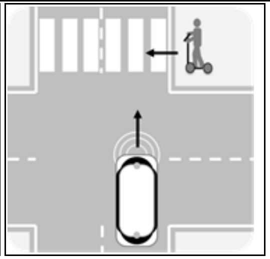
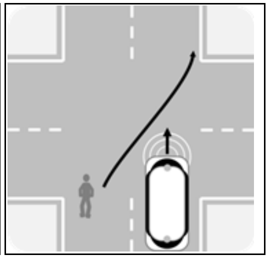
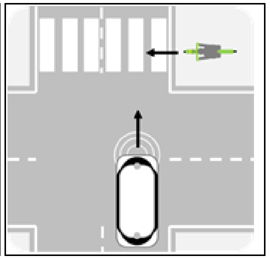
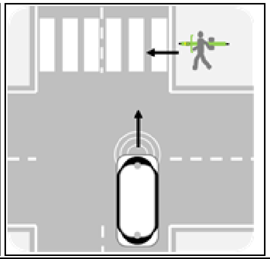
Motorcyclist in the same lane as AV riding towards AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• Motorcyclist	• Bidirectional roadway	• Going forward • Opposite direction of AV • In same lane as AV	• Going forward
Cyclist in the same lane as AV riding towards AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• Cyclist	• Bidirectional roadway	• Going forward • Opposite direction of AV • In same lane as AV	• Going forward
PMD user in the same lane as AV riding towards AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• PMD user	• Bidirectional roadway	• Going forward • Opposite direction of AV • In same lane as AV	• Going forward
Animal in the same lane as AV walking towards AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• Animal	• Bidirectional roadway	• Going forward • Opposite direction of AV • In same lane as AV	• Going forward

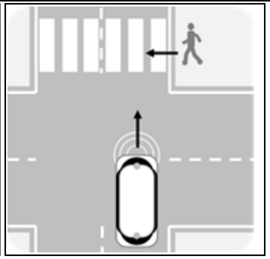
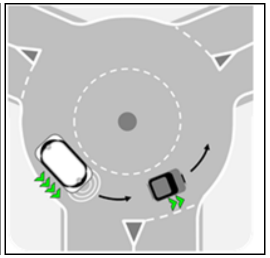
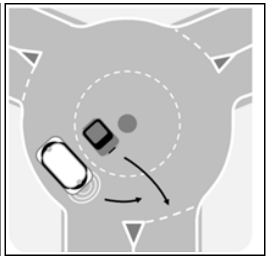
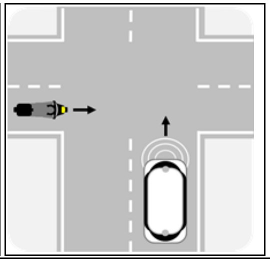
Pedestrian stopped in the same lane as AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• Pedestrian	• Bidirectional roadway	• In same lane as AV • Back facing AV • Front facing AV • Stopped	• Going forward
Cyclist stopped in the same lane as AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• Cyclist	• Bidirectional roadway	• In same lane as AV • Back facing AV • Front facing AV • Stopped	• Going forward
Motorcycliste stopped in the same lane as AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• Motorcyclist	• Bidirectional roadway	• In same lane as AV • Back facing AV • Front facing AV • Stopped	• Going forward
Animal stopped in the same lane as AV while being masked by a moving obstacle - AV going straight		• Detect and respond to Pedestrians and other Vulnerable Road Users in Road (out of Intersection or Crosswalk) • Detect and respond to lane changes	• Animal	• Bidirectional roadway	• In same lane as AV • Back facing AV • Front facing AV • Stopped	• Going forward

