Autonomous Vehicles to Evolve to a New Urban Experience

DELIVERABLE

D6.1 First Iteration 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

This document reflects only the author's view and the European Commission is not responsible for any use that may be made of the information it contains.

Document Information

Grant Agreement Number	**769033**
Full Title	Autonomous Vehicles to Evolve to a New Urban Experience
Acronym	AVENUE
Deliverable	D6.1 First Iteration Methodology for Safety Evaluation
Due Date	1.11.2019
Work Package	WP6
Lead Partner	CEESAR
Leading Author	Clément VAL, CEESAR
Dissemination Level	Public, restricted

Document History

Version	**Date**	**Author**	**Description of change**
0.1	16.10.2019	CEESAR	First draft
0.9	30.10.2019	CERTH (Antonios Lalas, Konstantinos Votis)	Review
1.0	31.10.2019	CEESAR	Final

Table of Contents

Disclaimer II
Document Information II
Document History II
Table of Contents III
List of Figures V
Executive Summary VII
1 Introduction 1
1.1 Preamble 2
2 WP6 methodology overview 5
2.1 Outline 5
2.2 Field data collection 8
2.3 Scenarios creation 9
2.4 Injury risk assessment 12
2.5 Performance targets definitions 13
2.6 Concrete scenarios sampling 14
2.7 Test track trials 14
2.8 Simulations 15
2.9 Risk assessment 16
3 Current Status 17
3.1 Field data collection 17
3.1.1 Incident reports 17
3.1.2 Focus groups 17
3.1.3 Vehicle data collection 18
3.2 Scenarios creation 20
3.3 Injury risk assessment 22
3.4 Scenario Simulations 23
3.4.1 Tool selection 23
3.4.2 Vehicle model development 24
3.4.3 Scenarios implementation 25
4 Injury Risk Study 26
4.1 Literature Review - passenger balance and fall 27
4.1.1 Sense of balance - equilibrioception 27
4.1.2 Balance recovery approaches 27
4.1.3 Balance recovery tolerance to external perturbation 28

4.1.4 Regulation EN 13452-1 31
4.1.5 Injury tolerance and criteria 32
4.1.6 Summary: passenger balance and fall 34
4.2 Literature Review – Pedestrian Impact 35
4.2.1 The importance of the vehicle speed 35
4.2.2 The importance of the vehicle shape and stiffness 36
4.2.3 Impact against the ground 37
4.2.4 Injury tolerance and criteria 38
4.2.5 Vehicle safety standards for pedestrian and cyclist safety 40
4.2.6 Summary: Pedestrian Impact 42
4.3 Head injury risk for standing passengers in case of AV harsh braking 43
4.3.1 Preamble 43
4.3.2 Methods 43
4.3.3 Preliminary results: standing passengers 47
4.3.4 Future work: standing passengers 49
4.4 Head injury risk for pedestrians in case of AV collision 50
4.4.1 Preamble 50
4.4.2 Methods 50
4.4.3 Preliminary results: pedestrian collision 53
4.4.4 Future work: pedestrian collision 55
5 Conclusion 56
Acknowledgement 57
References 58
Appendix A: Focus groups outline 61
Appendix B: Measures requirements 62
Appendix C: Functional scenarios template 64

List of Figures

Figure 1. AVENUE's safety challenges 3
Figure 2. Tasks 6.1 and 6.2 methodology and interactions 7
Figure 3. Pedestrian front collision / emergency braking situation........ 12
Figure 4. Risk (e.g. AIS ≥ 3 probability) as a function of dynamic parameters........ 13
Figure 5. Configurations taken into account in injury risk study. Red stars represent most critical and therefore prioritized configurations........ 13
Figure 6. Urban driving scene, as simulated by CARLA tool........ 15
Figure 7. Functional scenarios within the safety assessment methodology 20
Figure 8. Overview of the simulation procedure. 23
Figure 9. Image series of a scenario from top left to bottom right. 25
Figure 10. Configurations taken into account in injury risk study. Red stars represent most critical and therefore prioritised configurations........ 26
Figure 11. Different strategies for retaining balance. The neutral position; ankle strategy; hip strategy; stepping strategy (Vallée, 2015). 28
Figure 12. Acceptability of acceleration/jerk levels (Hiroaki, 1995). 29
Figure 13. 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). 30
Figure 14. Experimental corridors for head tangential velocity as a function of its X-coordinate, for the 6 tests configurations (Robert, Beillas, Maupas, & Verriest, 2007). 30
Figure 15. Passenger discomfort in function of the jerk and the acceleration (adapted from Robert & Vallée, 2014). 31
Figure 16. Illustration adapted from standard EN 13452-1 representing the braking profile and parameters used in the standard. 32
Figure 17. Probability of death according to impact speed, with 95% CI (Martin & Wu, 2018). 35
Figure 18. Potentially critical areas in tram front geometries (Weber, Muser, & Schmitt, 2015). 36
Figure 19. Potentially critical areas under the tram (Weber, Muser, & Schmitt, 2015). 37
Figure 20. Different test procedures for pedestrian impact testing (BASt / carhs). 40
Figure 21. Pedestrian impact testing according to EC78/2009 (figure by carhs). 41

Figure 22. NAVYA Shuttle. Left: operating on the open road in the city of Lyon (NAVYA). Right: CAD provided by NAVYA. 44
Figure 23. Vehicle interior model. 44
Figure 24. Parametric deceleration pulse used in this study. 45
Figure 25. Hybrid III 50th Percentile Male Standing (LTSC). 46
Figure 26. Free Motion Headform (LTSC). 47
Figure 27. Risk (e.g. AIS ≥ 3 probability) as a function of dynamic parameters. 47
Figure 28. Deceleration curve provided as input of the simulation. 48
Figure 29. Dynamic responses of a standing passenger within the baseline scenario. 48
Figure 30. Head velocity time history obtained in the baseline scenario. At impact (t = 781 ms, indicated by the star), the head velocity was 4.5 m/s relative to the vehicle. 48
Figure 31. Vehicle front-end model. 51
Figure 32. Hybrid III 50th Percentile Male Standing (LTSC) and Piper pedestrian model. 52
Figure 33. Model integration with vehicle. 52
Figure 34. Risk (e.g. AIS ≥ 3 probability) as a function of dynamic parameters. 53
Figure 35. Pedestrian impact locations. 54
Figure 36. Front vehicle deformation after impact. 54

Table 1. Distinction between functional, logical and concrete scenarios 10
Table 2. Scenario examples from the functional scenario catalogue (V1.0) 21
Table 3. Scenario Ranking by PTOs. 22
Table 4. Approaches for vehicle simulation .... **Erreur ! Signet non défini.**
Table 5. Operational performances defined in standard EN 13452-1 according to braking types for a tram or a light vehicle. 31
Table 6. Comfort performance defined in standard EN 13452-1 according to the types of braking for a tram or light vehicle. 32
Table 7. HIC results and associated risk assessments 49
Table 8. HIC results and associated risk assessments 54

Acronyms

BMM	Business Modelling Manager
CB	Consortium Body
DC	Demonstration Coordinator
EAB	External Advisory Board
EC	European Commission
EM	Exploitation Manager
F2F	Face-To-Face Meetings
LA	Leading Author
MEM	Monitoring and Evaluation Manager
PC	Project Coordinator
PEB	Project Executive Board
PGA	Project General Assembly
QRM	Quality and Risk Manager
QRMB	Quality and Risk Management Board
RN	Risk Number
SA	Scientific Advisor
SMB	Site Management Board
TM	Technical Manager
WP	Work Package
WPL	Work Package Leader

Executive Summary

To gain relevance and therefore acceptance, autonomous shuttles 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 autonomous shuttles. 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, an initial catalogue of safety-relevant scenarios has been constituted. Those scenarios will now be prioritised and complemented thanks to upcoming data collection. Following extensive literature review, an injury risk study is currently building risk functions for both passengers and pedestrians in case, respectively, of harsh braking or collision. Finally, a simulation environment is being set-up. It will allow virtual testing of an autonomous shuttle model by staging aforementioned safety-relevant scenarios.

1 Introduction

The target of the AVENUE project is to demonstrate and pilot the adaptability and efficiency of the deployment of small and medium autonomous vehicles (AV's) in Lyon, Luxembourg, Geneva, Copenhagen and 2-3 replicator cities as of the 3d year of the project. The AVENUE vision for future public transport in urban and suburban areas is that autonomous vehicles will ensure safe, rapid, economic, sustainable and personalised transport of passengers, while minimising vehicle changes. The goal is to provide door to door autonomous transport allowing commuters to benefit from autonomous vehicles.

At the end of the AVENUE project - 4 year period - the mission is to have demonstrated that autonomous vehicles will become the future solution for public transport. The AVENUE project will demonstrate the economic, environmental and social potential of autonomous vehicles - for both companies and public commuters - while assessing the vehicle road behaviour safety.

Making autonomous shuttles 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 autonomous shuttles**. 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 D6.3 describes the methodology for safety evaluation and the current state of implementation for task 6.2, notably including an extensive literature review and our vision for injury risk assessment for both passengers and pedestrian exposed to a collision with an autonomous shuttle, as well as the initial development of the catalogue of safety-relevant scenarios.
We also include known limitations, current risks for upcoming activities, and measures envisaged to cope with them.

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 already 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 provides WP6 with the initial inputs allowing designing safety-related scenarios based on the planned infrastructure and operating conditions for the shuttle.

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. The first draft of this deliverable has provided input for the work in this report.

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. The first drafts of these deliverables have provided input for this report.

1.1 Preamble

Small and medium sized, shared autonomous vehicles (i.e. autonomous shuttles) 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 autonomous vehicles for different transport models that are under development in Europe. Its goals are not only to assess the safety of autonomous vehicles in public transports, but also to demonstrate the economic, environmental and social advantages of autonomous vehicles for both the exploiting companies and the users, opening the way for a full scale adoption of autonomous vehicles in public transport after the end of the project.

Four experimentation/demonstration sites are already 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: shuttles currently 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 shuttles, both in economic and quality of services terms. To demonstrate any relevance, their flexibility would need to be improved (on-demand service), 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).

Figure 1. AVENUE's 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 autonomous shuttles. With nobody behind the wheel, proper situational awareness and swift response to danger from embedded systems are crucial to ensure safety. **Autonomous shuttles 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 from the field tests, description of future plans, and a mix of simulation and physical testing, tasks 6.1 and 6.2 from WP6 will attempt at:

- Identifying situations which might cause safety problems when the operational design domain of the shuttles 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 shuttle in mixed traffic…)

WP6 will concentrate its effort on safety issues which are specific to autonomous shuttles, 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 autonomous shuttle, 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 autonomous vehicles and already understood and addressed 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 vehicles magically "won't crash" thanks to the embedded technology, it is WP6's 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). Occupants in an autonomous shuttle such as NAVYA's Arma can take a much wider range of positions compared to passenger cars, which creates a very challenging environment. This will be addressed within AVENUE 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, NAVYA, as any autonomous shuttle manufacturer, should take great care in ensuring functional and passive safety of its vehicles, but tasks 6.1 and 6.2 in WP6 will focus on risks which are particular to the limitations of autonomous 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?")

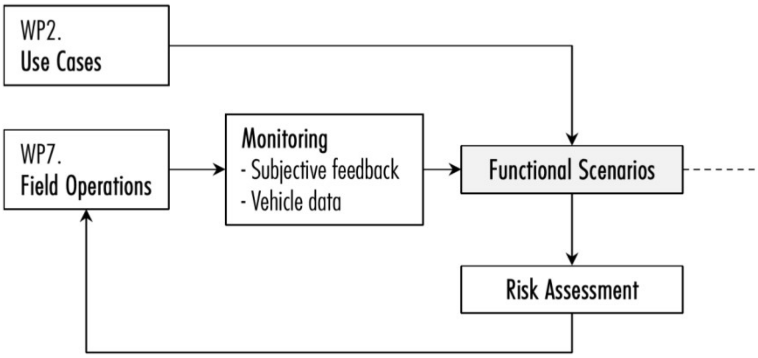
The following chapter presents the methodological approach retained for this safety study. Chapter 3 then summarises the current status of WP6 activities. Chapter 4 focuses on injury risk assessment criteria.

2 WP6 methodology overview

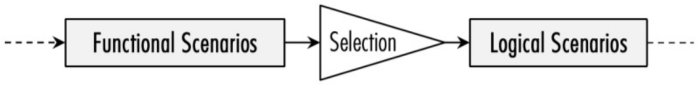
2.1 Outline

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 will be 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 will be carried out.

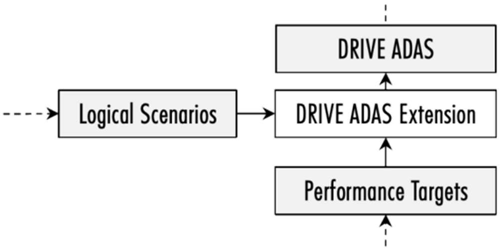


- Safety-relevant scenarios which are specific to autonomous shuttles will be selected and further described, in a quantitative way (i.e. by measurable parameters and their possible range and/or distribution).

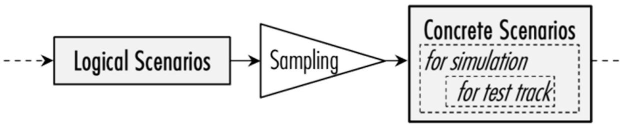


- An injury risk study, taking into account the geometry of autonomous shuttles will be carried out. It will deliver risk functions based on the most important parameters (e.g. passengers injury risk during a braking, based on their position and deceleration profile).

