AVENUE

Autonomous Vehicles to Evolve to a New Urban Experience

DELIVERABLE

D6.4 Controlled environment vehicle safety evaluation report

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Table of Contents

Acronyms

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

T7.1	Task 7.1
TM	Technical Manager
TOF	Target Object Front
TPG	Transport Publics Genevois
UITP	Union Internationale des Transports Publics (International Transport Union)
V2I	Vehicle to Infrastructure communication
ViL	Vehicle-intheLoop
VSM	value stream map
VTD	Virtual Test Drive
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, Task 6.1's aim is to carries out controlled environment trials to assess that performance targets are met, before evolutions are deployed on the field. A methodology and a toolchain are designed and implemented to allow this evaluation to largely be done using numerical simulation, although ideally, these will be consolidated by physical tests. To that effect, experimental procedures will be defined to closely match conditions of worst-case scenarios and reproduce them in a safe way (i.e., dummy obstacles and empty vehicle). Safety-critical scenarios will be analysed and evaluated in controlled (simulated) environment to mitigate the involved risks. This task aims at identifying and designing appropriate quality measures for safety and comfort and to evaluate to which degree safety of the automated vehicle function has been achieved. This includes the definition of the metrics to evaluate the automated vehicle functions and the subjective safety feeling. Those metrics were implemented in the AVL-DRIVE™ AD software, which became capable of assessing the drivability of automated vehicles in different driving conditions.

1 Introduction

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

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

At the end of the AVENUE project's four-year period, the mission is to have demonstrated that 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.

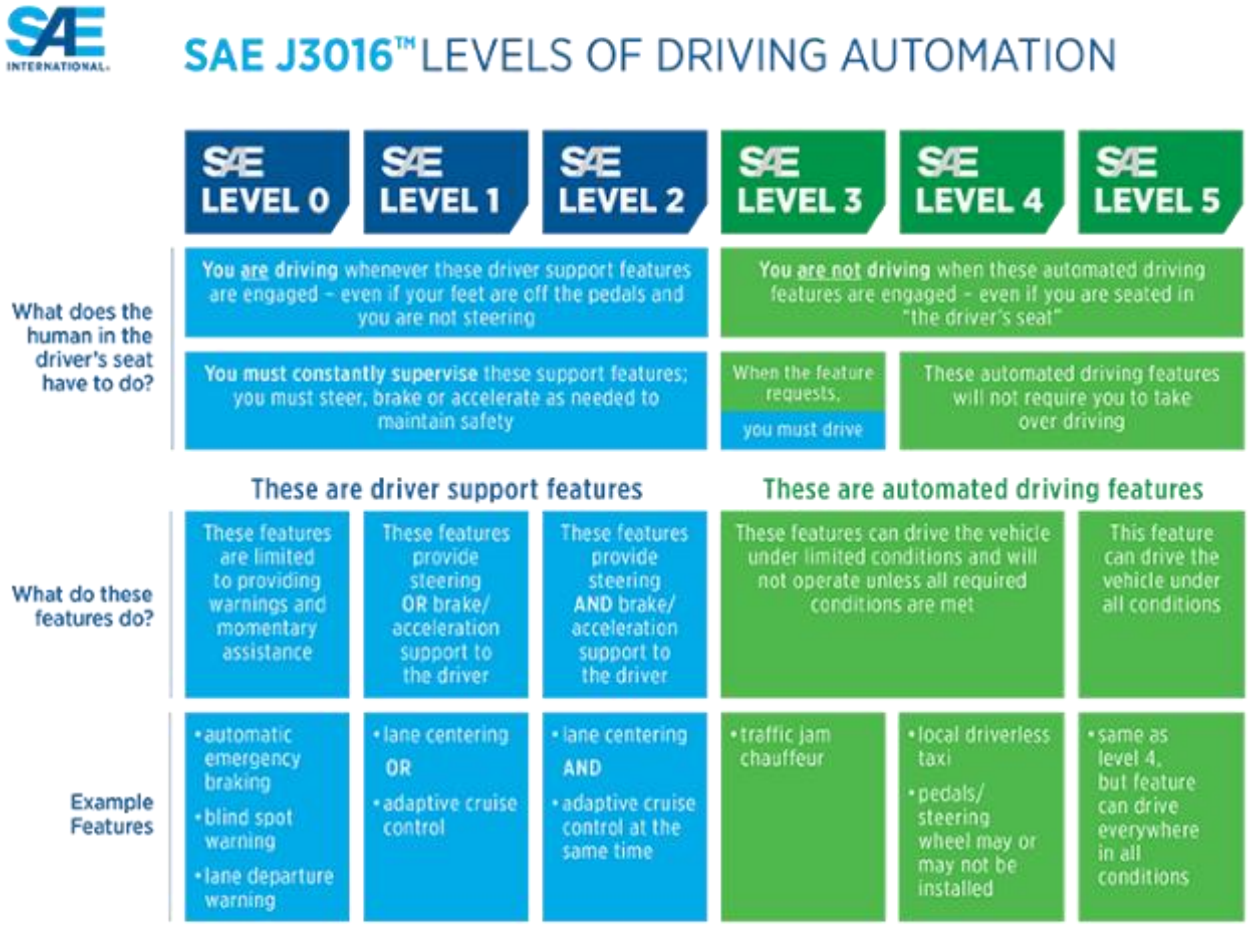
1.1 On-demand Mobility

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

1.2 Autonomous Vehicles

A self-driving car, in the AVENUE project referred to as **an Autonomous Vehicle** (AV), is a vehicle that is capable of sensing its environment and moving safely with no human input. The choice of "autonomous" vs "automated" was made in AVENUE since, in the current literature, most of the vehicle concepts have a person in the driver's seat, utilize a communication connection to the Cloud or other vehicles, and do not independently select either destinations or routes for reaching them, thus being "automated". The automated vehicles are considered to provide assistance (at various levels) to the driver. In AVENUE, there will be no driver (so no assistance will be needed), while the route and destinations will be defined autonomously (by the fleet management system). The target is to reach a system comprising of vehicles and services that independently select and optimize their destination and routes, based on the passenger demands.

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



1.2.1 Autonomous vehicle operation overview

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

For micro-navigation, Autonomous Vehicles combine a variety of sensors to perceive their surroundings, such as 3D video, lidar, sonar, GNSS, odometry and other types of sensors. Control software and systems, integrated in the vehicle, fusion and interpret sensors' information to identify the current position of the vehicle, detecting obstacles in the surrounding environment, and choosing the most appropriate reaction of the vehicle, ranging from stopping to bypassing the obstacle, reducing its speed, making a turn etc.
For the macro-navigation, the Autonomous Vehicle receives the information from either the in-vehicle operator (in the current configuration with a fixed path route), or from the remote control service via a dedicated 4G/5G communication channel, for a fleet-managed operation. The fleet management system takes into account all available vehicles in the services area, the passenger request, the operator policies, the street conditions (closed streets) and send route and stop information to the vehicle (route to follow and destination to reach).

1.2.2 Autonomous vehicle capabilities in AVENUE

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

The shuttles used in the AVENUE project technically can achieve speeds of more than 60km/h. However, this speed cannot be used in the project demonstrators for regulatory and safety reasons. Under current regulations, the maximum authorised speed is 25 or 30km/h, depending on the site. In the current demonstrators, the speed does not exceed 23km/h, with an operational speed of 14 to 18km/h. Another, even more important reason for limiting the vehicle speed is safety of passengers and pedestrians. Due to the fact that current LIDAR systems have a range of 100m and the obstacle identification is done for objects not further than 40 meters, and considering that the vehicle must safely stop in case of an obstacle on the road (which will be "seen" at less than 40 meters distance), we cannot guarantee a safe braking at speeds above 25km/h. Technically, the vehicle could perform a harsh break and stand still within 40 meters at higher speeds (40-50km/h), but then the break process would be very harsh, such that passenger safety could not be guaranteed. The project is working in finding an optimal point between passenger and pedestrian safety. . Table 2 provides and overview of the AVENUE sites and OODs.