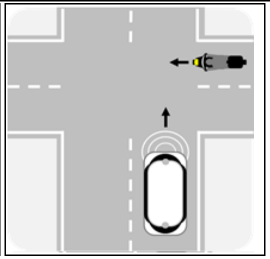
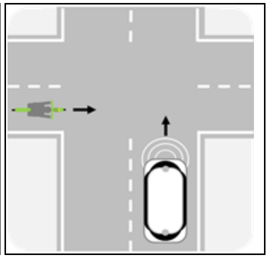
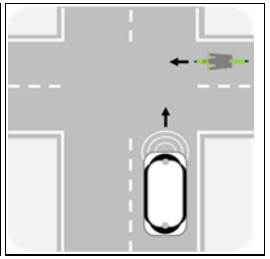
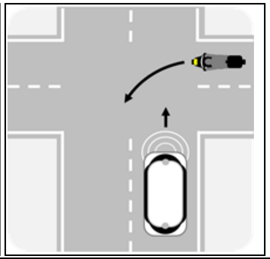
AV stops at red light		• Detect and respond to Traffic Signals and Stop/Yield Signs	• Cyclist • PMD user • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • Turning farside • Turning nearside • At intersection • Opposite direction of AV • From nearside to farside • On the opposite lane • Turning across path • Turning into path	• At intersection • Stopped
Pedestrian crosses diagonally from nearside to farside, front facing AV - AV turning farside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection	• Going forward • At intersection • From nearside to farside • Front facing AV • Diagonally	• Turning farside • At intersection
Pedestrian crosses diagonally from nearside to farside, front facing AV - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection	• Going forward • At intersection • From nearside to farside • Front facing AV • Diagonally	• Going forward • At intersection
Pedestrian crosses diagonally from nearside to farside, back facing AV - AV turning nearside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection	• Going forward • At intersection • From nearside to farside • Back facing AV • Diagonally	• Turning nearside • At intersection

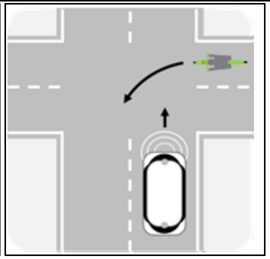
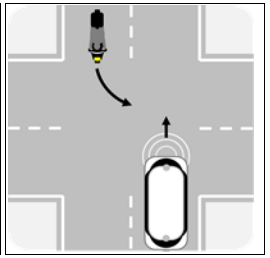
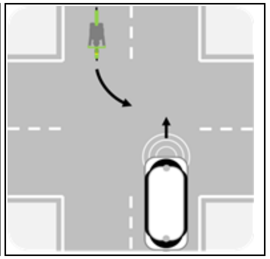
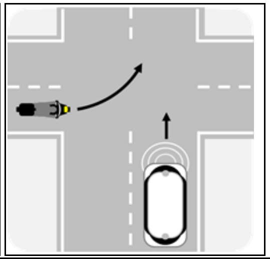
Pedestrian crosses diagonally from nearside to farside, back facing AV - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection	• Going forward • At intersection • From nearside to farside • Back facing AV • Diagonally	• Going forward • At intersection
PMD user crosses diagonally from nearside to farside, back facing AV - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• PMD user	• Unidirectional roadway • Bidirectional roadway • X intersection	• Going forward • At intersection • From nearside to farside • Back facing AV • Diagonally	• Going forward • At intersection
Pedestrian crosses diagonally from farside to nearside, back facing AV - AV turning farside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection	• Going forward • From farside to nearside • At intersection • Back facing AV • Diagonally	• Turning farside • At intersection
Pedestrian crosses diagonally from farside to nearside, front facing AV - AV turning nearside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection	• Going forward • From farside to nearside • At intersection • Front facing AV • Diagonally	• Turning nearside • At intersection