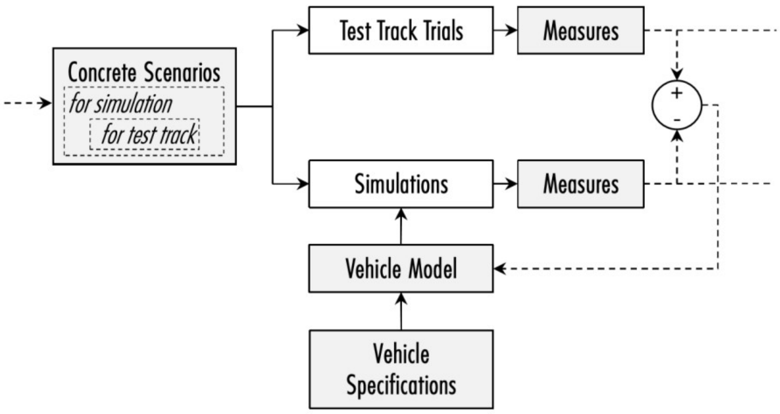
- Relevant scenarios need to be detected and the associated Key Performance Indicators need to be compared to Performance Targets. To this end, AVL's software DRIVE-ADAS will be extended.



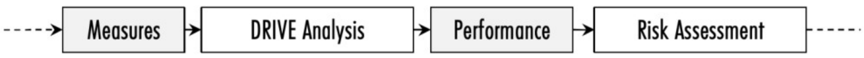
- Some instances of the relevant scenarios will be sampled (i.e. parameters values will be fixed), either to sweep the entire parameter space and build a representative set for a comprehensive risk estimation, or to explore boundary conditions (i.e. conditions where the desired outcome is known, e.g.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



- Those scenarios will be 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 will be 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.

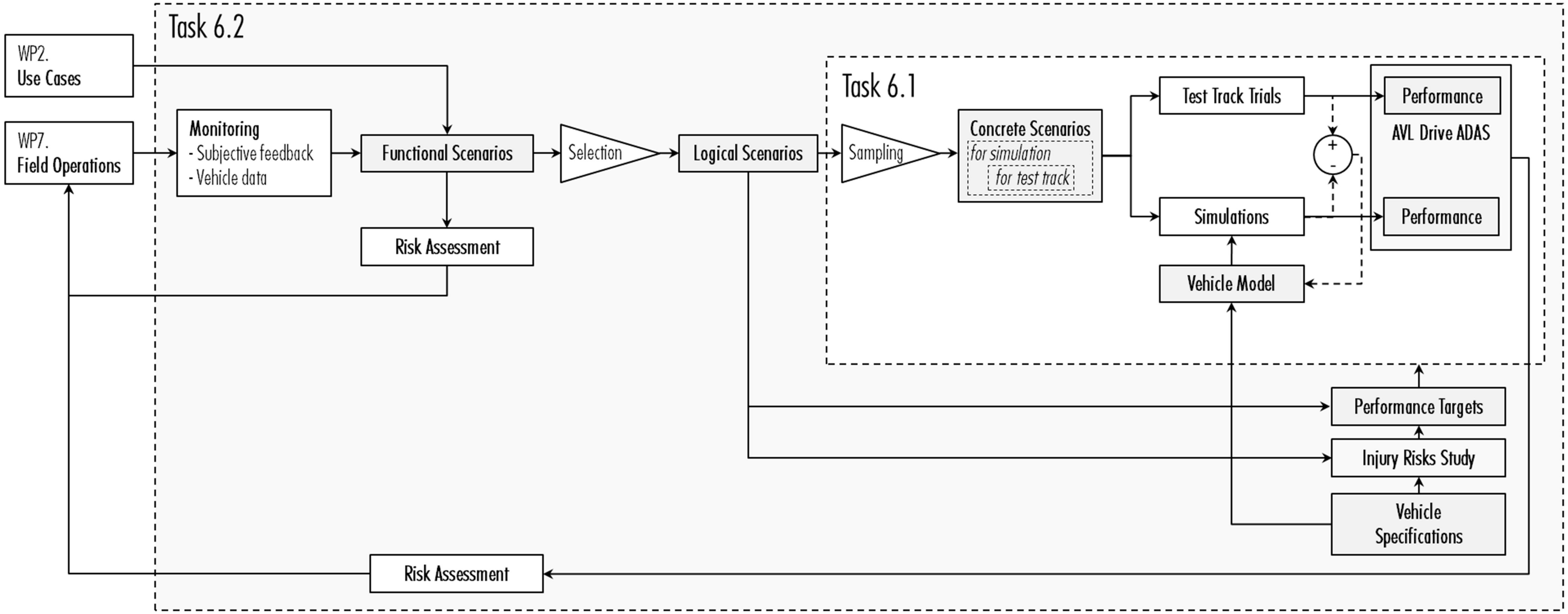


Figure 2. Tasks 6.1 and 6.2 methodology and interactions

2.2 Field data collection

Little feedback exists on the operation of autonomous shuttles. 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 (both currently and during the course of the project, when new routes will be opened).

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 will be described and classified as “high-level” functional scenarios (see definition Section 2.3 below). The importance of each situation will be graded in terms of expected frequency and criticality (e.g. safety perception issue vs actual injury risk).

The proposal is to start this data collection 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 is to systematically collect data during operations in all four test sites, which should provide more quantitative indicators. The data to collect would consist of:

- Dynamic behaviour of the vehicle: speed, acceleration and angular speeds.
- Global state of the decision layer: autonomous 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 will be implemented to detect situations of interest, notably harsh braking and disengagement, which will allow further analysis. This data collection will complement 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 will be 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):

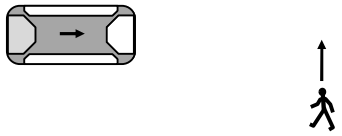
- *Functional Scenarios*: functional scenarios consist of a high level description of a safety-relevant situation. It describes the actors (vehicles, pedestrians…), the environment and the overall timeline/steps of the situation. It is documented as a pictogram and a textual description. Subjective data collection (questionnaires, focus groups) can be sufficient 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 autonomous 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 of 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.

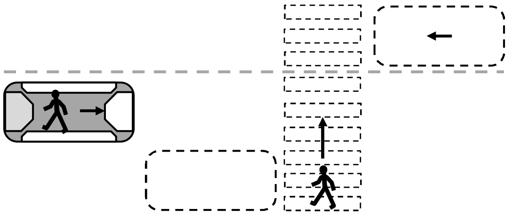
Table 1. Distinction between functional, logical and concrete scenarios

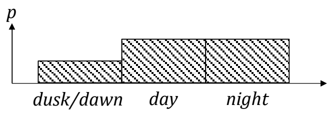
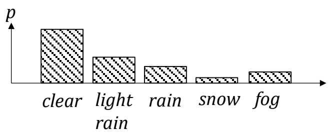
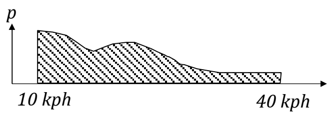
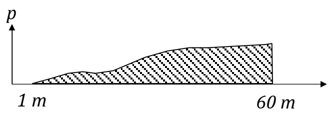
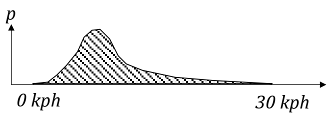
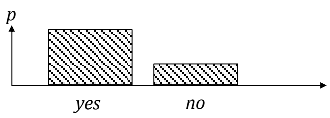
Functional Scenario *(describes the situation in a generic way)*:

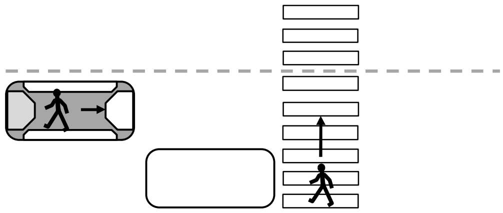
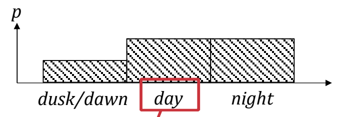
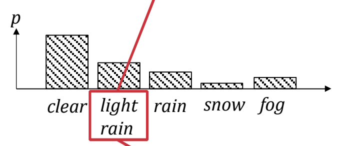
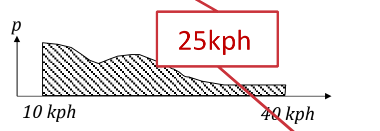
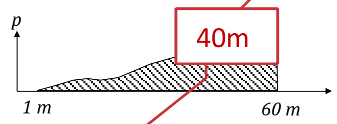
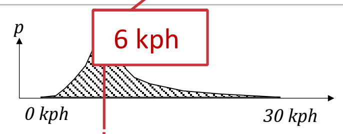
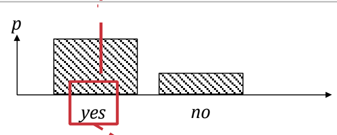
Giving way to pedestrian crossing road.



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	
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	…
…	

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 parameters values (e.g. position, jerk and deceleration, speed at impact…).

As previously explained, our study will largely focus on safety issues which are particular to autonomous vehicles.

We consider being collided by other vehicles a definite probability, likely raised by the currently reported tendency of experimental autonomous shuttles to perform unexpected harsh brakings or stops. 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 autonomous vehicles.
Consequently, AVENUE will first concentrate 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 will allow treating some of the most risky 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 task will produce, 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 will be 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).

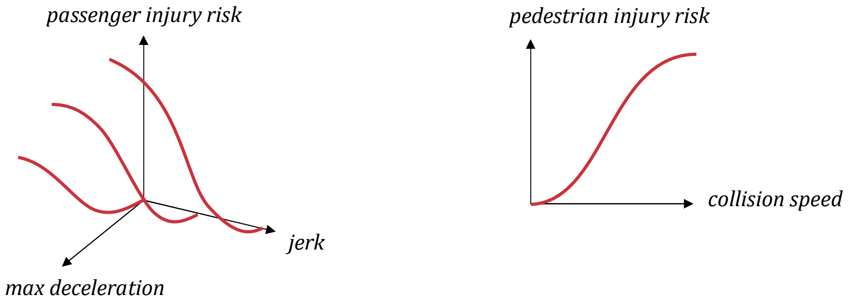


Figure 4. Risk (e.g. AIS ≥ 3 probability) as a function of dynamic parameters

The study will span 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 will be created.

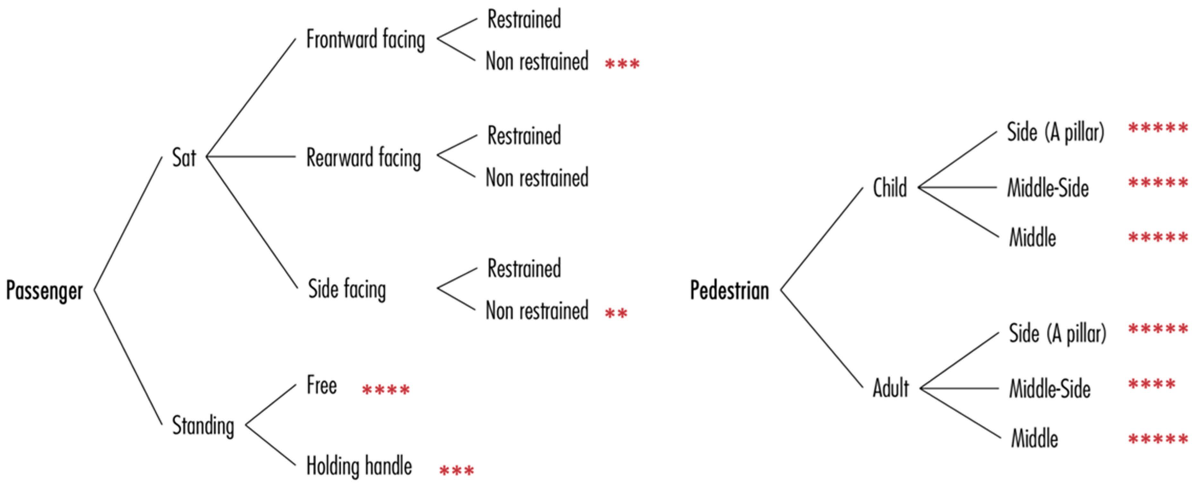


Figure 5. Configurations taken into account in injury risk study. Red stars represent most critical and therefore prioritized configurations

The study, which is already under way, will rely as much as possible on existing literature, but also on finite-element simulations of braking/crash conditions. Those simulations will 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 will be used for each part (e.g. windscreen material will be defined as standard automotive windscreen material).

2.5 Performance targets definitions

Performance targets will be defined for each logical scenario. They will 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 within the project will entirely be under the responsibility of public transport operators.

Logical scenarios detection, calculation of KPIs and assessment of performance targets being attained (or not) will be 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. Test tracks trials scenarios will themselves be a sub sampling of simulation scenarios, to allow direct comparison of the outcomes of both approaches (and therefore improvement of the simulation models).

Ideally, extensive data collection and modelling would allow describing the entire activity of the shuttles 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 autonomous 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 won't allow even such activity to take place at full scale. Therefore, concrete scenarios will be manually sampled to allow exploring most frequent and/or most feared conditions, as defined by, and under the responsibility of public transport operators, which will also specify associated performance targets.

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 are planned in Task 6.1, the project did not allocate specific funding for facility and equipment renting, neither for the necessary on-site support. Solutions therefore need to be found, such as, e.g. provision of previously existing test data, external funding, budget shifts within the project.

[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 will be extended within AVENUE to support scenarios which are specific to autonomous shuttles.

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 are 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 autonomous vehicle can be modelled and used.

The autonomous 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).

In AVENUE, the initial 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, improving obstacles behaviour prediction.

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

Simulations will produce outputs such as speed, acceleration, relative position to obstacles, in a wide variety of scenarios. Those outputs will then be given as inputs to AVL-DRIVE ADAS, which will calculate 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 autonomous shuttles, and a desired reusability of project results for new vehicles / routes dictate that tasks 6.1 and 6.2 from AVENUE will focus on:

- Safety Of The Intended Functionality (SOTIF),
- for autonomous, urban shuttles,
- 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 won't allow carrying out a complete probabilistic risk assessment. However, the currently offered methodology will allow:

- 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 chapter describes the implementation work carried out so far, the difficulties encountered and potential ways to circumvent them.

3 Current Status

This chapter describes the current status of work within WP6, for each activities previously described.