	Summary of AVENUE operating sites demonstrators						
	TPG		Holo		Keolis	Sales-Lentz	
	Geneva		Copenhagen	Oslo	Lyon	Luxembourg	
Site	Meyrin	Belle-Idée	Nordhavn	Ormøya	ParcOL	Pfaffental	Contern
Funding	TPG	EU + TPG	EU + Holo	EU + Holo	EU + Keolis	EU + SLA	EU + SLA
Start date of project	August 2017	May 2018	May 2017	August 2019	May 2017	June 2018	June 2018
Start date of trial	July 2018	June 2020	September 2020	December 2019	November 2019	September 2018	September 2018
Type of route	Fixed circular line	Area	Fixed circular line	Fixed circular line	Fixed circular line	Fixed circular line	Fixed circular line
Level of on-demand service*	Fixed route / Fixed stops	Flexible route / On-demand stops	Fixed route / Fixed stops	Fixed route / Fixed stops	Fixed route/Fixed stops	Fixed route / Fixed stops	Fixed route / Fixed stops
Route length	2,1 km	38 hectares	1,3 km	1,6 km	1,3 km	1,2 km	2,3 km
Road environment	Open road	Semi-private	Open road	Open road	Open road	Public road	Public road
Type of traffic	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed	Mixed
Speed limit	30 km/h	30 km/h	30 km/h	30 km/h	8 to 10 km/h	30 km/h	50 km/h
Roundabouts	Yes	Yes	No	No	Yes	No	No
Traffic lights	No	No	No	No	Yes	Yes	Yes
Type of service	Fixed line	On demand	Fixed line	Fixed line	Fixed line	Fixed line	Fixed line
Concession	Line (circular)	Area	Line (circular)	Line (circular)	Line (circular)	Line (circular)	Line (circular)
Number of stops	4	> 35	6	6	2	4	2
Type of bus stop	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed	Fixed
Bus stop infrastructure	Yes	Sometimes, mostly not	Yes	Yes	Yes	Yes	Yes
Number of vehicles	1	3-4	1	2	2	2	1
Timetable	Fixed	On demand	Fixed	Fixed	Fixed	Fixed	Fixed
Operation hours	Monday-Friday (5 days)	Sunday-Saturday (7 days)	Monday-Friday (5 days)	Monday-Sunday (7 days)	Monday-Saturday (6 days)	Tuesday & Thursday Saturday, Sunday & every public holiday	Monday - Friday
Timeframe weekdays	06:30 – 08:30 / 16:00 – 18:15	07:00 – 19:00	10:00 – 18:00	7:30 – 21:30	08:30 – 19:30	12:00 – 20h00	7:00 – 9:00 16:00 – 19:00
Timeframe weekends	No service	07:00 – 19:00	No service	9:00 – 18:00	08:30 – 19:30	10:00 – 21:00	No Service
Depot	400 meters distance	On site	800 meters distance	200 meters distance	On site	On site	On site
Driverless service	No	2021	No	No	No	No	No
Drive area type/ODD	B-Roads	Minor roads/parking	B-Roads/minor roads	B-Roads	B-Roads	B-Roads	B-Roads/parking
Drive area geo/ODD	Straight lines/plane	Straight lines/ plane	Straight lines/ plane	Curves/slopes	Straight Lines/ plane	Straight lines/ plane	Straight lines/ plane
Lane specification/ODD	Traffic lane	Traffic lane	Traffic lane	Traffic lane	Traffic lane	Traffic lane	Traffic lane
Drive area signs/ODD	Regulatory	Regulatory	Regulatory, Warning	Regulatory	Regulatory	Regulatory	Regulatory
Drive area surface/ODD	Standard surface, Speedbumps	Standard surface, Speedbumps	Standard surface Speedbumps, Roadworks	Frequent Ice, Snow	Standard surface, Potholes	Standard surface	Standard surface

Table 2: Summary of AVENUE operating site (+ODD components)

1.3 Preamble

Making autonomous shuttles relevant in the public transportation landscape requires improving quality of service (higher operating speeds, 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 deliverable *D6.1 First Iteration Methodology for Safety Evaluation*.

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 activities in WP6 therefore concentrate 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 to **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 for autonomous shuttles operating in an urban environment.

This deliverable D6.4 describes the methodology for a *controlled* environment safety evaluation and the current state of implementation for task 6.1, notably the implementation of a **scenarios simulation toolchain**.

Relation to other tasks and deliverables

As previously written, tasks 6.1 and 6.2 are interleaved in a common methodology. This methodology has been thoroughly described in *D6.1 - First Iteration Methodology for Safety Evaluation.* In addition to the overall methodology, this deliverable also contains first results of the *injury risk study*, which provides insights for criteria to be used when evaluating simulation outputs to simultaneously assess risk for passengers and surrounding pedestrians.

2 Vehicle Safety Evaluation Methodology

The following section is a reminder of the overall methodology, presented in *D6.1 First Iteration Methodology for Safety Evaluation*, with a focus on the contribution of task 6.1 to this global approach.

2.1 Overview

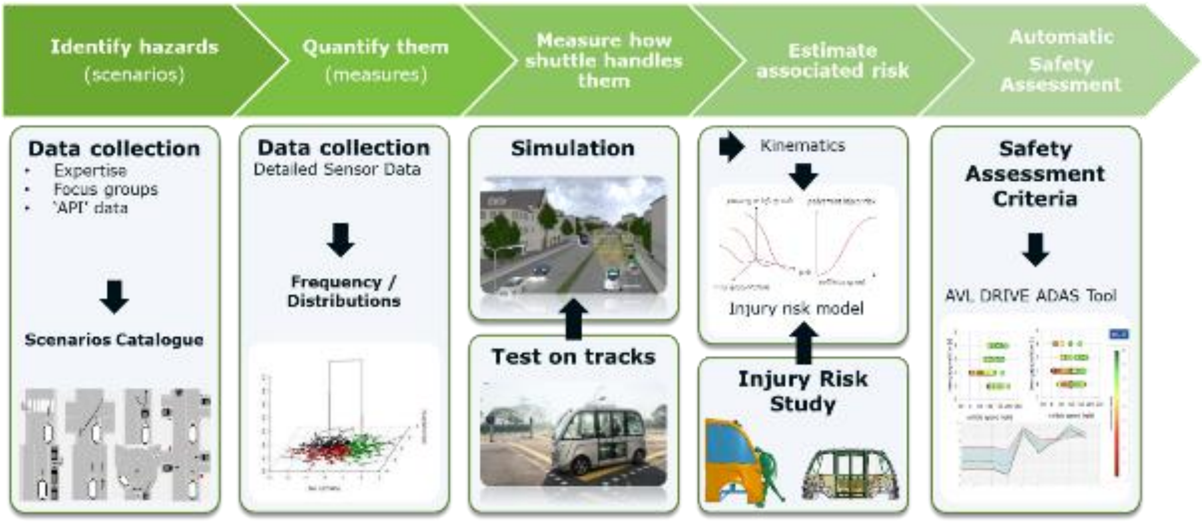
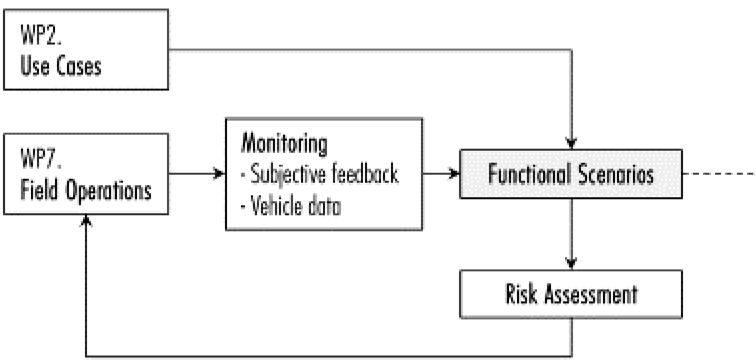


Figure 1. T6.1 & 6.2 Safety Evaluation

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

More specifically:

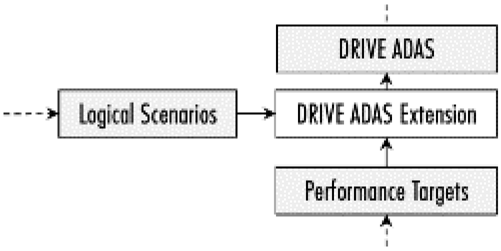
- Both subjective and objective data are collected from the test sites (WP7) and combined with use cases (i.e., future plans, WP2) to identify safety relevant scenarios. Based on those scenarios, a preliminary safety assessment will be carried out.



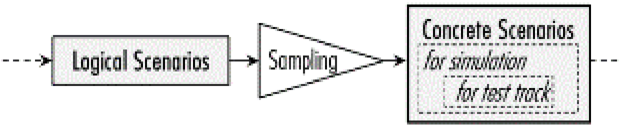
- Safety-relevant scenarios which are specific to autonomous shuttles will be selected and further described, in a quantitative way (i.e., by measurable parameters and their possible range and/or distribution).