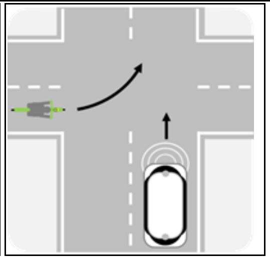
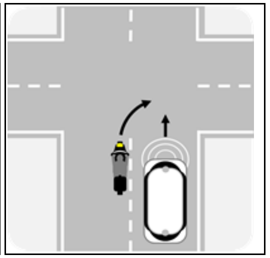
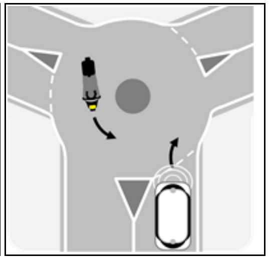
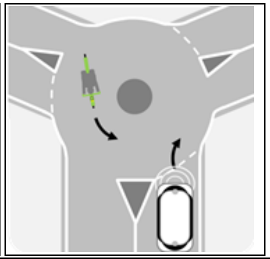
PMD user crosses diagonally from farside to nearside, front facing AV - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• PMD user	• Unidirectional roadway • Bidirectional roadway • X intersection	• Going forward • From farside to nearside • At intersection • Front facing AV • Diagonally	• Going forward • At intersection
PMD user crosses diagonally from farside to nearside, back facing AV - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• PMD user	• Unidirectional roadway • Bidirectional roadway • X intersection	• Going forward • From farside to nearside • At intersection • Back facing AV • Diagonally	• Going forward • At intersection
PMD user crosses diagonally from nearside to farside, front facing AV - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• PMD user	• Unidirectional roadway • Bidirectional roadway • X intersection	• Going forward • At intersection • From nearside to farside • Front facing AV • Diagonally	• Going forward • At intersection
Pedestrian crosses diagonally from farside to nearside, front facing AV - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection	• Going forward • From farside to nearside • At intersection • Front facing AV • Diagonally	• Going forward • At intersection

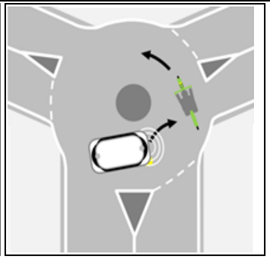
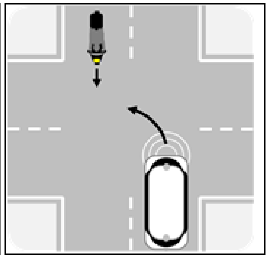
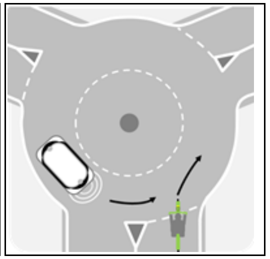
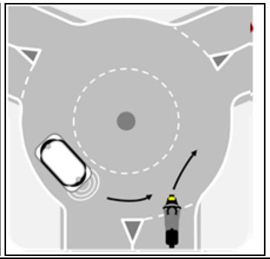
PMD user crosses on crosswalk from nearside to farside after intersection - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• PMD user	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From nearside to farside • After intersection	• Going forward • At intersection
Pedestrian crosses diagonally from farside to nearside, back facing AV - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection	• Going forward • From farside to nearside • At intersection • Back facing AV • Diagonally	• Going forward • At intersection
Cyclist crosses on crosswalk from nearside to farside after intersection - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• Cyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From nearside to farside • After intersection	• Going forward • At intersection
Cyclist pushing bike crosses on crosswalk from nearside to farside after intersection - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• Cyclist pushing bike	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From nearside to farside • After intersection	• Going forward • At intersection

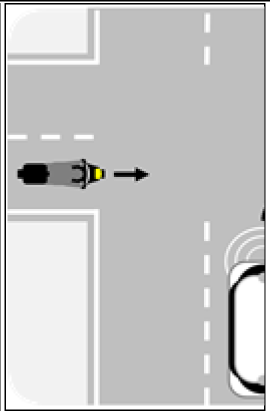
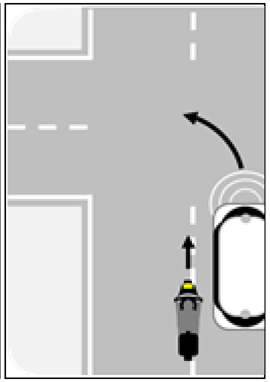
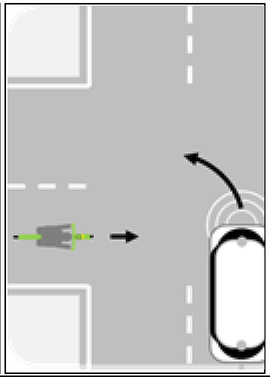
Pedestrian crosses on crosswalk from nearside to farside after intersection - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From nearside to farside • After intersection	• Going forward • At intersection
Preceeding vehicle moves slower than AV inside roundabout		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to lane changes • Detect and respond to other vehicles at intersections	• Cyclist • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Roundabout	• Going forward • At intersection • In same lane as AV • In front of AV	• Going forward • At intersection
Cut-in by a cyclist exiting roundabout		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to lane changes • Detect and respond to other vehicles at intersections	• Cyclist	• Roundabout	• At intersection • Not in the same lane as AV • In front of AV • Lane change to the right	• Going forward • At intersection
AV crossing path of a motorcycle going from farside to nearside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Motorcyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • At intersection	• Going forward • At intersection