3.1 Field data collection

As previously exposed, field data collection relies on the availability of different data sources:

- Incident reports from operators;
- Safety drivers feedback, collected through focus groups;
- Continuous data acquired from vehicles.

3.1.1 Incident reports

No harmonised data collection currently exists within AVENUE regarding incident reports. This means that each operator keeps 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 many technical difficulties which are 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 shuttle. Although undoubtedly useful, this data also has limitations in the sense that the exact driving environment was not necessarily being described and also 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.

Therefore, WP6 considers organising a centralised data collection of safety-relevant incidents through a WP6-developped framework. While the feasibility of such centralised data collection and corresponding database is under consideration, focus groups, which provide more guidance in data collection, will be organised.

3.1.2 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).

They will consist of open but guided discussions between groups of safety drivers and an interviewer/moderator, around the topic of safety.

Each focus group will gather between 4 and 8 participants, which ideally:

- 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.

The discussion will 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.

This discussion will be followed by a workshop where relevant safety-relevant scenarios will be discussed and pinned on a map of the shuttles' route.

Depending on the status and availabilities of different operation sites, focus groups will be carried out during the first semester of 2020. It is expected to start at one of the demonstration sites in a very short term, learn from this experience to adjust if necessary and perform it in other demonstrators.

The complete outline to be used during those focus groups is presented in Annex A.

3.1.3 Vehicle data collection

As previously exposed, data collection should be performed in three different kinds of contexts, to build three complementing datasets addressing different goals:

- **Events dataset** (i.e. each automation disengagement / harsh braking / operator takeover):
  - To understand their cause, particularly in which driving scenario they occur;
  - To identify parameters characterising the corresponding scenario, and the values which lead to an undesired event;
  - To assess their occurrence.

  → This dataset should ideally be continuously collected during operation and therefore, data collection should be automated, i.e. part of the API.
  → Data for each event should include a few seconds of continuous data acquisition before and after the event.

- **Continuous dataset** (i.e. rich, continuous data, collected during complete trips):
  - To count occurrence of each driving scenario which has been identified as potentially safety relevant ;
  - To measure values of parameters which are relevant for each scenario (i.e. those that, when reaching a certain combination of values, would lead to an undesired event) and therefore, build the parameters space for each scenario.

→ This dataset should ideally be collected for a period of one year to include seasonal effects. However, as data collection will likely be a manual operation, it is estimated that a few weeks of continuous collection for each route will already bring a lot of useful data.

- Additionally, a **test track dataset** (i.e. rich, continuous data, collected in controlled environment, i.e. test track, in predefined scenarios) will be constituted:
  - For direct safety assessment in select scenarios
  - To tune model used in simulation

Ideally, only data collection context / data download methods would vary between the three aforementioned dataset. The content of data made available should be the same. The necessary measurements have been listed by WP6 (the complete list is reproduced in Appendix B) and that list has been transferred to both NAVYA and operators to assess feasibility.

It appears that two ways to collect data coexist:

- **Data collection through NAVYA's API,** which contains:
  - Low frequency state of each shuttle (e.g. speed, location, driving mode)
  - Events, including strong & severe braking and switch to manual mode

  This data could allow gathering general statistics about operations (e.g. speed distribution depending on time/traffic) and identify problematic conditions (by e.g. creating heat maps of undesired events over maps of the routes). It partially covers the requirements of the events dataset. Practical ways to access and log it, either through NAVYA or using AVENUE's infrastructure are currently being investigated. Authorisations are also currently being asked to operators.
- **"Blackbox" data access**, which contains:
  - High frequency raw sensor data, including video
  - Preprocessed data (e.g. objects detection)
  - The complete state of the system

  This data is continuously recorded by the vehicle itself and written over if not retrieved after a few hours of operation. It could address continuous dataset and test track dataset requirements. However, it requires daily manual data collection (direct access on the vehicle), which will unfortunately constrain continuous data collection to rather short durations. NAVYA is currently investigating how much of the available measurements they are willing to share while still protecting their own intellectual property, while discussions are ongoing with operators to address both logistics (data collection organisation) and legal (GDPR) concerns.

3.2 Scenarios creation

Safety-relevant scenarios are the core of task 6.2. They result from different forms of data collection, and are the foundation upon which simulations and test track trials are built in task 6.1. They describe the breadth of challenges that an autonomous shuttle has to address, in a usable way.

As the goal of an autonomous shuttle is to reliably follow a predefined path at a certain speed, safety-relevant scenarios are defined, in the context of WP6, as **situations in which, had the shuttle continued its programmed trajectory and speed, a collision would have occurred**.

As previously stated, and as the following figure shows, the first step in scenario definition consists in describing at a high-level those safety-related situations based on inputs coming from the use cases definition, and data gathered from field operations.

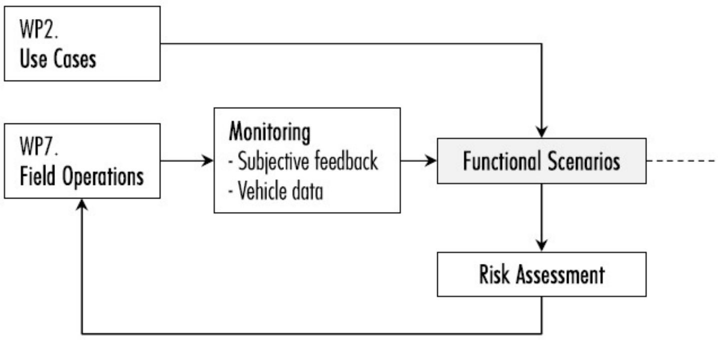


Figure 7. Functional scenarios within the safety assessment methodology

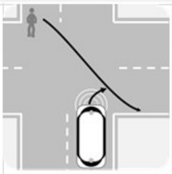
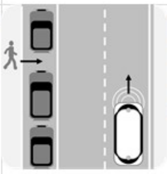
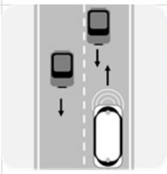
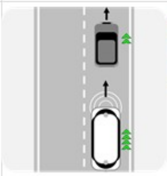
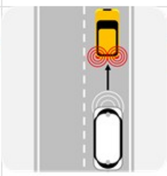
Following this workflow, WP6 was able to utilise deliverables from WP2 (namely from the first iteration and a draft on the second iteration) and from WP7 (namely drafts for the first iteration) in order to prepare the typology of scenarios that would prove relevant from a safety stand-point according to the use cases defined and refined by each one of the operators.

The functional scenarios produced at this stage in WP6, as well as the template to define them, stem from previous research in driver behaviour and accident causation studies. Regarding driver behaviour, Naturalistic Driving Studies (NDS) such as the UDRIVE project (UDRIVE Project, 2017) and research studies deriving from the exploitation of such databases provide configurations of Safety Critical or Safety Relevant Events (SCE or SRE). Analogously, the VOIESUR database fulfils this purpose from the accident research perspective in conjunction with other sources such as the IGLAD project (IGLAD Project, 2018) and the Waymo Safety Report (WAYMO, 2018).

Combining all those sources, task 6.2 was able to develop an initial version of a **functional scenarios catalogue, which currently consists of 64 main scenarios**, each of which having multiple variants.

The scenario catalogue is provided in a separate document and the template is provided in Appendix C. The following table provides some examples of scenario definitions.

Table 2. Scenario examples from the functional scenario catalogue (V1.0)

Scenario	Pictogram	Scenario specific parameters	Other Road User(s)	Infrastructure	Trajectory Other Road User	Trajectory AV
Pedestrian crosses diagonally in intersection from farside to nearside, front facing AV - AV turning right		• AV programmed speed • Pedestrian speed and height • Infrastructure type	• Pedestrian	o • Unidirectional roadway • X intersection o • Bidirectional roadway • X intersection	• Diagonally • From farside to nearside • Front facing AV	• Turning right • On intersection
Pedestrian crosses outside of crosswalk from nearside to farside and is masked by static obstacle(s) - AV going straight		• AV programmed speed • Pedestrian speed and height • Infrastructure type • Obstacles number, dimensions, and position	• Pedestrian	o Unidirectional roadway o Bidirectional roadway	• Going forward • From nearside to farside	• Going forward
Pedestrian crosses outside of crosswalk from farside to nearside and is masked by static obstacle(s) - AV going straight		• AV programmed speed • Pedestrian speed and height • Infrastructure type • Obstacles number, dimensions, and position	• Pedestrian	o Unidirectional roadway o Bidirectional roadway	• Going forward • From farside to nearside	• Going forward
AV is in roundabout and other vehicles become prioritary due to traffic signalling		AV programmed speed and trajectory, traffic lights state detection, other road user's trajectory, and speed.	Light vehicle or heavy vehicle or motorcycle or Cyclist	Roundabout	• Inserting into intersection • In front of AV • Going forward	• On intersection • Going forward
AV is in roundabout and a prioritary vehicle inserts in front of it		AV programmed speed and trajectory, traffic lights state detection, other road user's trajectory, speed, priority detection signal, delay of absolute priority confirmation before encountering the priority vehicle.	Priority vehicle	Roundabout	• Inserting into intersection • In front of AV • Going forward	• On intersection • Going forward
Cut-in by another vehicle		AV programmed speed and trajectory, other road user's trajectory, speed and acceleration. Infrastructure type.	light or heavy vehicle	o Unidirectional roadway or o Bidirectional roadway	• In same direction as AV • Not in same lane as AV • Lane change to the right • In front of AV	• Going forward
Oncoming user takes AV's lane in order to overtake another user		AV programmed speed and trajectory, other road users trajectories, speeds and acceleration. Infrastructure type.	light or heavy vehicle	o Unidirectional roadway or o Bidirectional roadway	• In same direction as AV • Not in same lane as AV • Lane change to the right • In front of AV	• Going forward
AV follows vehicle going slower than the target speed		AV programmed speed, preceding vehicle speed and speed profile (decelerating progressively or at constant speed).	Light vehicle or heavy vehicle or motorcycle or Cyclist	o Unidirectional roadway or o Bidirectional roadway	• In same direction as AV • In same lane as AV • Going forward • In front of AV	• Going forward
AV follows a vehicle performing a harsh braking		AV programmed speed, preceding vehicle speed before braking, preceding vehicle braking profile.	Light vehicle or heavy vehicle or motorcycle or Cyclist	o Unidirectional roadway or o Bidirectional roadway	• Going forward • In same lane as AV • In front of AV	• Going forward

NOTE:
Unless indicated otherwise:
"•" stands for the 'AND' operator
"o" stands for the 'OR' operator

As can be seen on that table, each functional scenario identifies the most important parameters that may influence the outcome of a situation, such as speed, distance, braking… These parameters must then be measured or derived from continuous data collection in order to build logical scenarios, from which concrete scenarios can be sampled and weighted.

For now, the catalogue is under review by operators, in order to rank them (following Table 3 below) and possibly identify some which are missing, as well as by NAVYA, who should identify for each of them whether they are currently handled by the vehicle and if not, whether their support is planned to be deployed at a later stage within AVENUE.

Table 3. Scenario Ranking by PTOs

Scenario Ranking System			
High Priority	**Medium Priority**	**Low Priority**	**Will never occur**
scenario to be highly prioritised in the study due to current or future potential severity and/or occurrence rate.	scenario to be addressed if possible in the study due to current or future potential severity and/or occurrence rate.	scenario to be prioritised in the study due to current or future potential severity and/or occurrence rate.	its technically impossible for the scenario to occurr during the AVENUE project

These feedbacks, combined with focus groups outcomes, will result in a consolidated scenario catalogue. Most important scenarios will then be further described as **logical scenarios**, and proper sampling will constitute **concrete scenarios** to be simulated and reproduced on test tracks in task 6.1.

3.3 Injury risk assessment

As previously exposed, one of the starting points of the study is being able to estimate injury risk, notably for passengers and passers-by resulting, respectively, from harsh braking from and collision with an autonomous shuttle. This is the goal of the **injury risk study**, which has started from the onset of AVENUE project by an extensive literature review, and now continues in the form of numerical finite-element simulations. It aims at providing relevant but also practical criteria for injury risk as a function of dynamic measures (e.g. deceleration profile, speed at collision), measures which can either stem from test track studies or scenarios simulation.

As this study represents a significant effort, the accordingly significant reporting is given its own chapter (chapter 4, starting page 26).

3.4 Scenario Simulations

Although the selection of the most important scenarios to simulate has not yet been done, implementation work on the simulation environment has started. The aim here is to provide a virtual environment reproducing infrastructure and surrounding traffic, in which a model of the autonomous vehicle can be integrated and confronted to safety-relevant scenarios. The resulting dynamic measures can then be compared to performance targets to, for instance, estimate whether the probability of a passenger falling and hurting him/herself is acceptable or not.

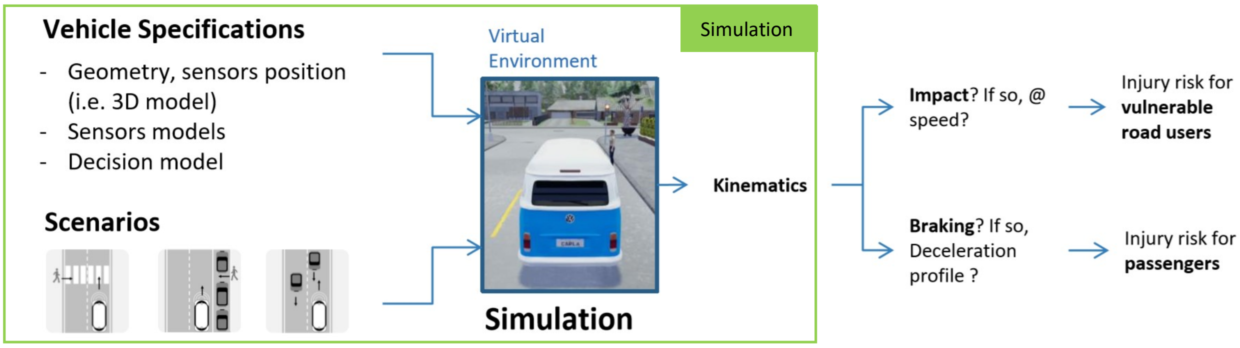


Figure 8. Overview of the simulation procedure.