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

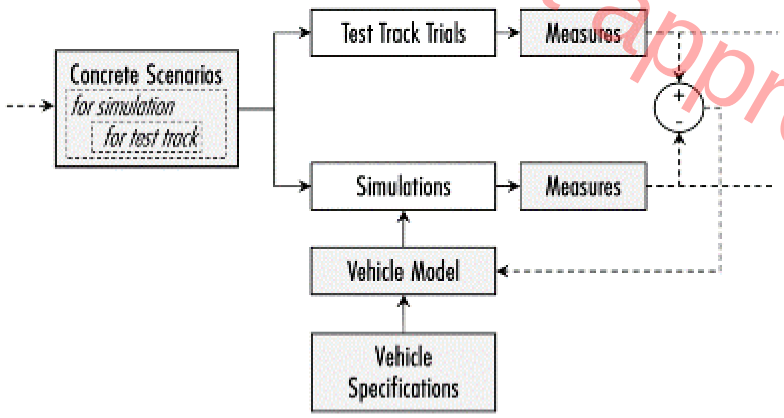
- Relevant scenarios need to be detected and the associated Key Performance Indicators need to be compared to Performance Targets. To this end, AVL's software AVL-DRIVE™ AD will be extended.



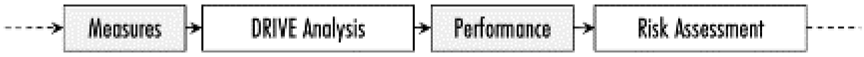
- Some instances of the relevant scenarios will be sampled (i.e. parameters values will be fixed), either to sweep the entire parameter space and build a representative set for a comprehensive risk estimation, or to explore boundary conditions (i.e. conditions where the desired outcome is known, e.g. "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, if possible, 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^{TM} AD 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.

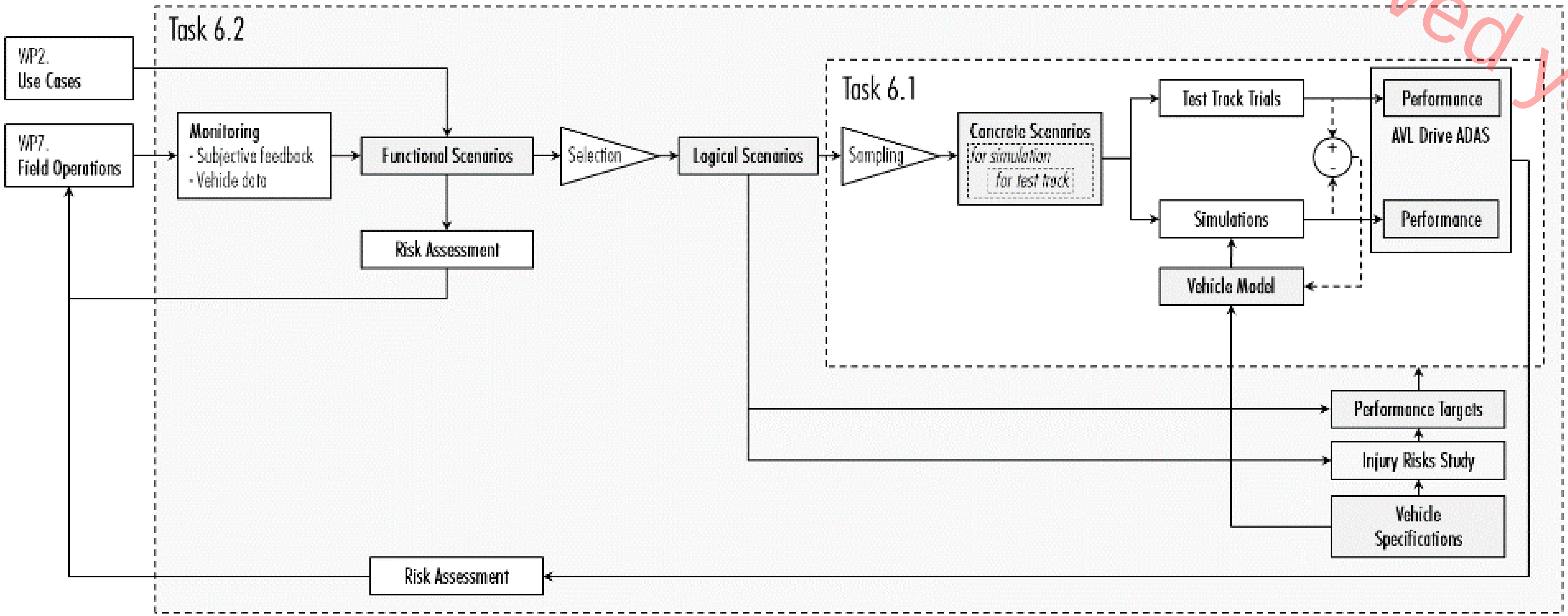


Figure 2. Tasks 6.1 and 6.2 methodology and interactions

2.1.1 Scope of Task 6.1

As previously described, Task 6.1 is responsible of the Vehicle Safety Evaluation based on the logical scenarios provided by Task 6.2:

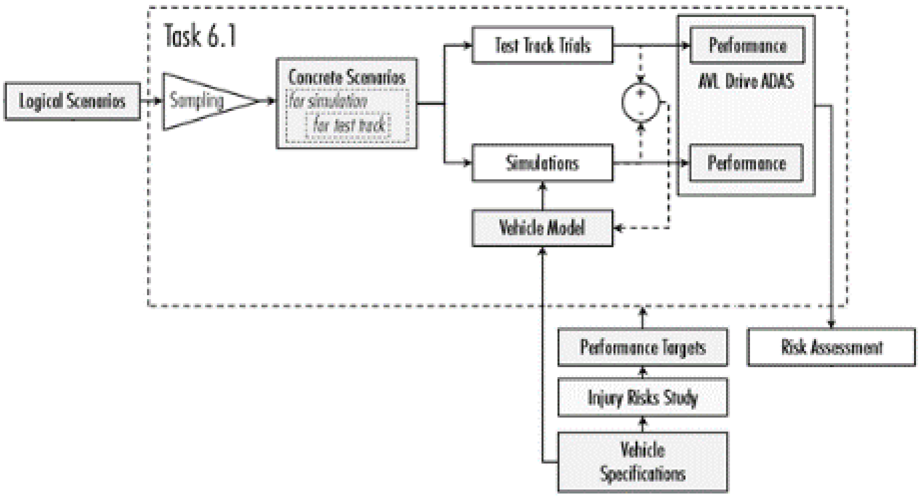


Figure 3. Task 6.1 scope

In order to perform this risk assessment, first a conversion of logical scenarios into concrete scenarios will be done with a definition of all variation and parameters we are considering as critical.
Thus, a controlled environment is defined, either in simulation or at the proving ground, in order to implement a safety evaluation in a way which can be applicable before the deployment of shuttle operation.

2.1.1.1 Simulation

Simulation activities were carried out to perform quantitative safety evaluation in a number of relevant traffic scenarios. Those simulations rely on a virtual environment including infrastructure geometry, traffic lights, other road actors, and various weather conditions, among others.

Several approaches to developing a simulation environment were carried out, working towards the following goals:

- Being able to simulate complex traffic scenarios, initially provided in the form of logical scenarios[1] ;
- Being able to vary parameters defining each of those logical scenarios over a wide range of possible values;
- Creating a simplified/generic vehicle model, which not only can be tuned to match current vehicle characteristics to an acceptable level, but can also be used to explore potential evolutions such as, e.g., sensor locations.

[1] D6.1 thoroughly defines *functional*, *logical* and *concrete* scenarios

- Implementing an environment where a much more detailed and specific vehicle model *could* also be used, i.e., provide a virtual and realistic proving ground.

Initial implementation efforts, carried out by VIF, relied on CARLA, an open-source simulation tool under development. Despite considerable improvements made within the course of AVENUE so far, CARLA proved not to be mature enough to reach the aforementioned goals.

As a consequence, AVL made some additional efforts to provide the WP6 partners with an appropriate simulation toolchain based on proprietary software which is still compatible with the original scenarios implemented by VIF to arrive at a sustainable solution. Details are given in chapter 3.

Simulations 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™ AD, which will calculate KPIs and compare them with performance targets, derived from Task 6.2's injury risk study, 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.

2.1.1.2 Real tests

To claim any credibility, simulations need to be confronted to (and then tuned to match) 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.

As a limited amount of proving ground tests are planned in WP6.1, those will focus on the most critical scenarios in order to verify the compliance of simulations with actual vehicle behaviour in similar situations.

This report thus focuses on **simulations**, as proving ground tests could not be carried out yet, but available data from were used. It first introduces the general architecture of a traffic scenario simulation solution, and then discusses the various implementations which have been made.

3 AVENUE Simulation Toolchain

3.1 Virtual Environment

Within the context of Task 6.1, simulations aim at **confronting the autonomous shuttle – and its characteristics – to specific situations**, and measure the resulting kinematics (position, speed, acceleration). Those kinematics properties will then be used to assess whether the simulated situations are handled by the vehicle in a safe way.