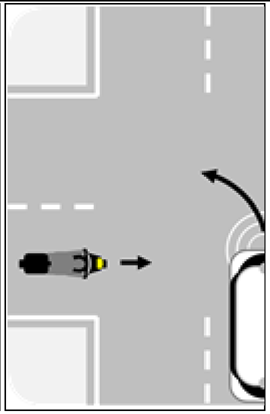
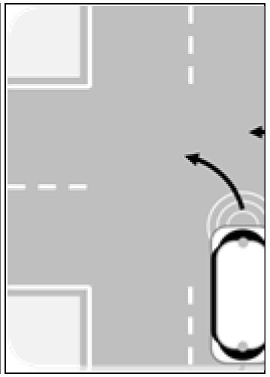
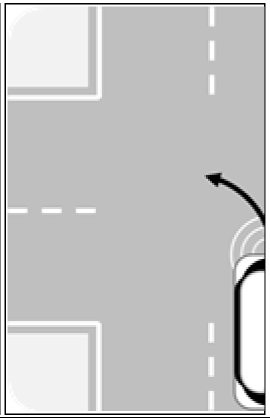
AV crossing path of a motorcycle going from nearside to farside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Motorcyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • At intersection • From nearside to farside	• Going forward • At intersection
AV crossing path of a cyclist going from farside to nearside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Cyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • At intersection	• Going forward • At intersection
AV crossing path of a cyclist going from nearside to farside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Cyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • At intersection • From nearside to farside	• Going forward • At intersection
AV going straight while a motorcycle turning across path from nearside to farside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Motorcyclist	• Bidirectional roadway • X intersection • Y intersection • T intersection	• At intersection • From nearside to farside • Turning across path	• Going forward • At intersection

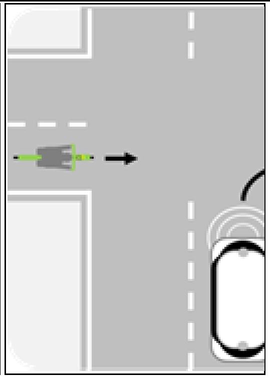
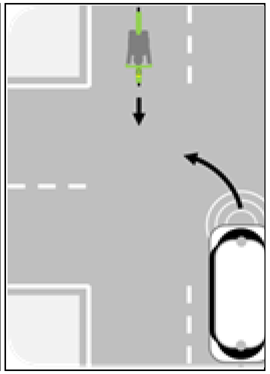
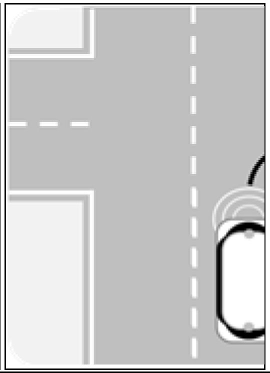
AV going straight while a cyclist turning across path from nearside to farside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Cyclist	• Bidirectional roadway • X intersection • Y intersection • T intersection	• At intersection • From nearside to farside • Turning across path	• Going forward • At intersection
AV going straight while a motorcycle turning across path from farside to nearside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Motorcyclist	• Bidirectional roadway • X intersection • Y intersection • T intersection	• From farside to nearside • At intersection • Turning across path	• Going forward • At intersection
AV going straight while a cyclist turning across path from farside to nearside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Cyclist	• Bidirectional roadway • X intersection • Y intersection • T intersection	• From farside to nearside • At intersection • Turning across path	• Going forward • At intersection
AV going straight while a motorcycle turning into path from farside to nearside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Motorcyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• From farside to nearside • At intersection • Turning into path	• Going forward • At intersection