3.4.1 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 selected for now. CARLA is free and open source software benefiting from an active community. It integrates 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 might negatively impact 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 arise concerning vehicle model development, using Vires Virtual Test Drive (VTD), which is a commercial alternative, is starting to make sense (see below).

However, at the moment of writing, CARLA is still AVENUE's first choice, and at least a good platform to test scenarios implemented in OpenSCENARIO format, which could later be used with another compatible tool.

3.4.2 Vehicle model development

As previously stated, a model representing the autonomous shuttle must 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 not to perfectly mimic NAVYA's own shuttle, but rather to develop a much simplified model. This model could be tuned to reasonably match NAVYA's Arma performance, but also 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 might be too much given AVENUE's resources. Two possibilities for this vehicle model are currently under consideration:

- **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 be tested with the actual software that is being used in currently operated shuttles. This would consolidate 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 would 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 have pros and cons which are summarised in Table 4 below. Both are still under consideration at the time of writing.

Table 4. 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 have to 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 - Complex interactions with NAVYA to define a proper description of the vehicle's behaviour/performance - Relies on expensive Vires VTD.

3.4.3 Scenarios implementation

Whatever the tool finally chosen (CARLA or VTD) and the approach favoured concerning vehicle model (NAVYA's software or VSM/Model.CONNECT), scenarios implemented using OpenSCENARIO can be used. Therefore, until definitive choices have been made, work focuses on implementing scenarios in OpenSCENARIO, and testing them with CARLA, using a generic vehicle model (VW T2, which has a footprint similar to that of a shuttle). Figure 9 shows stills from a simulation run in CARLA of a pedestrian crossing scenario, implemented in WP6.

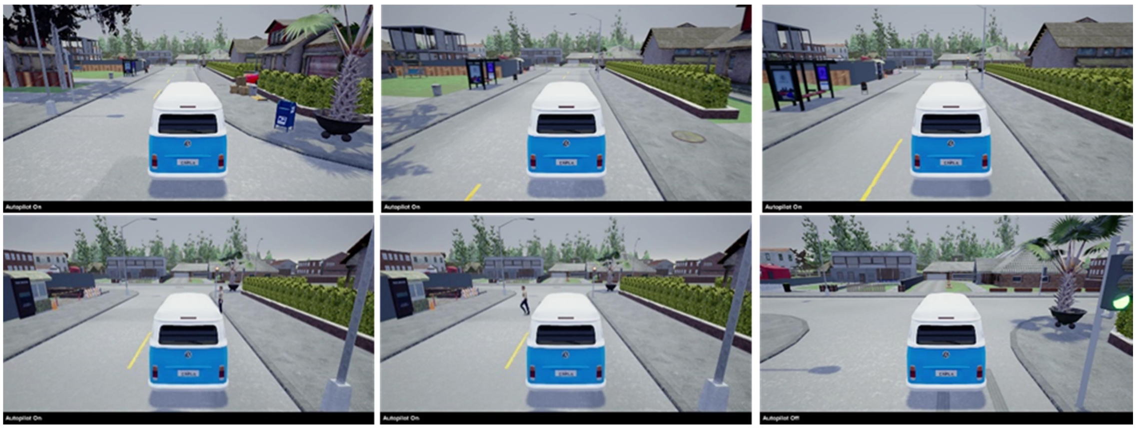


Figure 9. Image series of a scenario from top left to bottom right.

4 Injury Risk Study

As previously exposed in Chapter 2, section 2.4, page 12, 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 most risky 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 10 below).

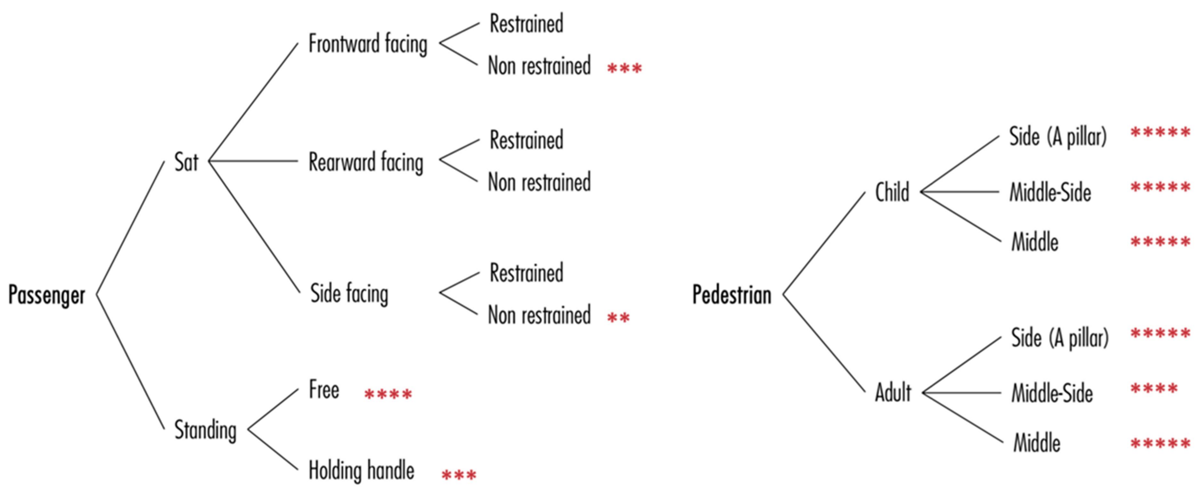


Figure 10. Configurations taken into account in injury risk study. Red stars represent most critical and therefore prioritised configurations

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 first simulation results.

4.1 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.

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).

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.

4.1.1 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 a 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 centers 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.

4.1.2 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 11). 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 11), 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 11).

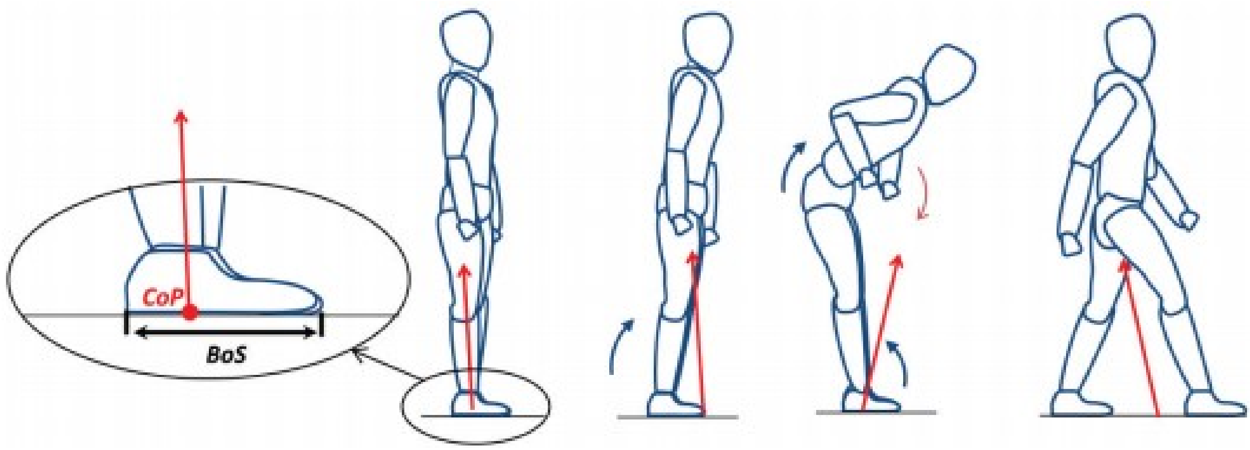


Figure 11. Different strategies for retaining balance. The neutral position; ankle strategy; hip strategy; stepping strategy (Vallée, 2015).

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.

4.1.3 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 a particular 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 also 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 12.

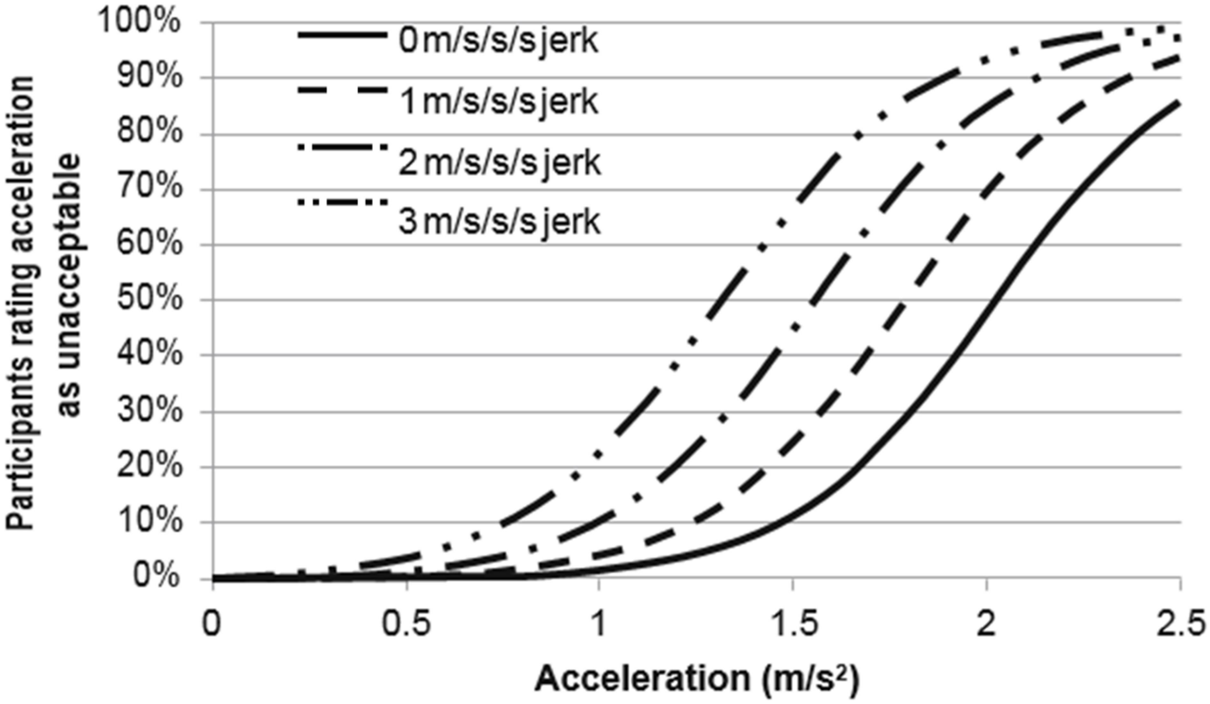


Figure 12. Acceptability of acceleration/jerk levels (Hiroaki, 1995).

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 13 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.

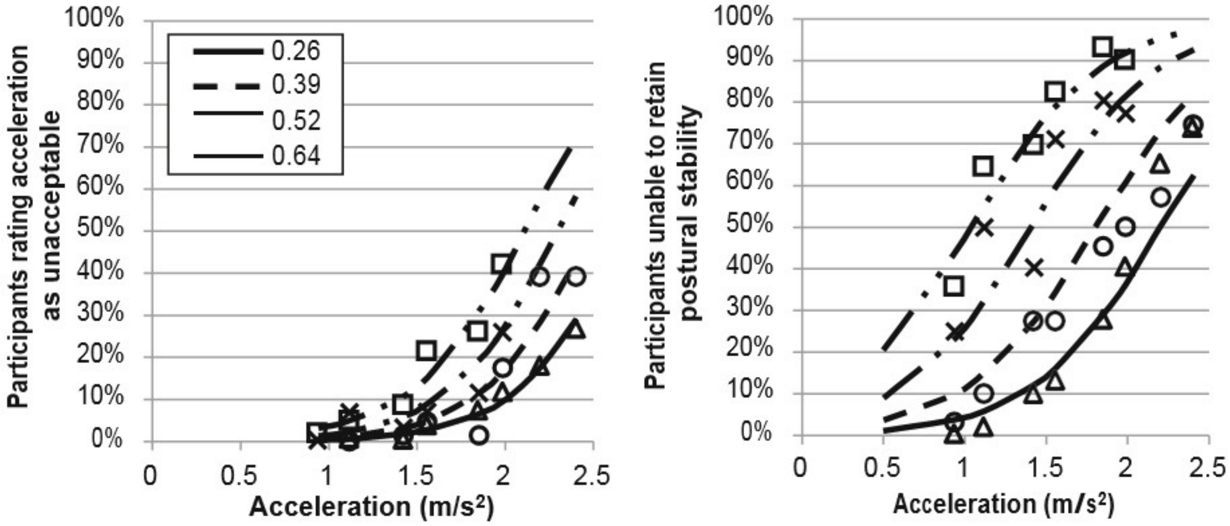


Figure 13. Subjective and objective results for forward-facing standing passengers (Koji, Hiroharu, Hiroaki, & Hiroshi, 2007). These figures were extracted from the article by Powell & Palacín (2015).

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 14). 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.