In a former report, the methodology to setup such a virtual environment has been detail allowing to cover relevant scenarios for safety evaluation:

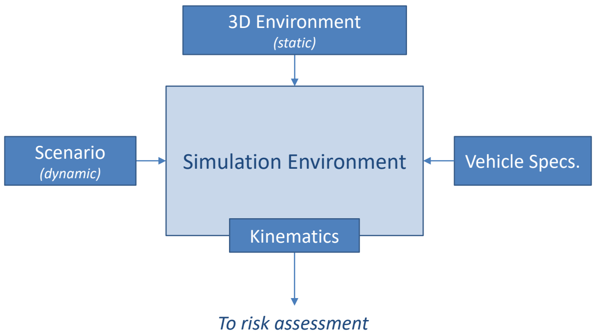


Figure 4. Scenarios simulation scope

Within 6.1 task, 2 different tools were assessed to setup virtual environment:

- Open source CARLA simulation tool
- Vires VTD (Virtual Test Drive) simulation tool

Figure 5. (a) Map of CARLA **town, (b)** CARLA**'s 3D environment**

Figure 6: Vires VTD

A first pilot structure of the AVENUE validation toolchain was built around the proprietary Vires VTD (Virtual Test Drive) simulation tool

This toolchain is able to cover task 6.1 vehicle safety evaluation methodology both in Simulation or via real tests on the shuttle.

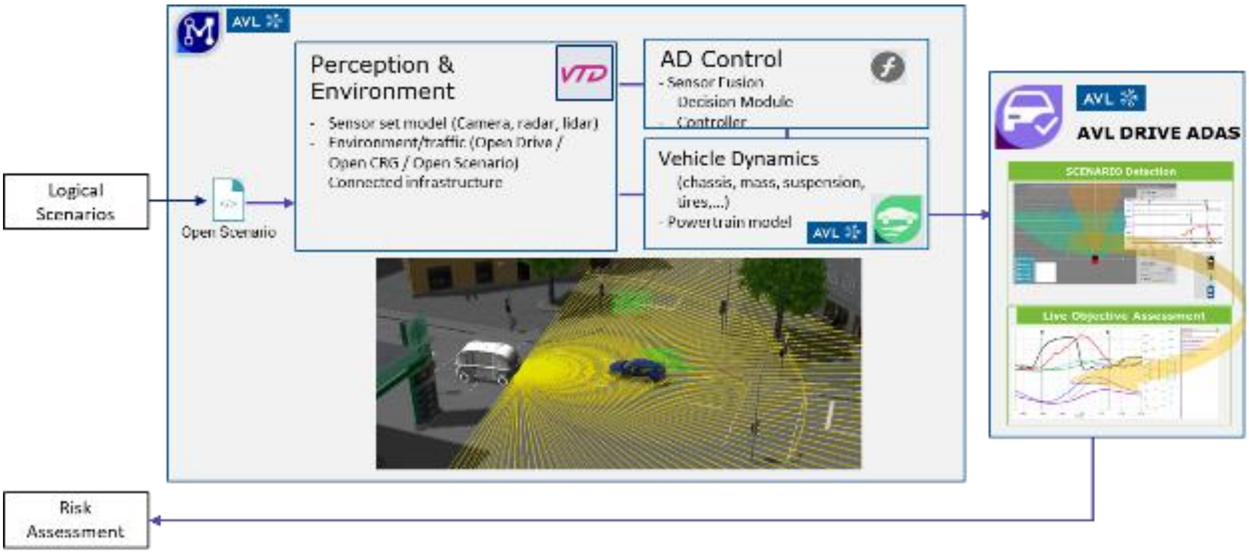


Figure 7. Schematic representation of the toolchain

Figure 8: Vehicle-in-the-Loop assessment

Implementing this toolchain on the AVENUE shuttle can directly provide a safety evaluation, life in the vehicle on the test site.

Simulations and eventual test-track trials provide kinematic measures, which can then be used to assess safety. The paragraph below will remind how safety can be assessed in both cases using the AVL-DRIVE™ AD tool.

3.2 Safety Evaluation

The vehicle safety evaluation method relies on AVL-DRIVE™ AD. This tool can directly read data from simulations running in the toolchain previously described. It requires some mandatory signals to evaluate the shuttle's performance. These signals are sampled with a 10 Hz frequency.

Table 1. List of signals

Signal	Unit	Type	Description
AccelerationChassis	m/s²	Acceleration	Longitudinal acceleration at the vehicle's center of gravity
AccelerationLateral	m/s²	Acceleration	Lateral acceleration at the vehicle's center of gravity
LaneDistance_L	m	Length	Left lane lateral distance to Ego center
LaneDistance_R	m	Length	Right lane lateral distance to Ego center
SteeringWheelAngle	deg	Angle	Ego steering wheel ange
TOF_Distance_X	m	Length	longitudinal relative distance of Target front
TOF_Distance_Y	m	Length	lateral relative distance of Target front
TOF_ID	m/s²	Identification	Target of front Identification
TOF_Speed_X	km/h	Velocity	longitudinal relative speed of Target front
TargetSpeed	km/h	Velocity	Target longitudinal speed
VehicleSpeed	km/h	Velocity	Ego speed

AVL-DRIVE™ AD has a trigger event mode which is used to isolate a part of the measurement to be analysed. This tool allows the system to trigger several events at the same time. Using this method, events can be categorized into operation modes to focus the analysis on specific parts (pedestrian events, turning events…).

To evaluate the use cases, we triggered an event to isolate data that needs to be analysed. We calculated six criteria over the event's duration, to evaluate shuttle's safety on different aspect of its behaviour. Each criterion gives a rate to evaluate the performance of the vehicle. A global rate is calculated from these criteria to evaluate the event.

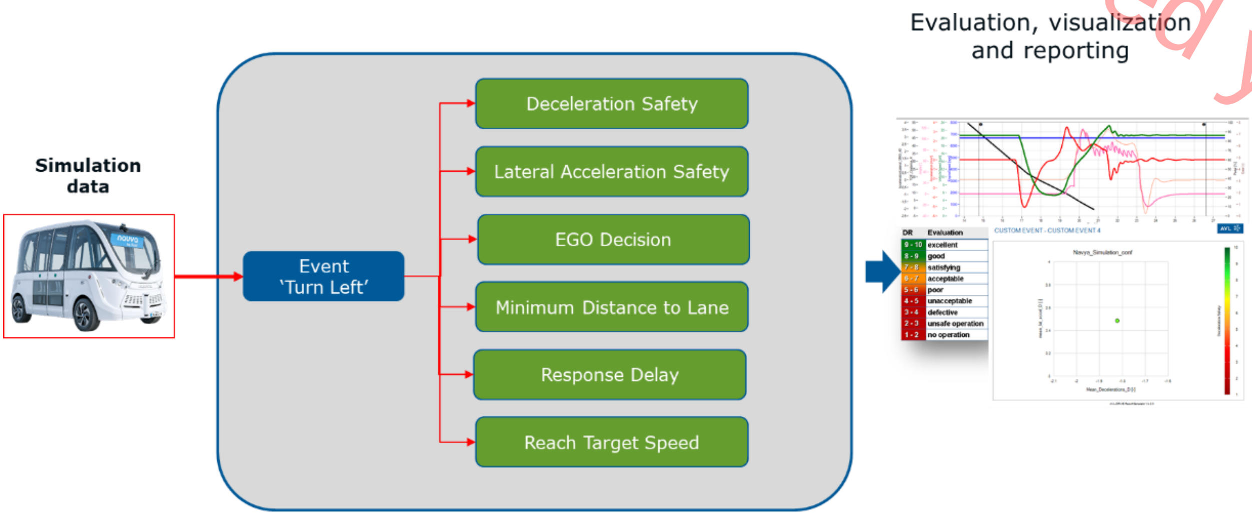


Figure 9: AVL-DRIVE^{TM} AD – Safety criteria architecture

The event detection works with input signals from the simulation. To detect the "Turn Left" use case (Fig 10 and 11), it focuses on the turn left action and TOF presence. To trigger the event, start and end conditions need to be verified:

- Start condition:
    - *SteeringWheelAngle* is greater than 90°,
    - *SpeedAssist* is equal to 1 (active).

  Event starts 5 seconds before the turn if the previous conditions are fulfilled.

- End condition:
    - *SteeringWheelAngle* must be between -5° and 5° for at least 2 seconds.

- Start recalculation:
    - If *TOF ID* is different from 0 on the event, start point is recalculated from the beginning of TOF presence.