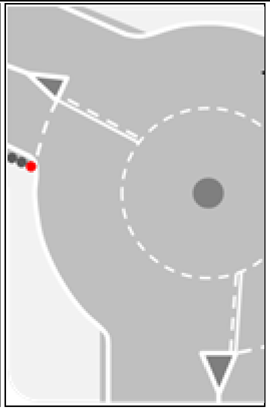
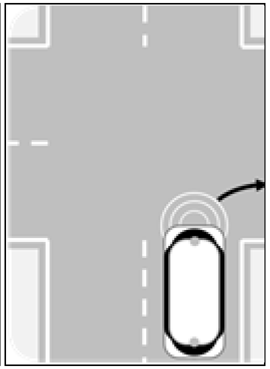
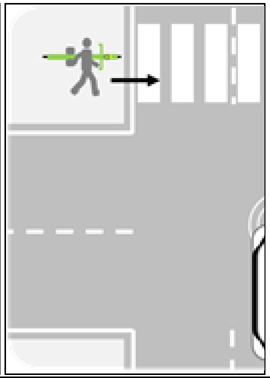
AV going straight while a cyclist turning into path from farside to nearside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Cyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• From farside to nearside • At intersection • Turning into path	• Going forward • At intersection
AV going straight while motorcycle riding between lanes is turning across path from farside to nearside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Motorcyclist	• Bidirectional roadway • X intersection • Y intersection • T intersection	• From farside to nearside • At intersection • Turning across path • Between lanes	• Going forward • At intersection
AV inserts into a roundabout while a motorcycle is in the roundabout		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Motorcyclist	• Roundabout	• At intersection	• Inserting into intersection
AV inserts into a roundabout while a cyclist is in the roundabout		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Cyclist	• Roundabout	• At intersection	• Inserting into intersection

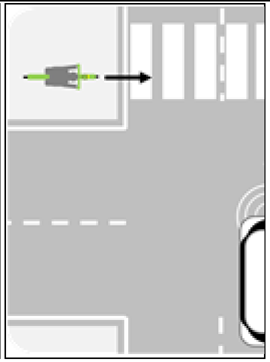
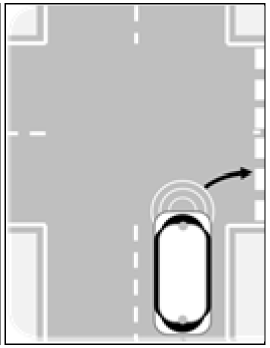
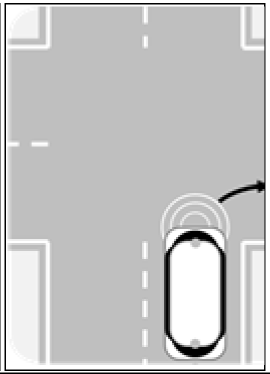
AV wants to exit a roundabout while being preceeded by a cyclist		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Cyclist	• Roundabout	• At intersection • In front of AV	• Exiting intersection
AV turning farside across path of a motorcycle which is going straight in opposite direction		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Motorcyclist	• Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • At intersection • Opposite direction of AV	• Turning farside • At intersection • Turning across path
Cut-in by a cyclist entering into roundabout		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Cyclist	• Roundabout	• At intersection • In front of AV • Inserting into intersection	• Going forward • At intersection
Cut-in by a motorcycle entering into roundabout		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Motorcyclist	• Roundabout	• At intersection • In front of AV • Inserting into intersection	• Going forward • At intersection