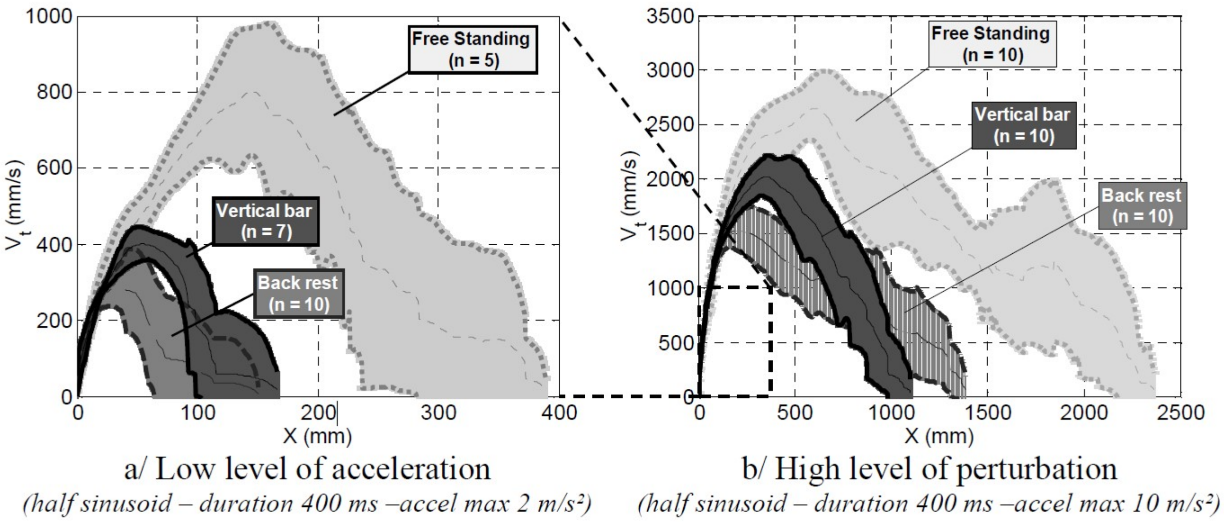


Figure 14. Experimental corridors for head tangential velocity as a function of its X-coordinate, for the 6 tests configurations (Robert, Beillas, Maupas, & Verriest, 2007).

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 15). 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.

	Discomfort scale (CP50 normalized)																				
	Discomfort = 2.02 * Jerk +20.6* Acceleration -0.51* Jerk*Acceleration																				
	Acceleration (m/s²) (directly normalized from F_{max})																				
Jerk (m/s³)	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9
2	15%	17%	19%	21%	23%	25%	27%	29%	31%	33%	35%	37%	39%	40%	42%	44%	46%	48%	50%	52%	54%
4	23%	25%	26%	28%	30%	32%	34%	35%	37%	39%	41%	43%	45%	46%	48%	50%	52%	54%	55%	57%	59%
6	30%	32%	33%	35%	37%	39%	40%	42%	44%	45%	47%	49%	51%	52%	54%	56%	58%	59%	61%	63%	64%
8	37%	39%	40%	42%	44%	45%	47%	49%	50%	52%	53%	55%	57%	58%	60%	62%	63%	65%	66%	68%	70%
10	45%	46%	48%	49%	51%	52%	54%	55%	57%	58%	60%	61%	63%	64%	66%	67%	69%	70%	72%	73%	75%
12	52%	53%	55%	56%	57%	59%	60%	62%	63%	65%	66%	67%	69%	70%	72%	73%	74%	76%	77%	79%	80%
14	59%	60%	62%	63%	64%	66%	67%	68%	70%	71%	72%	74%	75%	76%	78%	79%	80%	81%	83%	84%	85%
16	66%	68%	69%	70%	71%	72%	74%	75%	76%	77%	78%	80%	81%	82%	83%	85%	86%	87%	88%	89%	91%

Figure 15. Passenger discomfort in function of the jerk and the acceleration (adapted from Robert & Vallée, 2014).

4.1.4 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 16).

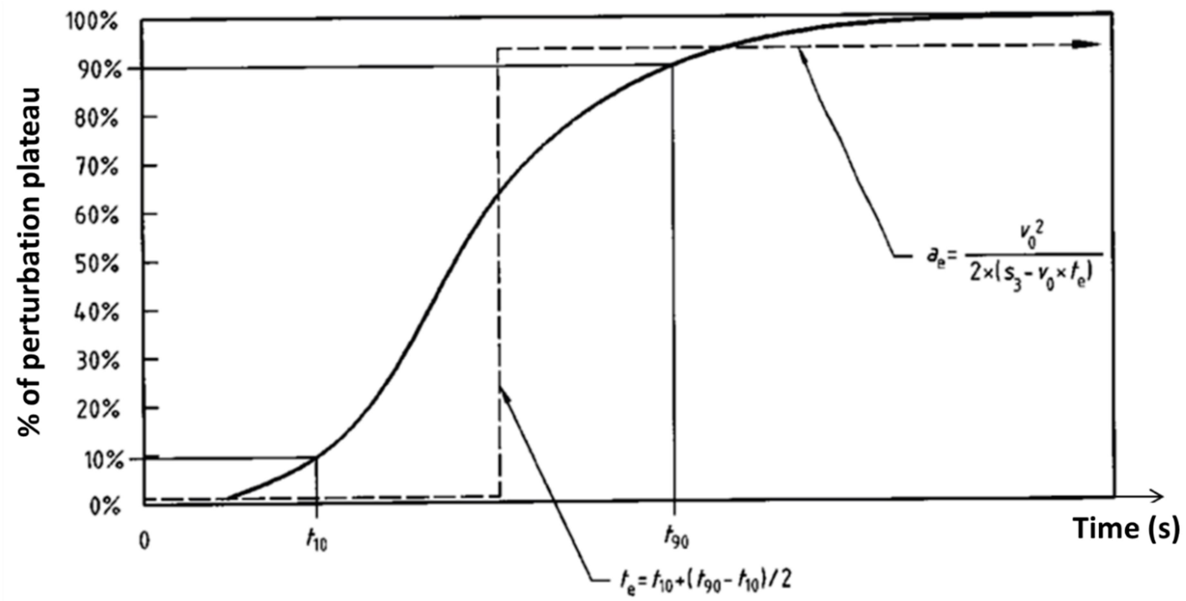


Figure 16. Illustration adapted from standard EN 13452-1 representing the braking profile and parameters used in the standard.

The choice of braking parameters, in particular 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.

4.1.5 Injury tolerance and criteria

Traumatic injuries occurred 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 related 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 which is in widespread use, and this is 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 every body assigning a score which ranges from 0 (AIS0) to 6 (AIS6) which represents a certain threat-to-life associated with an injury.

4.1.6 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 4.3 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 indicated 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 shuttle will be performed in Section 4.3.

4.2 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).

4.2.1 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 17). 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.

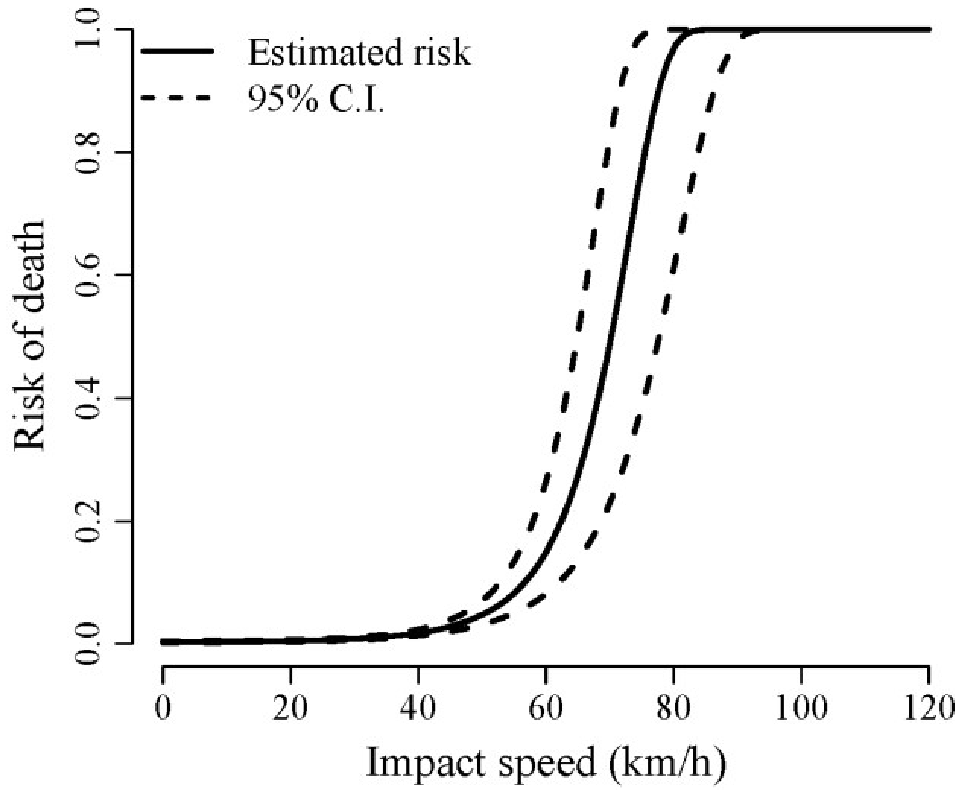


Figure 17. Probability of death according to impact speed, with 95% CI (Martin & Wu, 2018).

4.2.2 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 et al. (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.

The following front structure are of particular interest:

- **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 18, A) to avoid higher body rotations and higher injury risk at the secondary impact for child pedestrians.

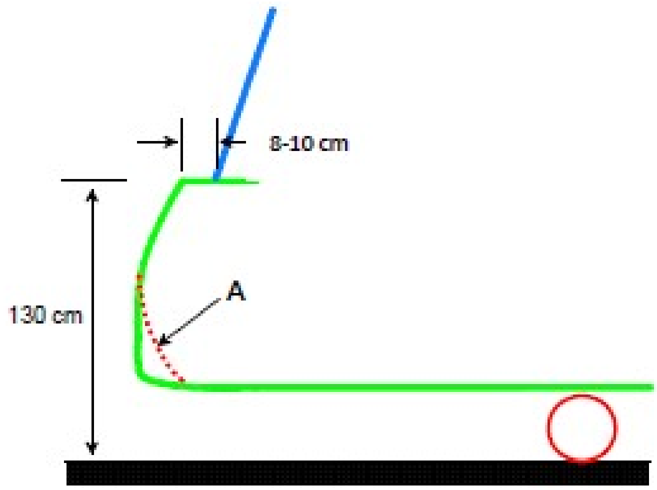


Figure 18. Potentially critical areas in tram front geometries (Weber, Muser, & Schmitt, 2015)

- **Bumpers**: often the initial contact structure in pedestrian impacts. The shape of today's bumper structures aim 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**: a sufficient 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 sufficient structural stiffness, in particular 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 19, A). Structural parts located higher than 5-8 cm but lower than 25 cm above the ground (Figure 19, 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 19, C) can prevent a contact with the wheels.

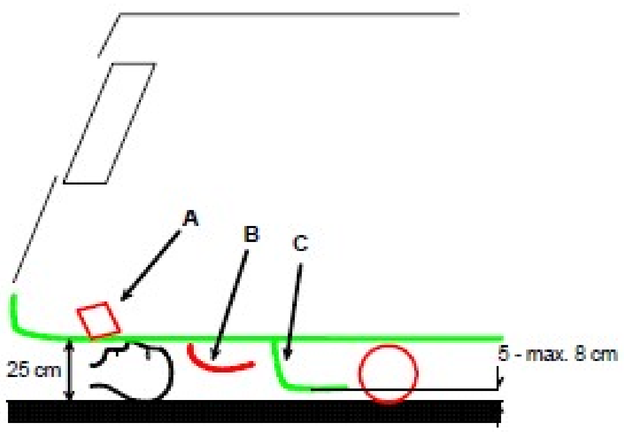


Figure 19. Potentially critical areas under the tram (Weber, Muser, & Schmitt, 2015).

4.2.3 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

4.2.4 Injury tolerance and criteria[2]

[2] This section shares contents with *Section 0 "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
ae minimal (m/s-2)	0-1.2	1.2	1.2	2.8	2.8
te 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
ae 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 te represents the equivalent braking time. It is calculated from the average between t10 (i.e. the delay time of braking demand up to 10% of maximum deceleration level) and t90 (i.e. the response time of the request for braking up to 90% of the maximum deceleration level). The value ae is the equivalent deceleration: it is determined from the initial speed of the vehicle (v0), braking distance (s3) and te (Figure 16).

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.

4.2.4.1 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 4.1.5 "Injury tolerance and criteria".
The criterion HIC, presented in Section 4.1.5 "Injury tolerance and criteria" is currently used to assess pedestrian safety

4.2.4.2 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 a large number of 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

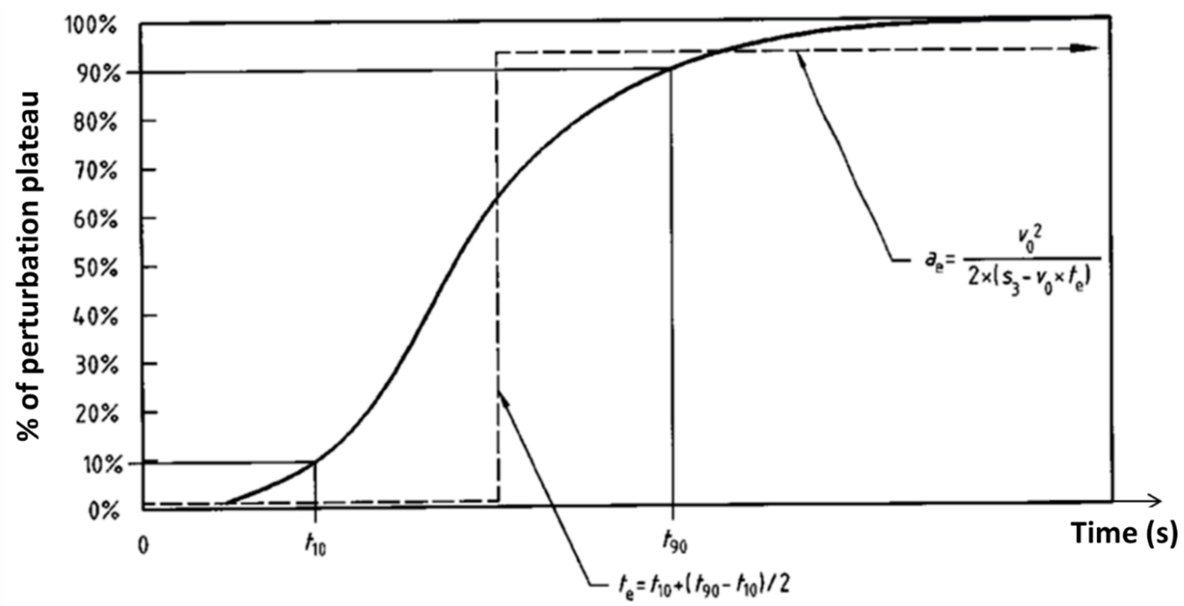


Figure 16. Illustration adapted from standard EN 13452-1 representing the braking profile and parameters used in the standard.