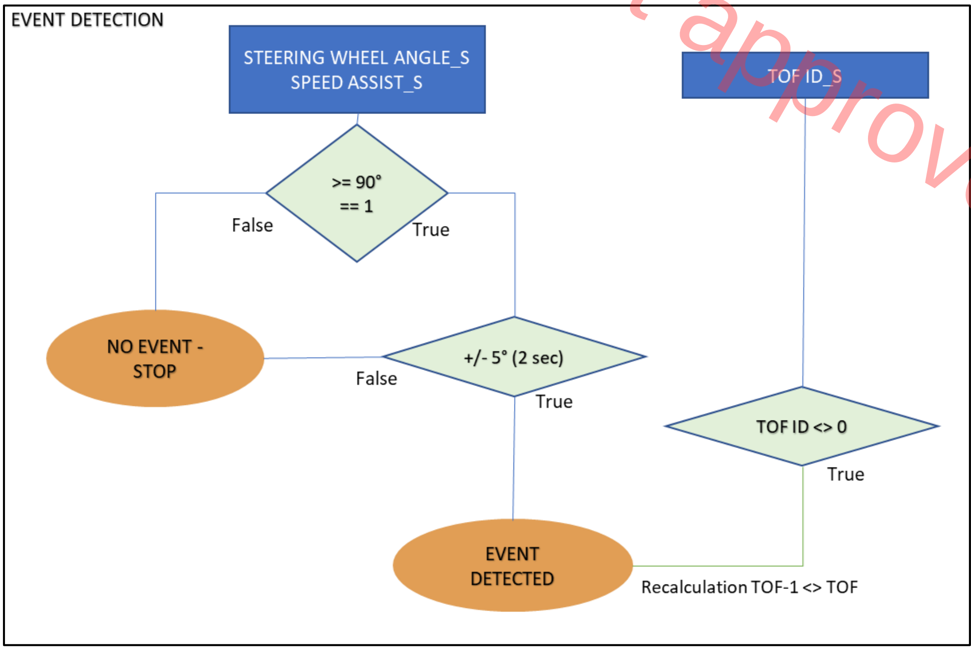


Figure 10: "Turn Left" use case - Event detection

Note: in terms of vehicle parameters, the assessment of longitudinal jerk is one of the principal relevant criteria for passenger safety. This parameter could not be considered until now, as virtual data are not representative for jerk evaluation. This parameter will be considered only based on real data that will be provided during the real test of critical driving situations.

3.3 Toolchain validation – Reference scenario

To test the complete toolchain, some scenarios, extracted from AVENUE's scenarios catalogue, have been implemented. To simulate them within AVENUE's context, one real example of Lyon test site has been reproduced:

Figure 11: Lyon test site example

The turn left situation from Lyon test site has been reproduced in simulation environment regarding all specific road markings, distances of the road, pedestrian crossings and connected traffic lights.

All moving objects (car, bicycle, pedestrian will also be implemented with regards to the tested scenario.

The connected infrastructure also allows to validate traffic lights sequences' calibration, to enhance traffic conditions (reduce shuttle braking or standstill sequences).

Based on this intersection, several scenarios out of AVENUE scenarios catalogue (see Deliverable D6.2) can be covered for safety evaluation. In a first step, the following scenarios have been considered:

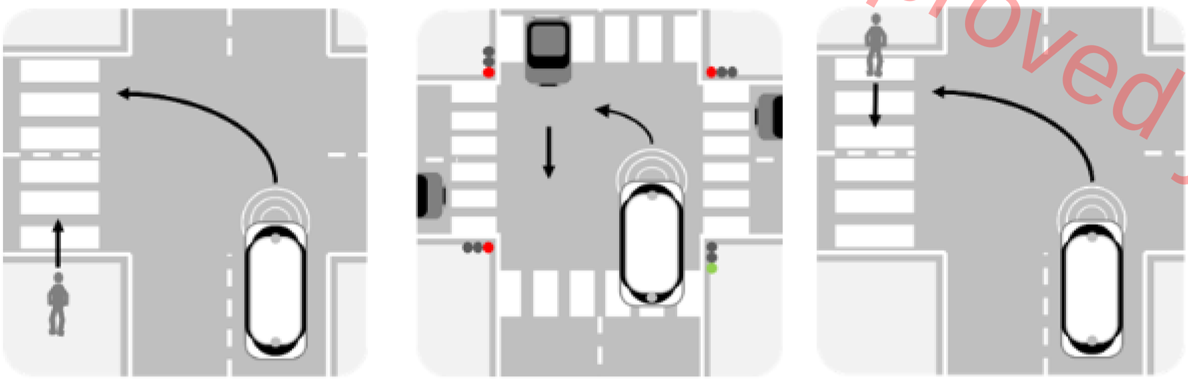


Figure 12. Extract AVENUE scenario catalog

The implementation is illustrated below, with an Ego shuttle based on T6.1 assumptions:

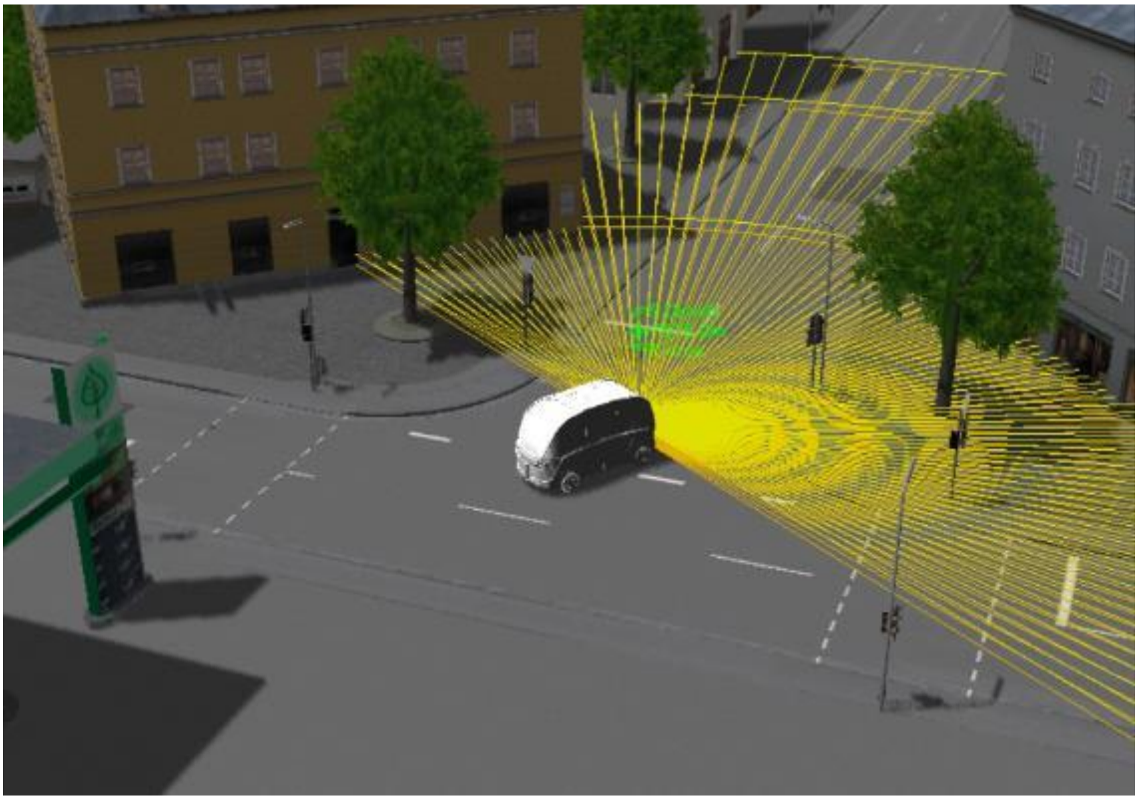


Figure 13. Virtual environment with 2D Lidars

4 Validation of simulation by real testing data

Data collection measurement will allow to refine and validate part of the simulation environment. In the following paragraph, correlation between simulation model and real data out of KEOLIS (Lyon test site) and Amobility (Copenhagen test site) is presented. Focus has been set on use cases related to safety, with emergency braking and critical perception situations.

 LYON DEMONSTRATOR SITE	 COPENHAGEN DEMONSTRATOR SITE

4.1 Keolis tests

These tests as shown on the Figure 14, allow to verify the safety behavior of the shuttle dynamic during deceleration, braking and docking.

For simulations, the test measurements as deceleration and braking profile are used to tune the longitudinal controller.

Figure 14: KEOLIS tests

Kinematic Data		GPS Data
PosLatdeg	AngleHeadingdeg	GpsPosMode
PosLondeg	AnglePitchdeg	GpsVelMode
PosAltm	AngleRolldeg	GpsAttMode
PosLocalNorthm	AngleHeadingFromSurfdeg	GpsPosInn1
PosLocalEastm	AnglePitchFromSurfdeg	GpsPosInn2
PosLocalXm	AngleRollFromSurfdeg	GpsPosInn3
PosLocalYm	AngleSlipdeg	GpsVelInn1
Distancem	AngleTrackdeg	GpsVelInn2
VelNorthms	Curvaturelm	GpsVelInn3
VelEastms	AngleRateXdegs	GpsNumSats
VelDownms	AngleRateYdegs	GpsDiffAges
VelForwardms	AngleRateZdegs	
VelLateralms	AngleRateForwarddegs	
VelLocalXms	AngleRateLateraldegs	
VelLocalYms	AngleRateDowndegs	
Speed2Dms	AngAccelXdegs	
AccelXms	AngAccelYdegs	
AccelYms	AngAccelZdegs	
AccelZms	AngAccelForwarddegs	
AccelForwardms	AngAccelLateraldegs	
AccelLateralms	AngAccelDowndegs	
AccelDownms		

Figure 15: Measured data from KEOLIS tests

These data represent position, orientation, speed, acceleration, and GPS coordinate of the shuttle.