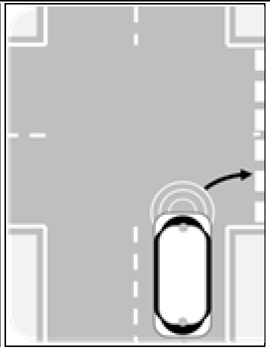
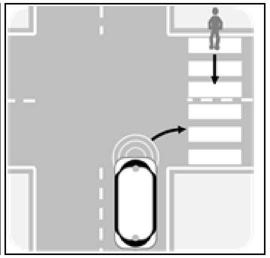
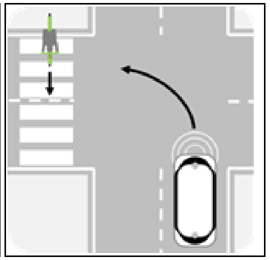
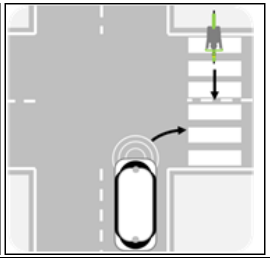
AV turning nearside into path of a motorcycle which is going straight from farside to nearside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Motorcyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • At intersection	• Turning nearside • At intersection • Turning into path
AV turning farside across path of a motorcycle which is going straight between lanes in the same direction		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Motorcyclist	• Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • At intersection • Same direction as AV • Between lanes	• Turning farside • At intersection • Turning across path
AV turning farside across path of a cyclist who is going straight from farside to nearside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Cyclist	• Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • At intersection	• Turning farside • At intersection • Turning across path

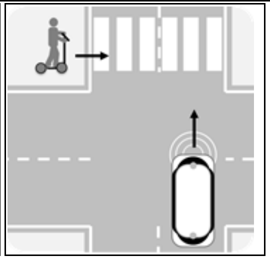
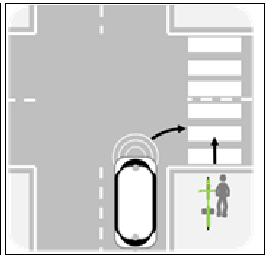
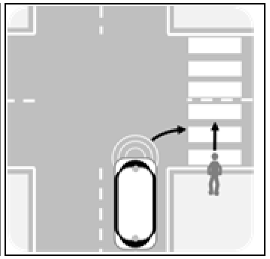
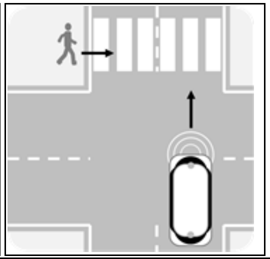
AV turning farside across path of a motorcycle which is going straight from farside to nearside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Motorcyclist	• Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • At intersection	• Turning farside • At intersection • Turning across path
AV turning farside into path of a cyclist who is going straight from nearside to farside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Cyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • At intersection • From nearside to farside	• Turning farside • At intersection • Turning into path
AV turning farside into path of a motorcycle which is going straight from nearside to farside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Motorcyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • At intersection • From nearside to farside	• Turning farside • At intersection • Turning into path

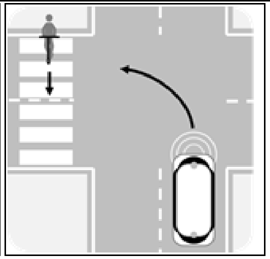
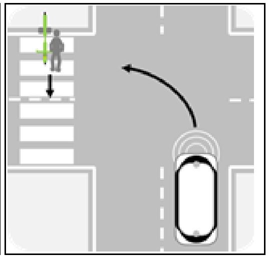
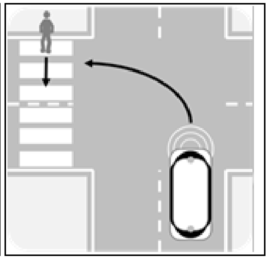
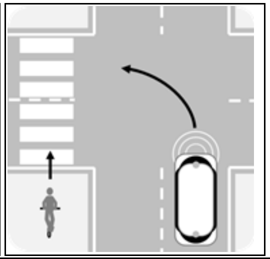
AV turning nearside into path of a cyclist who is going straight from farside to nearside		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Cyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • From farside to nearside • At intersection	• Turning nearside • At intersection • Turning into path
AV turning farside across path of a cyclist who is going straight in opposite direction		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Cyclist	• Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • At intersection • Opposite direction of AV	• Turning farside • At intersection • Turning across path
Cyclist going straight on bicycle lane and AV turning nearside across path at intersection		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections	• Cyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • At intersection • Same direction as AV • In protected lane	• Turning nearside • At intersection • Turning across path