The choice of braking parameters, in particular 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 (Amax = 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.
Injury tolerance and criteria"

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).

4.2.5 Vehicle safety standards for pedestrian and cyclist safety

Pedestrian safety standards were developed by the European Enhanced Vehicle Safery 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 20 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]		JNCAP		KNCAP C-NCAP		EU Regulations 78/2009 and 631/2009	UN R127 KMVSS 102-2	GTR No. 9	Japan Article 18 Attachment 99
		max. score	zero score	max. score	zero score	max. score	zero score	Phase 2			
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[2])		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[12]	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 20. 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 21). 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.

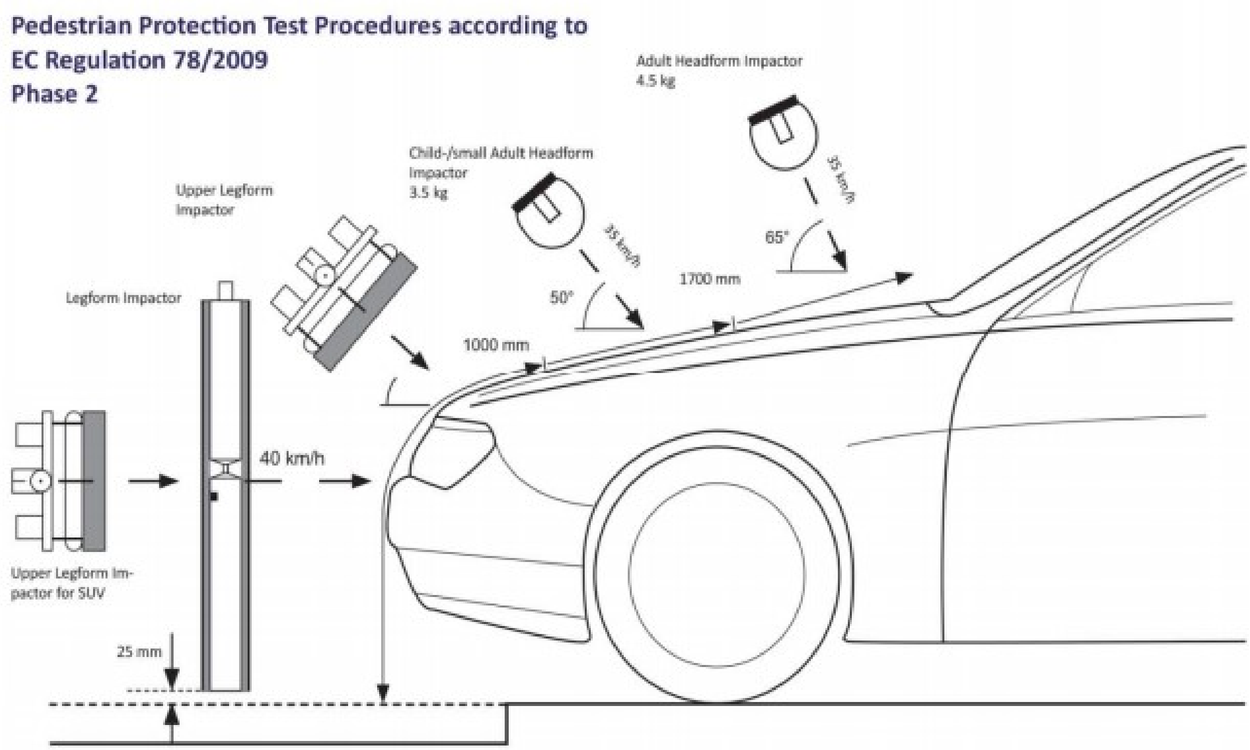


Figure 21. Pedestrian impact testing according to EC78/2009 (figure by carhs).

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 shuttle impacting a virtual pedestrian performed in Section 4.4 will allow a better understanding of the necessary updates.

4.2.6 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 shuttle impacting a virtual pedestrian will be performed in Section 4.4.

4.3 Head injury risk for standing passengers in case of AV harsh braking

4.3.1 Preamble

In Section 0, 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 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 beyond the budget and scope of the project to implement physical tests.

Numerical simulations involving a falling standing crash test dummy inside a braking shuttle 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.

4.3.2 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 autonomous shuttle. 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 autonomous shuttle. 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 shuttle
    - 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 shuttle. It also to speed up significantly the simulation of the standing passenger falling in the vehicle model since all vehicle components can be modelled as rigid bodies.

4.3.2.1 Vehicle interior model

The vehicle model used in this study is based upon the shuttle vehicle developed by NAVYA (Figure 22). A Finite Element model of the vehicle interior was generated based on the CAD surfaces provided by NAVYA.

Figure 22. NAVYA Shuttle. 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 23). 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.

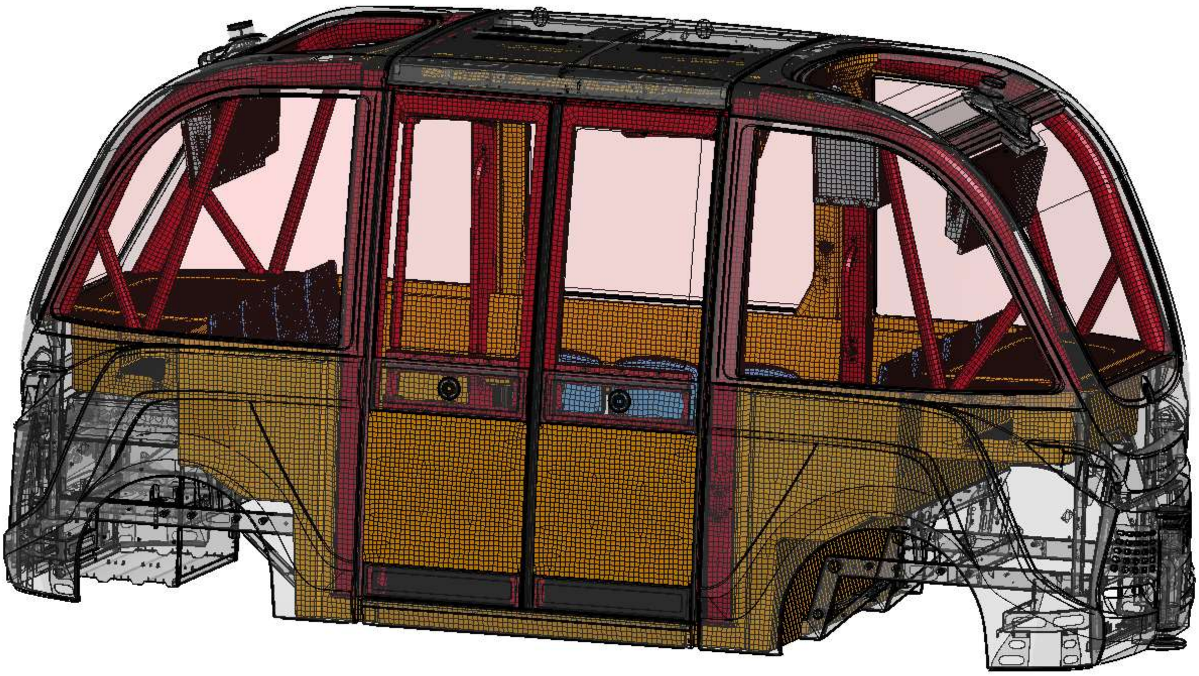


Figure 23. Vehicle interior model.

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 24). 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).

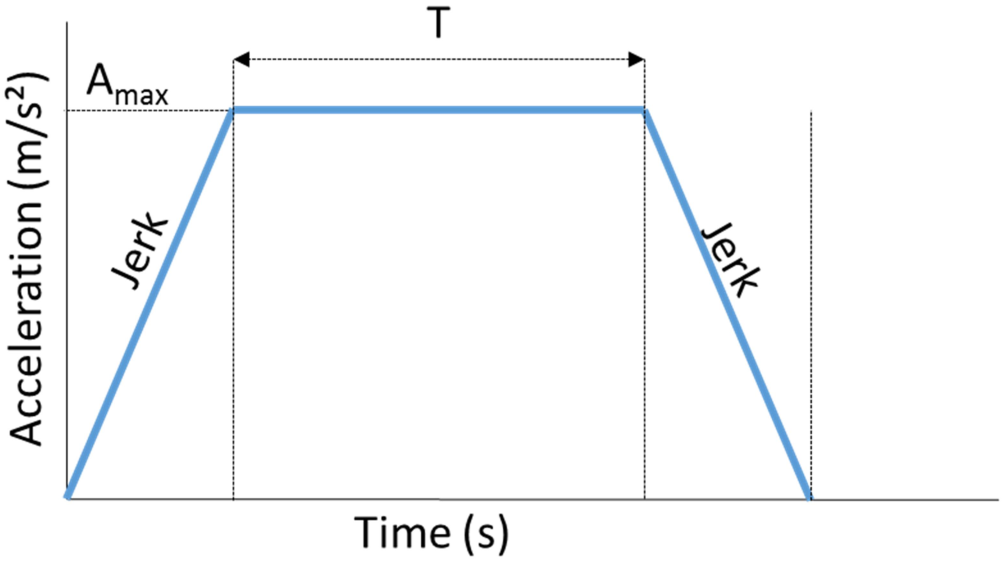


Figure 24. Parametric deceleration pulse used in this study.

4.3.2.2 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 a large number of simulations.

Therefore, the standing passenger was the Hybrid III 50th Percentile Male Standing model (1.74 m, 75.7 kg) distributed by LSTC (Figure 25). 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 25. 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.

4.3.2.3 Parametric study

CEESAR will develop a plan to investigate the passenger kinematics that falls during the emergency braking. This plan will outline a simulation matrix for a parametric study that will include different passenger positions, locations, and pulse characteristics for the models. It is expected that the simulation matrix will incorporate a structured sampling of the parameter space, either full factorial design or Latin Hypercube sampling design, depending on the number of factors and levels.

4.3.2.4 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 shuttle (Figure 26). 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.

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

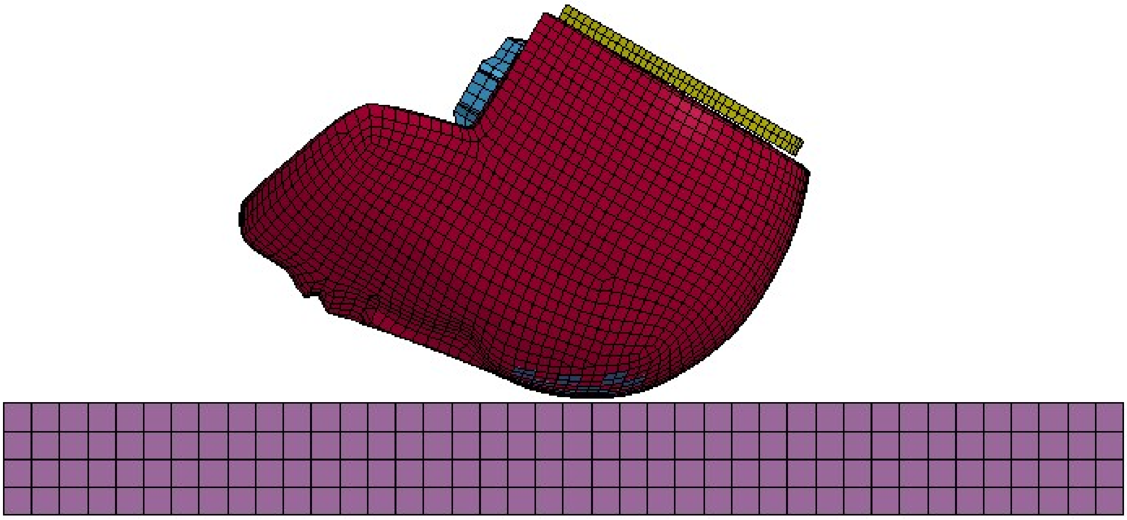


Figure 26. Free Motion Headform (LTSC).

4.3.2.5 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 27). 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).

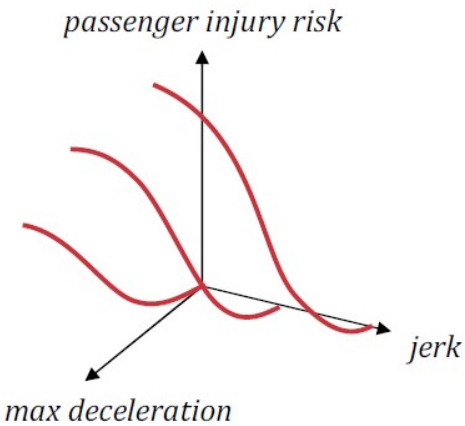


Figure 27. Risk (e.g. AIS ≥ 3 probability) as a function of dynamic parameters

4.3.3 Preliminary results: standing passengers

In order to represent the appropriate range of scenarios that can represent the investigation cases, and establish the suitability of the chosen models to evaluate injury risk for passenger in an automated shuttle, a preliminary simulation was performed.

In this scenario, the braking characteristics representing as the higher range of expected braking performance was chosen (Jerk = 8 m/s^3, Peak acceleration = 5 m/s^2; Figure 28). The passenger model was positioned in the center of the vehicle facing the opposite direction of the movement.