4.2 Copenhagen tests

These tests are made in Copenhagen to verify the safety of the shuttle in open road conditions.

Kinematic Data	Perception Data
mRobotX	
mRobotY	UID
mRobotHeading	Prediction
mRobotLongitudinalSpeed	Speed
mRobotSteeringFront	Headway
mRobotSteeringRear	PointsCount
mRobotLongitudinalAcceleration	BBoxXmin
mRobotYawRate	BBoxYmin
CMP_EgoCurvilinearAbscissa	BBoxXmax
CMP_EgoLateralDistanceFromEgoPath	BBoxYmax

Figure 16: Measured data from Copenhagen tests

These data represent the position, heading of the shuttles, the coordinates of the detected front object and the prediction status.

4.3 Validation and tuning of the longitudinal controller

For longitudinal controller tuning, the Keolis test "test LOT1_test_FU_LD_18_1S_VI_SE-000" is simulated in the following conditions:

- Emergency braking use case (FU: freinage d'urgence)
- Straight road (LD: route droite)
- Shuttle speed: 18km/h
- Time to collision: 1s
- Empty Shuttle (VI: Vide)
- Dry road (SE: Sol sec)

Figure 17 shows the environment of the simulation where Ego is coming to the stopped vehicle (TOF) with 18km/h as speed and starts the emergency breaking when TTC=1s (Distance Ego/TOF = 5m).

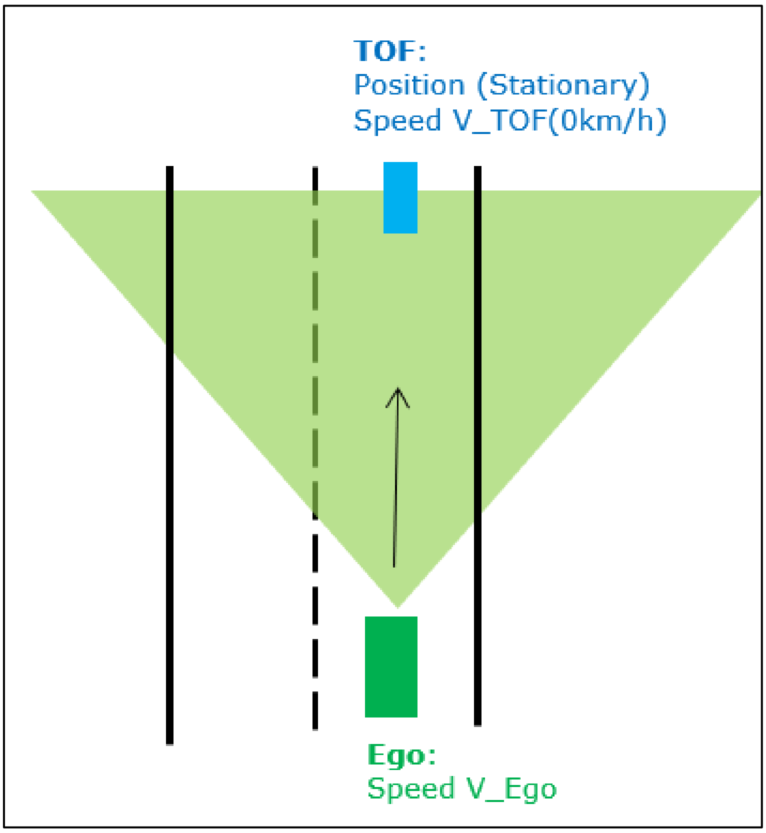
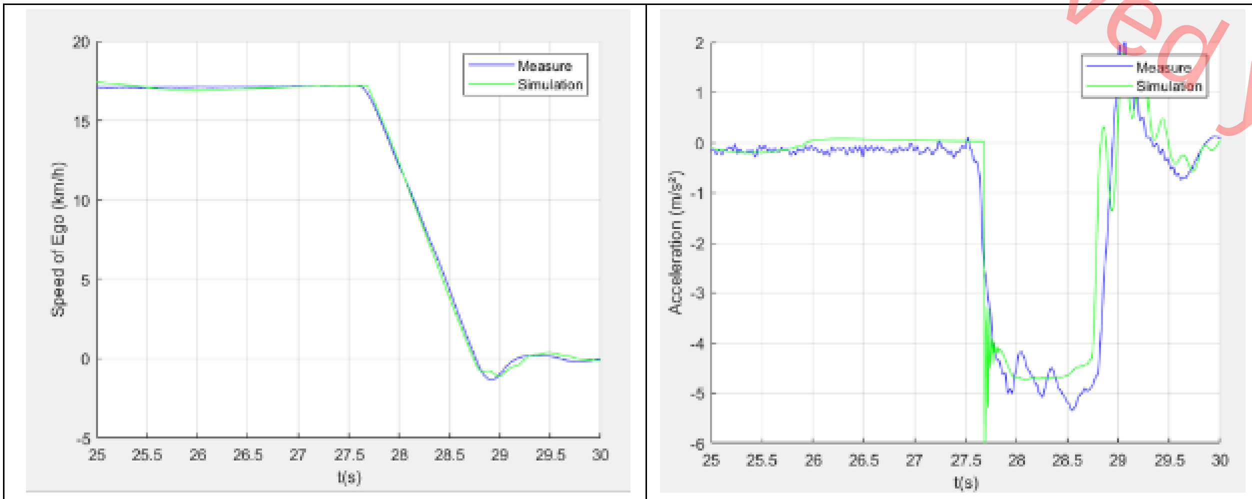


Figure 17: Simulation of emergency braking use case

Figure 18 shows the comparison of Ego speed and Ego deceleration between simulation and test. The evolution over time of Ego speed is correctly simulated, however the computed deceleration curve shows high peaks at the beginning of the braking.



Ego Speed | Ego deceleration

Figure 18: Comparison of speed and deceleration

To shave these peaks, the longitudinal controller described at the page n° 24 is replaced by the following model:

$$Brake = 100 * \left(1 - \frac{DistanceEgoTOF}{DistanceEgoTOFatTTC}\right)^{BrakingIntensity}$$

This model allows to tune the braking effort by adapting the constant parameter (*BrakingIntensity*). As shown on Figure 19, when the *BrakingIntensity* is higher than one, the brake effort is weak at the beginning and stronger at the end. However, when the *BrakingIntensity* is lower than one, the opposite effect is obtained. For the *BrakingIntensity* equal to one, the brake effort is linearly distributed.

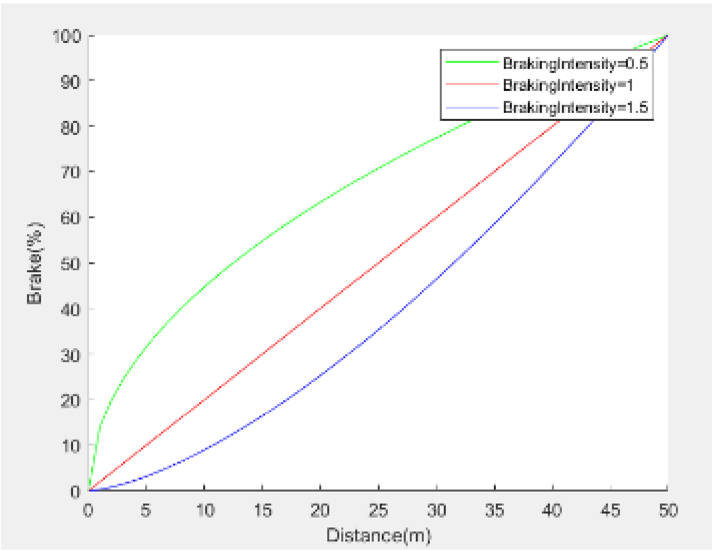


Figure 19: Effect of the BrakingIntensity

This parametric braking model allows to calibrate the longitudinal controller during deceleration and emergency braking to get the desired deceleration output close as much as possible to the tested operating point.

For other operating points, this model could be integrating in the optimization loop to choose the best compromise between decision making and perception of Ego to have a best safety/comfort compromise.

Figure 20 shows the improvement of the computed deceleration using the new longitudinal controller. All deceleration peaks are removed.