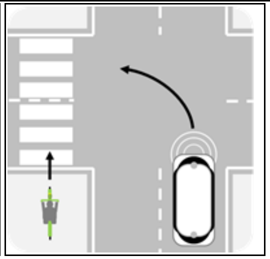
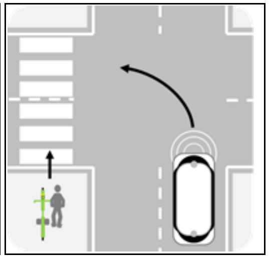
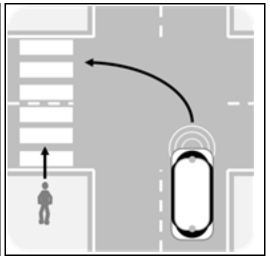
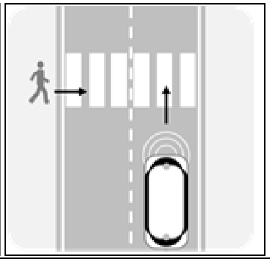
AV is in roundabout and other vehicles become prioritary due to traffic signalling		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Detect and respond to other vehicles at intersections • Detect and respond to Traffic Signals and Stop/Yield Signs	• Cyclist • Motorcyclist • Car • Light Goods Vehicle • Heavy Goods Vehicle • Truck	• Roundabout	• Going forward • In front of AV • Inserting into intersection	• Going forward • At intersection
Cyclist pushing bike crosses on crosswalk from farside to nearside - AV turning nearside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Cyclist pushing bike	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From farside to nearside • At intersection	• Turning nearside • At intersection • Turning across path
Cyclist pushing bike crosses on crosswalk from farside to nearside after intersection - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Cyclist pushing bike	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From farside to nearside • After intersection	• Going forward • At intersection

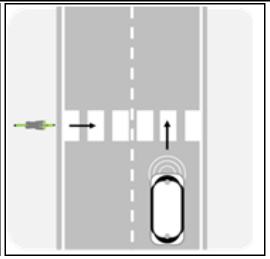
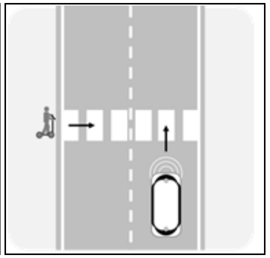
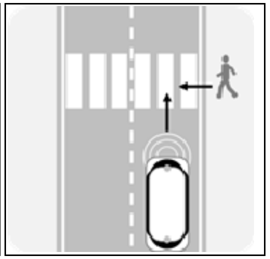
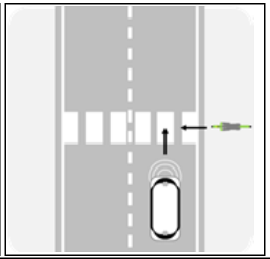
Cyclist crosses on crosswalk from farside to nearside after intersection - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Cyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From farside to nearside • After intersection	• Going forward • At intersection
Cyclist crosses on crosswalk from nearside to farside - AV turning nearside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Cyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • At intersection • From nearside to farside	• Turning nearside • At intersection • Turning across path
PMD user crosses on crosswalk from farside to nearside - AV turning nearside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• PMD user	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From farside to nearside • At intersection	• Turning nearside • At intersection • Turning across path