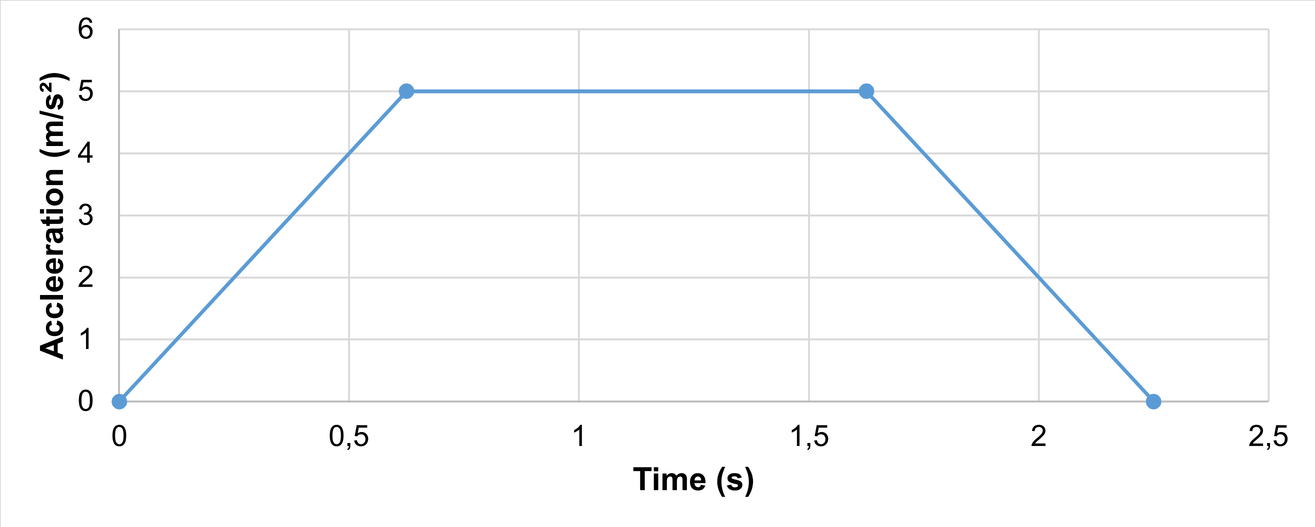
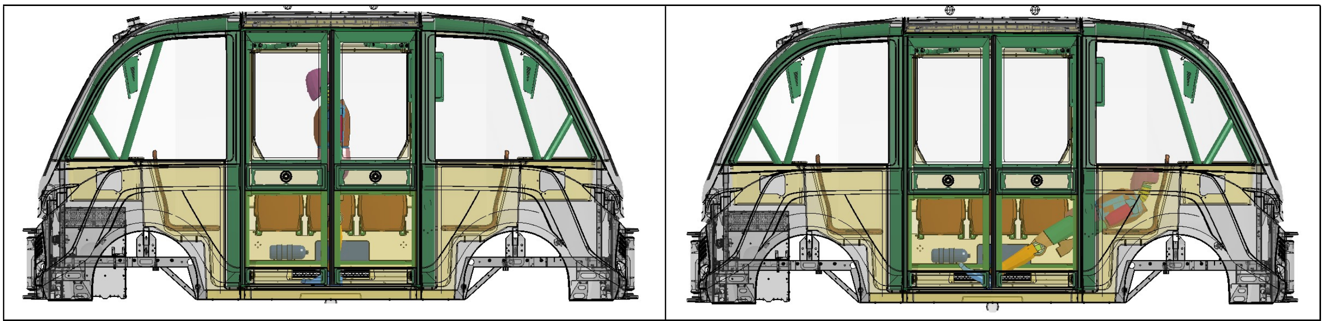


Figure 28. Deceleration curve provided as input of the simulation.

The simulation successfully terminated with no error. Head impact on the seat was recorded at 781 ms (Figure 29). At impact, the head velocity was 4.5 m/s relative to the vehicle (Figure 30).



0 ms	Head impact at 781 ms

Figure 29. Dynamic responses of a standing passenger within the baseline scenario.

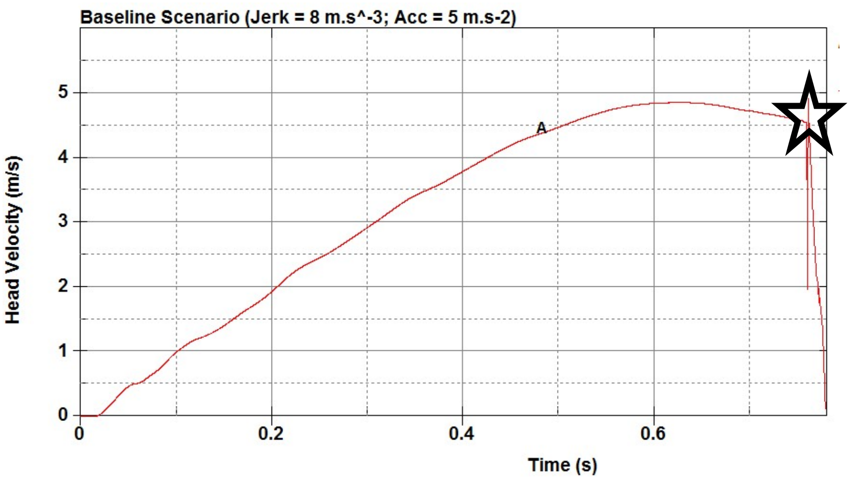


Figure 30. Head velocity time history obtained in the baseline scenario. At impact (t = 781 ms, indicated by the star), the head velocity was 4.5 m/s relative to the vehicle.

In order to quantify the head injury risk, a dummy head model (Free Motion Headform) was then projected against a floor of variable stiffness covering the range of material stiffness to be expected in the shuttle. The linear velocities, angular velocities, and linear acceleration extracted from the first simulation were used as inputs.
Table 7 summarizes the results obtained for the baseline scenario regarding the HIC and its associated injury risks. The maximum HIC15 was 1559 obtained with steel for impacted material associated with significantly high risk of severe head injury risk (90.7%). HIC was found to rapidly decrease with softer material down to 254 with seatfoam. The resulting probability of severe head injury obtained with seatfoam was judged very low (3.8 %) but minor head injury was not negligible (34 %).

Table 7. HIC results and associated risk assessments

	Stiffness (GPa)	HIC_{15}	Severe head injury risk (AIS3+)	Minor head injury risk (AIS1+)
Steel	207	1559	90.7%	100%
Aluminium	67	1466	87.3%	100%
Wood	15	740	28.8%	95%
Plastic	2	441	9.9%	71%
Seatfoam	0.01	254	3.8%	34%

4.3.4 Future work: standing passengers

The methods and preliminary results have been presented in this section, following the complete process for one case scenario. Preliminary results show that a fall caused by a severe emergency braking (EB3) against a rigid element can likely caused severe head injury which is consistent with previous events (tram accident in Montpellier, France).
For the next step, CEESAR will execute the parametric study that will include different passenger positions, locations, and pulse characteristics for the models. An analysis on these results will be available in the next report.
The statistical model estimating head injury risk as a function of jerk and braking deceleration will be further developed as a final item.

4.4 Head injury risk for pedestrians in case of AV collision

4.4.1 Preamble

In Section 4.2, 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 shuttle 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.

4.4.2 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 autonomous shuttle. The vehicle is subjected to an initial velocity, impacting the pedestrian to impact the front of the vehicle and sustain injury. It should be noted that due to data availability, the materials were assumed referring to common forms in existing vehicle models.

4.4.2.1 Vehicle model

The vehicle model used in this study is based upon the shuttle vehicle developed by NAVYA (Figure 22). 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 31). 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.

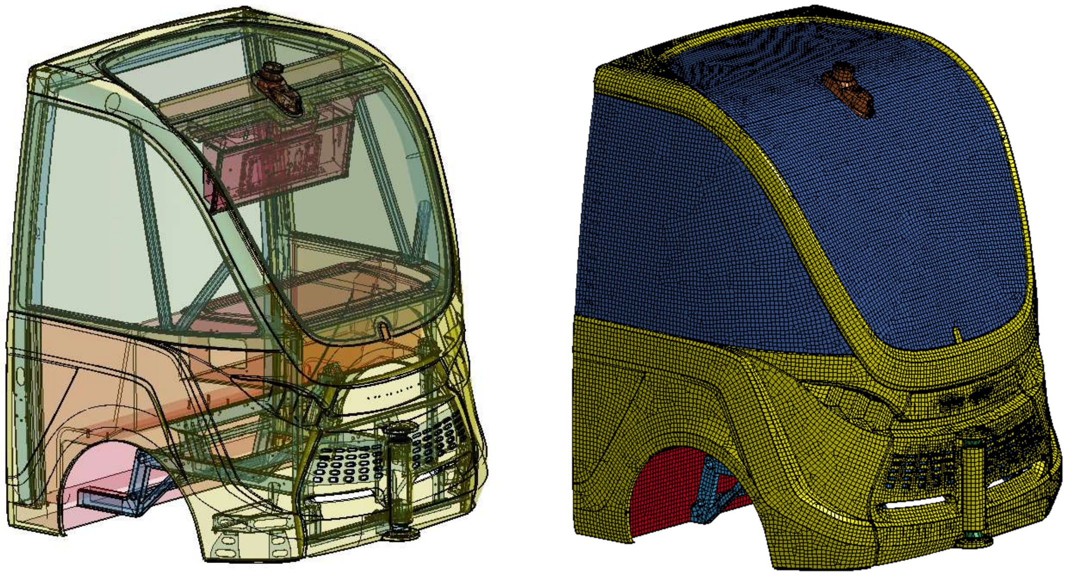


Figure 31. Vehicle front-end model.

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).

4.4.2.2 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 25).
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 similar to 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.

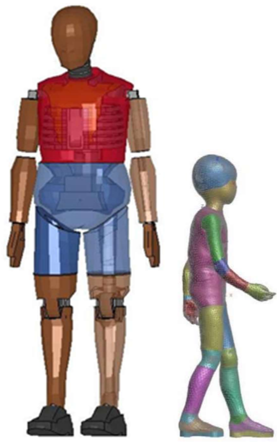


Figure 32. Hybrid III 50th Percentile Male Standing (LTSC) and Piper pedestrian model.

The pedestrian model will be positioned in front of the vehicle at different locations and orientations to cover the vehicle space (Figure 33).

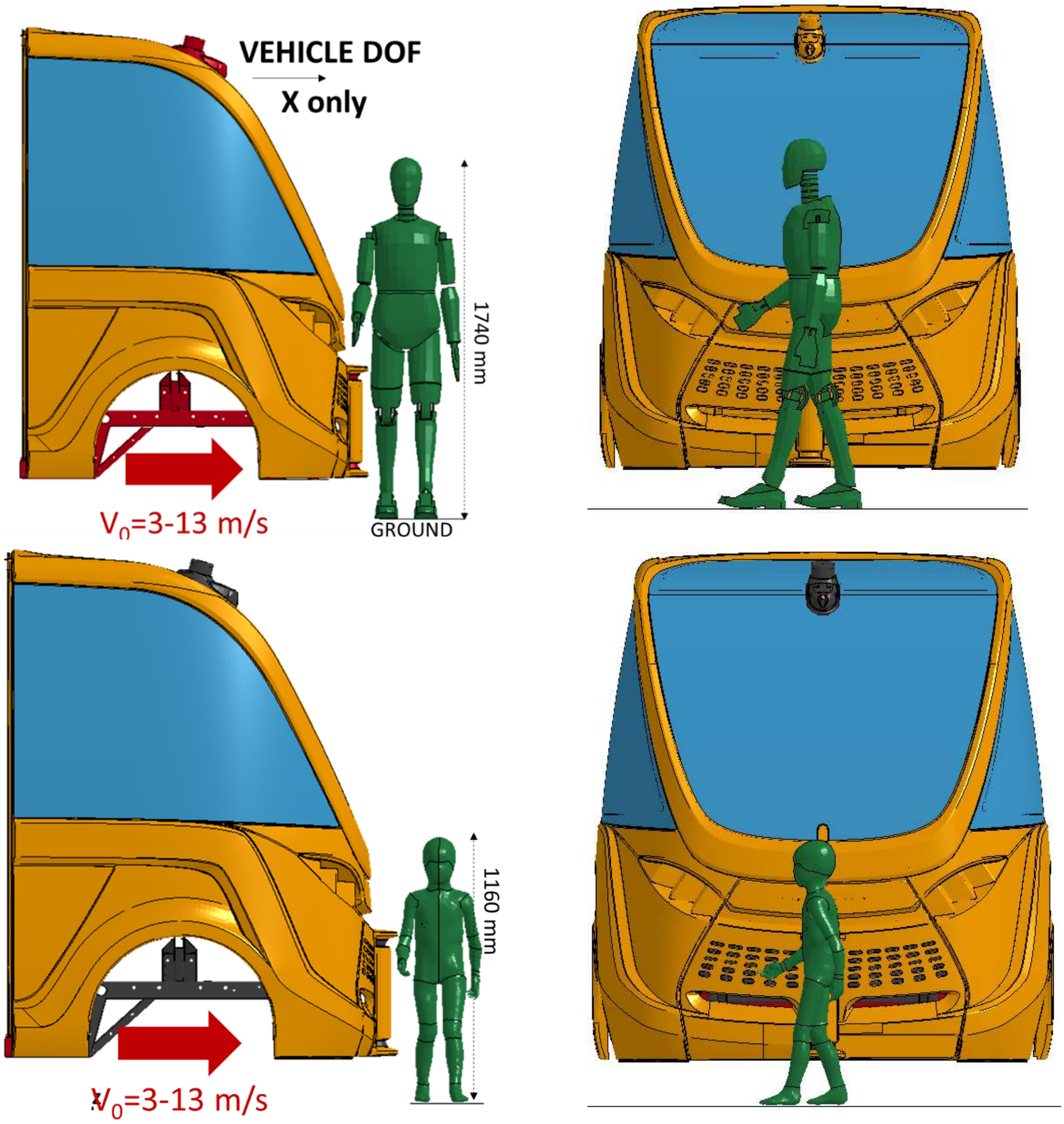


Figure 33. Model integration with vehicle.

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.

4.4.2.3 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 34). 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).