However, the main oscillations showed by the test during maximum braking plateau (blue curve) which are dues to ABS effect are not considering in the simulation.

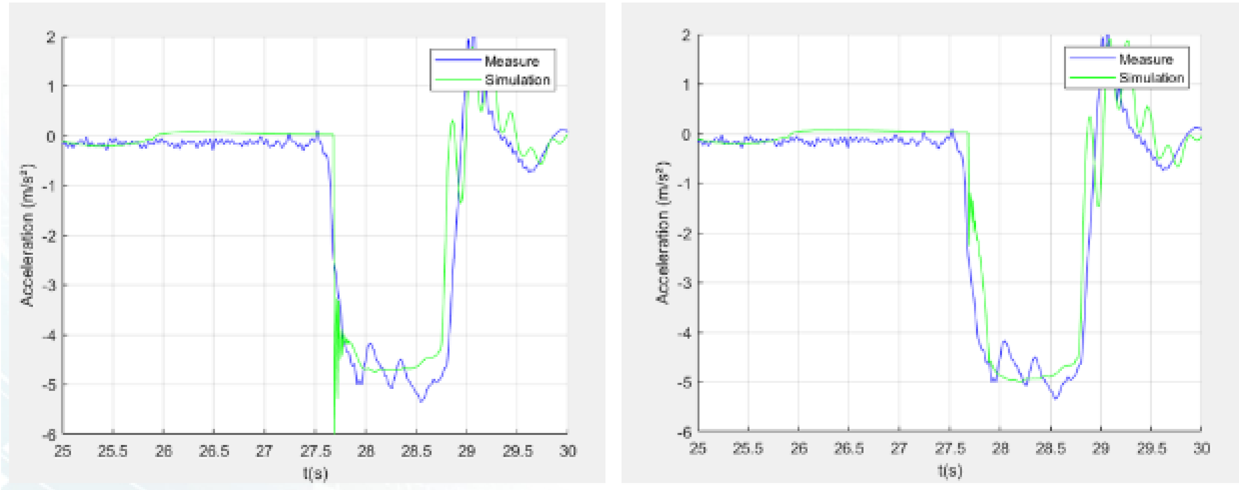


Figure 20: New longitudinal controller results

For emergency braking, the test shows that the request deceleration is around (-5m/s²) corresponding to the maximum braking effort for the shuttle. Consequently, to use the same model in the smooth deceleration cases, the parameter *DistanceEgoTOF* is used to reduce braking effort according the distance of the front vehicle.

4.4 Improvement of lateral controller

As described on page 25, the lateral controller is based on the crossing of a predefined path including straight road, 1/4 of circle and straight road.

Figure 21 shows that there are two high peaks located at both beginning and end of the circular path. These zones correspond to the road shape transition (straight to circle and circle to straight) where the curvature value changes suddenly from 0 in the straight road to constant curvature of the circle and vice versa.

The lateral acceleration is highly impacted during these curves transition due to the proportionality between lateral acceleration and curvature of the path:

$$LateralAcceleration = \frac{V^2}{PathRadius} = V^2 * PathCurvature$$

Where V is the speed of the shuttle.

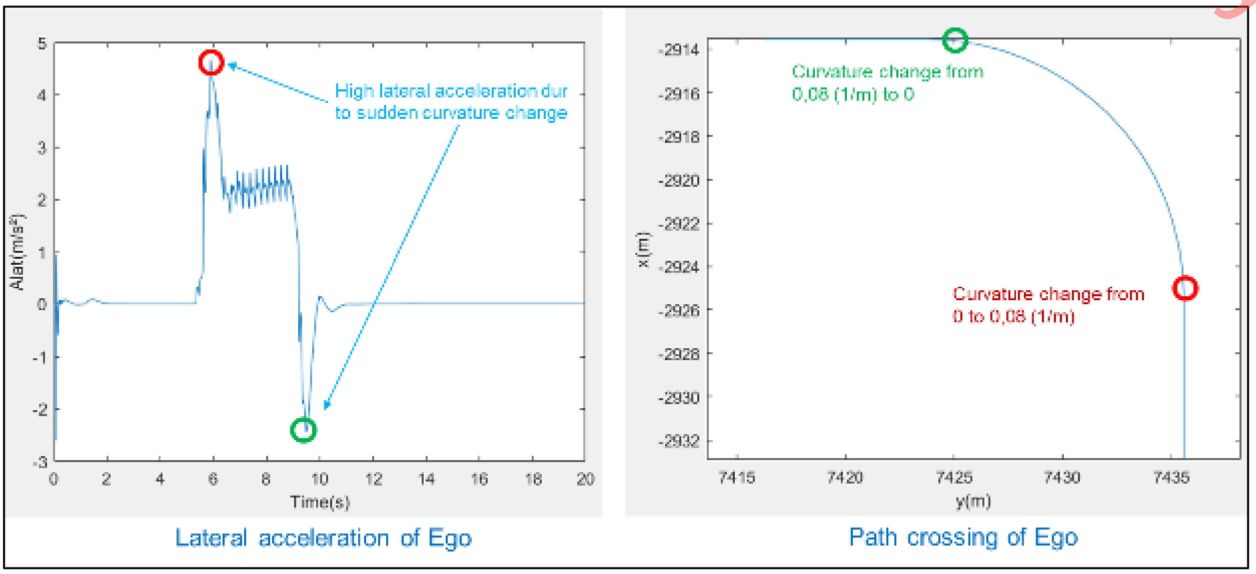


Figure 21: Lateral acceleration during path crossing

To remove these peaks and ensure a safe and comfortable lateral acceleration, new path crossing is built based on Euler spiral as shown on Figure 22. This new path provides a linear variation of curvature during straight/curve and curve/straight transitions.

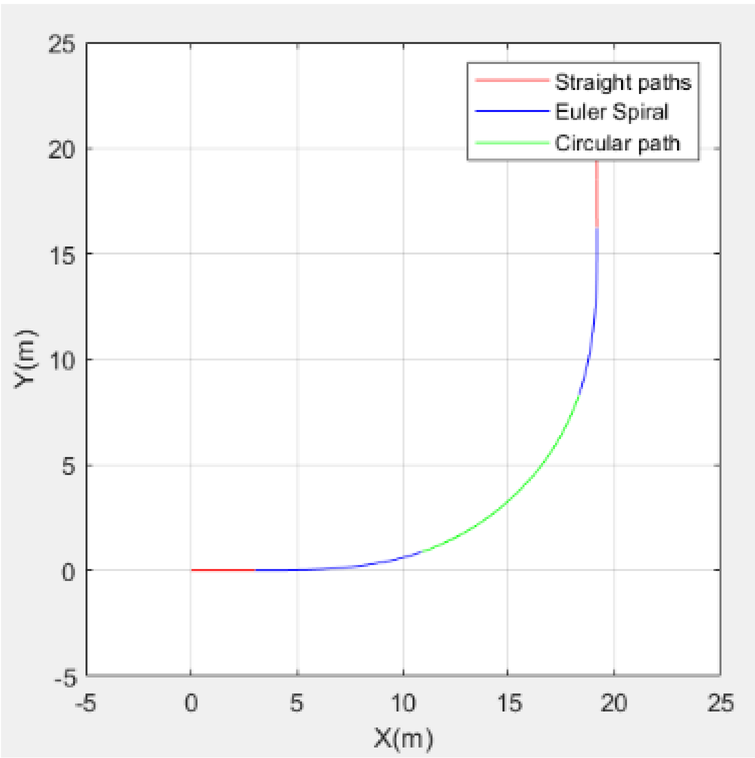


Figure 22: New Path using Euler spiral curve

Figure 23 shows the evolution over time of lateral acceleration using the new path and compared to the old one.

The new path crossing is slightly extended by insertion of two Euler spirals at both straight/curve transitions. Consequently, the peaks of lateral acceleration are removed by means of linear variation of path curvature.