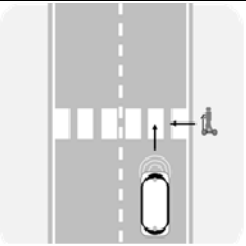
PMD user crosses on crosswalk from nearside to farside - AV turning nearside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• PMD user	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • At intersection • From nearside to farside	• Turning nearside • At intersection • Turning across path
Pedestrian crosses on crosswalk from farside to nearside - AV turning nearside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From farside to nearside • At intersection	• Turning nearside • At intersection • Turning across path
Cyclist crosses on crosswalk from nearside to farside - AV turning farside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Cyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • At intersection • From nearside to farside	• Turning farside • At intersection • Turning across path
Cyclist crosses on crosswalk from farside to nearside - AV turning nearside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Cyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From farside to nearside • At intersection	• Turning nearside • At intersection • Turning across path

PMD user crosses on crosswalk from farside to nearside after intersection - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• PMD user	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From farside to nearside • After intersection	• Going forward • At intersection
Cyclist pushing bike crosses on crosswalk from nearside to farside - AV turning nearside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Cyclist pushing bike	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • At intersection • From nearside to farside	• Turning nearside • At intersection • Turning across path
Pedestrian crosses on crosswalk from nearside to farside - AV turning nearside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • At intersection • From nearside to farside	• Turning nearside • At intersection • Turning across path
Pedestrian crosses on crosswalk from farside to nearside after intersection - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From farside to nearside • After intersection	• Going forward • At intersection

PMD user crosses on crosswalk from nearside to farside - AV turning farside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• PMD user	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • At intersection • From nearside to farside	• Turning farside • At intersection • Turning across path
Cyclist pushing bike crosses on crosswalk from nearside to farside - AV turning farside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Cyclist pushing bike	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • At intersection • From nearside to farside	• Turning farside • At intersection • Turning across path
Pedestrian crosses on crosswalk from nearside to farside - AV turning farside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • At intersection • From nearside to farside	• Turning farside • At intersection • Turning across path
PMD user crosses on crosswalk from farside to nearside - AV turning farside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• PMD user	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From farside to nearside • At intersection	• Turning farside • At intersection • Turning across path

Cyclist crosses on crosswalk from farside to nearside - AV turning farside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Cyclist	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From farside to nearside • At intersection	• Turning farside • At intersection • Turning across path
Cyclist pushing bike crosses on crosswalk from farside to nearside - AV turning farside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Cyclist pushing bike	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From farside to nearside • At intersection	• Turning farside • At intersection • Turning across path
Pedestrian crosses on crosswalk from farside to nearside - AV turning farside across path		• Yield to Pedestrians and other Vulnerable Road Users at Intersections • Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Pedestrian	• Unidirectional roadway • Bidirectional roadway • X intersection • Y intersection • T intersection	• Going forward • On crosswalk • From farside to nearside • At intersection	• Turning farside • At intersection • Turning across path
Pedestrian crosses on crosswalk from farside to nearside - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• Going forward • On crosswalk • From farside to nearside	• Going forward • Before crosswalk

Cyclist crosses on crosswalk from farside to nearside - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • On crosswalk • From farside to nearside	• Going forward • Before crosswalk
PMD user crosses on crosswalk from farside to nearside - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• PMD user	• Unidirectional roadway • Bidirectional roadway	• Going forward • On crosswalk • From farside to nearside	• Going forward • Before crosswalk
Pedestrian crosses on crosswalk from nearside to farside - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Pedestrian	• Unidirectional roadway • Bidirectional roadway	• Going forward • On crosswalk • From nearside to farside	• Going forward • Before crosswalk
Cyclist crosses on crosswalk from nearside to farside - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• Cyclist	• Unidirectional roadway • Bidirectional roadway	• Going forward • On crosswalk • From nearside to farside	• Going forward • Before crosswalk

PMD user crosses on crosswalk from nearside to farside - AV going straight		• Yield to Pedestrians and other Vulnerable Road Users on Crosswalks	• PMD user	• Unidirectional roadway • Bidirectional roadway	• Going forward • On crosswalk • From nearside to farside	• Going forward • Before crosswalk