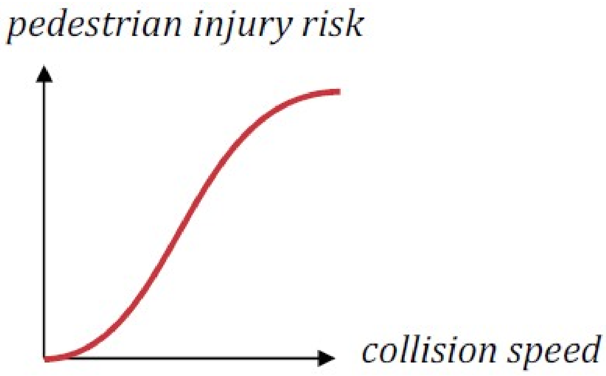


Figure 34. Risk (e.g. AIS ≥ 3 probability) as a function of dynamic parameters

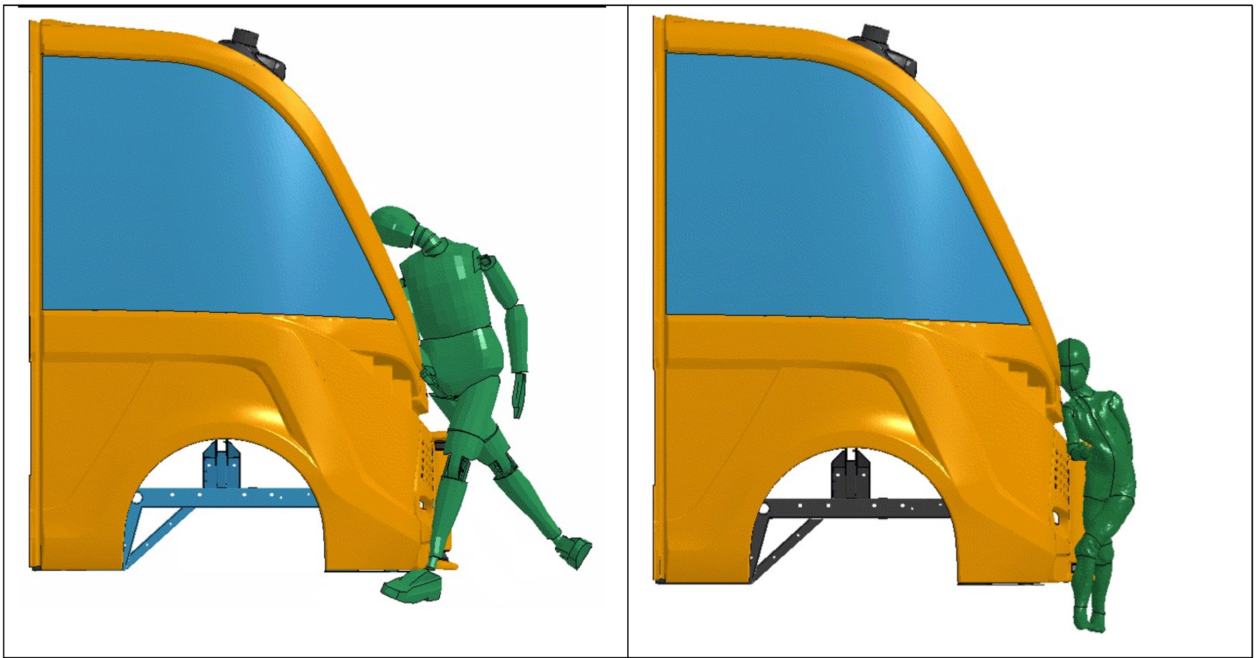
4.4.3 Preliminary results: pedestrian collision

In order to represent the appropriate range of scenarios that can represent the investigation cases, and establish the suitability of the chosen models to evaluate injury risk for pedestrian, preliminary simulations were performed.

In these scenarios, the dummy model and the child were impacted laterally by the vehicle traveling at 10 m/s. Both models were positioned in the center of the vehicle, their head facing orthogonally to the direction of the movement. All simulations successfully terminated with no error.

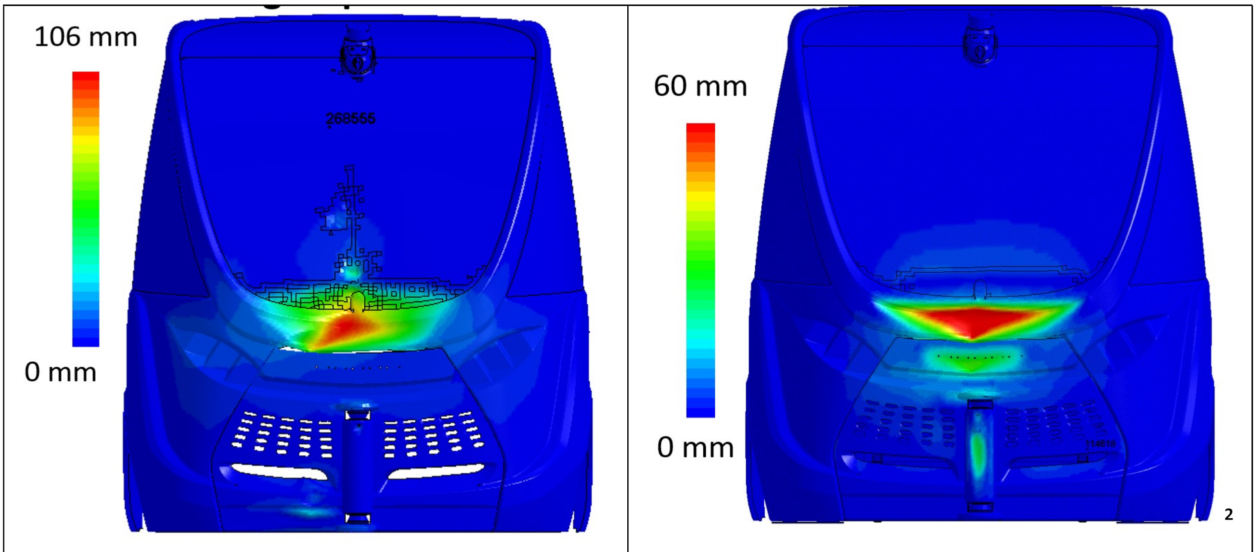
Key differences between the trajectories of the dummy and the child model were observed due to the difference of stature (Figure 35). The Hybrid III 50th Percentile Male Standing model wrap around the front panel and its head hit the center of the windshield which cracked under the impact (Figure 36). The Piper child model was struck by an almost flat and vertical surface due to its lower center of gravity. As a result, very little rotation is observed which lead to its head hitting the bonnet leading edge.

Table 8 summarizes the results obtained for both simulations regarding the HIC and its associated injury risks. The maximum HIC15 was 1766 obtained with the Piper child model associated with significantly high risk of severe head injury risk (96%). This value can be explained because the impacted component, bonnet leading edge represents a very stiff structure and can lead to serious head injuries. The resulting probability of severe head injury obtained for Hybrid III was lower (15%) but not negligible, because the windshield is one of the 'softer' structures of the vehicle front.



Hybrid III 50th Percentile Male Standing model	Piper child model

Figure 35. Pedestrian impact locations.



Hybrid III 50th Percentile Male Standing model	Piper child model

Figure 36. Front vehicle deformation after impact.

Table 8. HIC results and associated risk assessments

	Velocity (m/s)	Impact location	Head velocity at impact (m/s)	HIC_{15}	Severe head injury risk (AIS3+)	Minor head injury risk (AIS1+)
Hybrid III 50^{th}	10	Center	11 m/s	537	15 %	83 %
Piper child	10	Center	14 m/s	1766	96 %	100 %

4.4.4 Future work: pedestrian collision

The methods and preliminary results have been presented in this section, following the complete process for one case scenario. Preliminary results show key differences between the trajectories of the dummy and the child model which lead to different injury outcomes.

For the next step, CEESAR will execute the parametric study that will include different collision speeds, impact locations. An analysis report on these results will be available in the next report. The statistical model estimating head injury risk as a function of collision speed will be further developed as a final item.

5 Conclusion

As Work Package 6 started on the 7th month of the project, the present document describes results from tasks 6.1 and 6.2, for the first year of activity.

A methodology integrating both tasks has first been refined. It relies on multiple forms of data collection, analysis and aggregation; numerical simulations of the shuttle's behaviour in traffic situations; numerical simulations of passengers' and pedestrians' kinematics in the event of harsh braking or collision; and physical, test-track tests. **It will contribute in identifying major hazards and establishing the relationship between vehicle capabilities, operational conditions, and the resulting risk.**

As safety is and remains the responsibility of vehicle manufacturer and public transport operators, WP6's methodology does not focus on issues which would be very particular to a specific vehicle model or a specific operation site. It also does not focus on issues which are not particular to autonomous vehicles. WP6 rather **aims at providing a universal framework, applied in the context of AVENUE's deployments, which can later be used to assess the risk associated with using other autonomous shuttles in different operating environments**. Vehicle performance, environment and operations' characteristics are the inputs of that evaluation framework. Safety impact from changes in any or all of them should therefore be assessable using that methodology.

After the aforementioned methodology had been designed and agreed upon, development of **a safety-relevant scenarios catalogue** started. It currently comprises 64 main scenarios, each including multiple variants.

An **injury risk study** also began, first by an extensive literature review, and now continues in the form of numerical simulations. Literature provides guidelines for braking profiles minimising passengers fall risk, and models to estimate probability of falling. Numerical simulations are being made to estimate severe injury risk in case a passenger actually falls. Given the particular front-end design of autonomous shuttles, dedicated simulations are also run to build injury risk functions for pedestrians, depending on collision speed, age/height of pedestrians, and relative positions at the impact.

Finally, setup of a **simulation environment for traffic scenarios** has seen significant progress.

Following this largely theoretical foundation work, WP6 will now start collecting data, both subjective and objective, which requires critical support from AVENUE's public transport operators and NAVYA. **This data will allow the application of the methodology to the concrete challenges met in AVENUE's test sites**. Data sharing is therefore under discussion and being organised at time of writing. Intellectual property as well as data protection constrains might limit the scale and coverage of data that will be accessible to WP6. Hence, every possible effort is currently made to match options and restrictions of each stakeholder to WP6's requirements to make sure that WP6 can provide sound results, ultimately helping improving quality of service while maintaining and possibly improving passengers' and road users' safety.

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 is developed and maintained by Karla Quintero, with initial help from Jacques Saadé (CEESAR).

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

Peter Lorenz (VIF) handles scenario simulations in CARLA, and has implemented the first 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.

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.

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.

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.

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 shuttle, what do you enjoy about your job?
    - What do you dislike?
    - What are the difficulties of your job?
- **Safety**
    - Are you concerned about autonomous shuttles 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 shuttles? *(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: Measures requirements

Misc.
UTC Time

System State
Driving mode: *standby, auto drive, disengaged, operator takeover...*
Current manoeuver: *straight riding, turning left, right, roundabout, giving way to another actor...*
Freeflow *(i.e. following programmed speed) / constrained (i.e. not following programmed speed because of other road users)*
Desired speed

Activation of actuators
Steering Angle
Steering Torque
Acceleration request
Brake request

Dynamic behaviour of the vehicle
Longitudinal Speed
Longitudinal Acceleration
Lateral Acceleration
Yaw Rate
Individual wheel speeds

Vehicle location
Latitude ***(using RTK corrections)***
Longitude ***(using RTK corrections)***
Altitude ***(using RTK corrections)***
Heading ***(using RTK corrections)***
Lateral deviation from reference trajectory
Driving lane width
Driving lane curvature
Driving lane yaw angle
Distance to right lane
Distance to left lane
Right lane detection quality
Left lane detection quality

Other actors *(i.e. dynamic objects, including those which are currently standing still), For each:*
Unique ID
Type *(e.g. car, truck, bike, pedestrian…)*
Confidence

Distance on X axis
Distance on Y axis
Speed on X axis
Speed on Y axis
Acceleration on X axis
Width
Length
Heading
Is most risky/constraining obstacle

Context

Interior and exterior video views

Appendix C:

Functional scenarios template

A.1 General Template (Functional Scenario) V1.0

Categories	Attributes	Values
Infrastructure	Road	☐ Unidirectional roadway ☐ Y intersection ☐ Bidirectional roadway ☐ Railroad crossing ☐ T intersection ☐ Roundabout ☐ X intersection ☐Motorway
	Traffic regulation mechanism	☐ Traffic lights ☐ Traffic agent ☐ Traffic signs ☐ No explicit traffic regulation ☐ Pavement Marking ☐ NA
AV's Trajectory	Longitudinal	__ Going forward __ Going in Reverse __ Stopped
	Lateral	__ Lane change to the right __ Turning right __ Diagonally __ Lane change to the left __ Turning left
	Intersection	__ Inserting into intersection __ On intersection __ Exiting intersection
General TP[3] Related Attributes	Number of traffic participants	__ Passenger car __ Other AV __ Scooter __ Segway __ Bus __ Cyclist __ Pedestrian __ Other __ Truck __ Motorcycle __ Priority vehicle

1

N

One template per each TP (TP template)

[3] TP : Traffic Participant

Traffic Participant Template V1.0

Attributes	Values			
TP type	☐ Passenger car	☐ Priority Vehicle	☐ Motorcycle	☐ Pedestrian
	☐ Bus	☐ Other AV	☐ Segway	☐ Other
	☐ Truck	☐ Cyclist	☐ Scooter	
TP's trajectory	**VRU**	**Longitudinal**		**Lateral**
	__ On crosswalk	__ Same direction as AV		__ Lane change to the right
	__ Out of crosswalk	__ Opposite direction as AV		__ Lane change to the left
	__ Before crosswalk	__ In same lane as AV		__ Turning right
	__ After crosswalk	__ Not in same lane as AV		__ Turning left
	__ From farside to nearside	__ In protected lane		__ Diagonally
	__ From nearside to farside	__ Front facing AV		**Intersection**
		__ Back facing AV		__ Inserting into intersection
		__ Going forward		__ On intersection
		__ Going in Reverse		__ Exiting intersection
		__ Stopped		
		__ In front of AV		
		__ Behind AV		