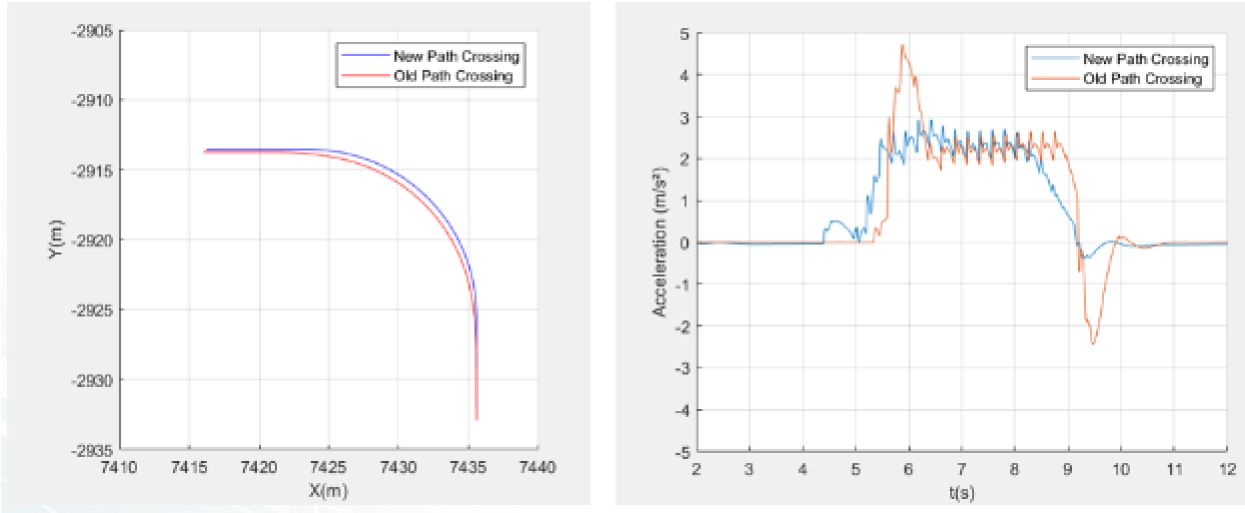


Figure 23: Comparison of lateral acceleration using two paths crossing

4.5 Decision algorithm

The following decision-making function is a simple prototype coded especially by AVL for this tool chain based on the rules of the road and dynamic of the shuttle.

The decision of crossing or braking during the turn left is based on the following two conditions:

$$\left(X_{TOF} > X_{Braking}\right)\ \&\ \left(\frac{Distance\ Ego\_TOF}{V_{Ego} + V_{TOF}} < TTC\right)$$

The first condition allows to avoid an unexpected braking before the turn left zone as shown on Figure 24. A position *X_Braking* is defined as the start point of the turn left zone where the braking system is ready to act at any front vehicle detection. This position could be varied in massive simulation to find the optimized value ensuring safety and comfort of Ego and their passengers.

The second condition depends on the dynamic for the front vehicle by estimating the distance between Ego and TOF when they drive with constate speeds *V_Ego* and *V_TOF*.

The main parameter for the decision making is the time to collision (TTC) which is the duration needed by Ego to reach TOF.

For example, if Ego speed is 20km/h (5.5m/s) and detects TOF at distance of 60m and speed of 40km/f (11m/s), the collision will take place at TTC of 3.6s. Therefore, a TTC of 5s allows a smooth braking and TTC of 4s will causes a high braking intensity and consequently a high deceleration.

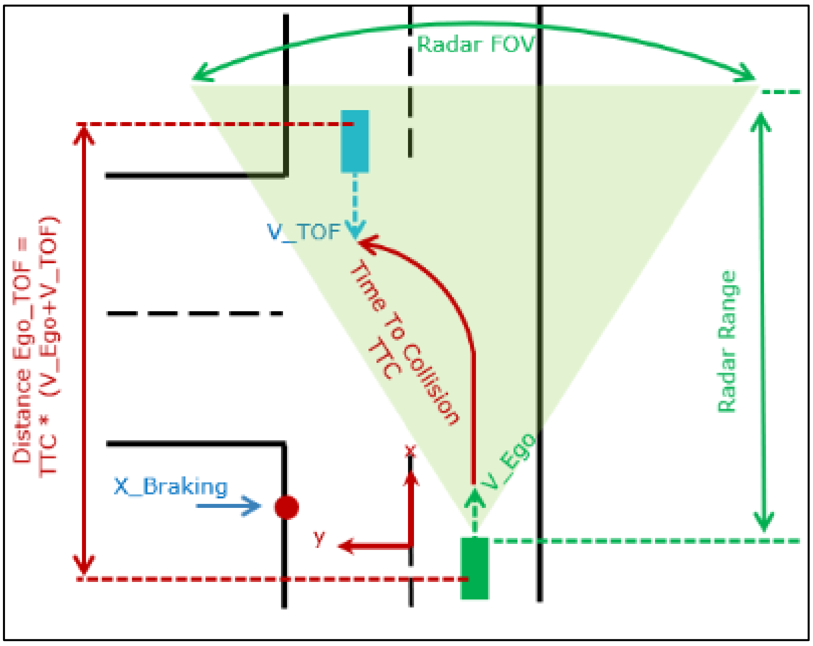


Figure 24: Parameters of the decision function

4.6 Outputs of simulations

- **Minimum distance Ego/TOF:**

The minimum distance between Ego and TOF as shown on Figure 25 is computed as the minimum over time of the cartesian distance between their bodies.

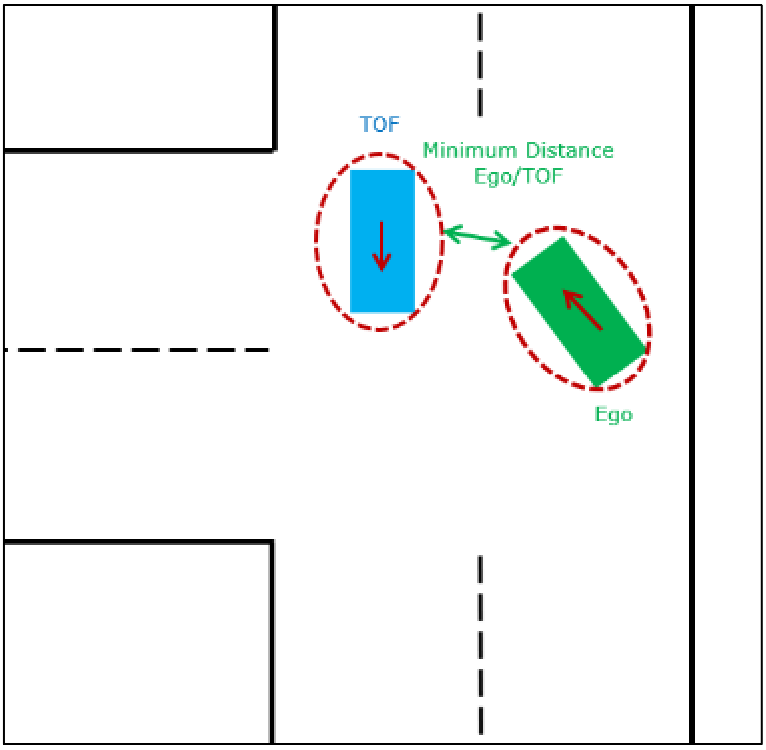


Figure 25: Safe minimum distance Ego/TOF

The threshold of 2m is defined as a safe minimum distance Ego/TOF that the Shuttle must observe based on its surrounding short-range sensors.

In this simulation, the front radar is used to get the minimum distance when TOF is detected. However, in the case where TOF is outside of the field of view as shown on Figure 26, this distance computed mathematically using their future trajectories.

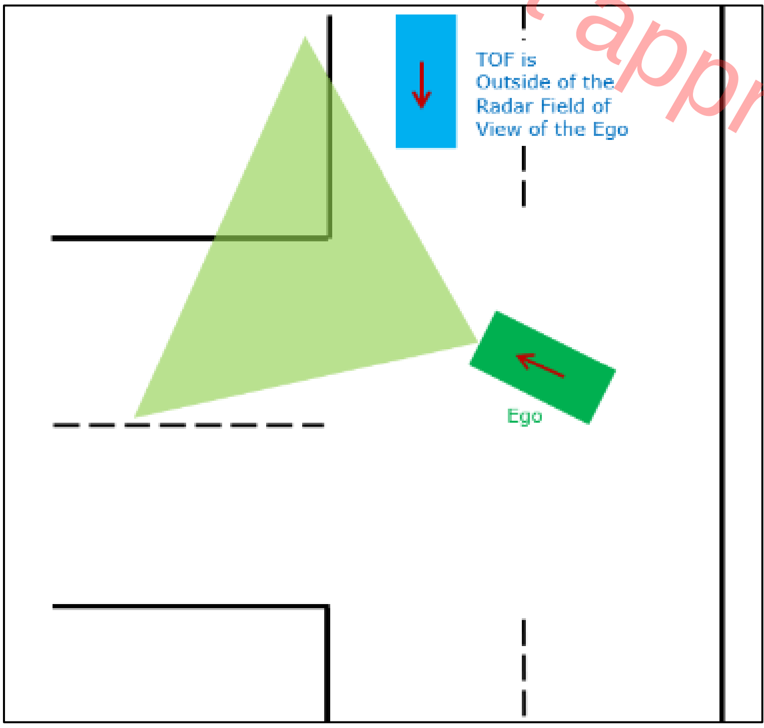


Figure 26: TOF not detected by Ego despite close position to each other

Based on the minimum distance Ego/TOF, the decision making could be tested by massive simulations to define all miss use cases, safe/unsafe use cases as shown on Figure 27and Figure 28.

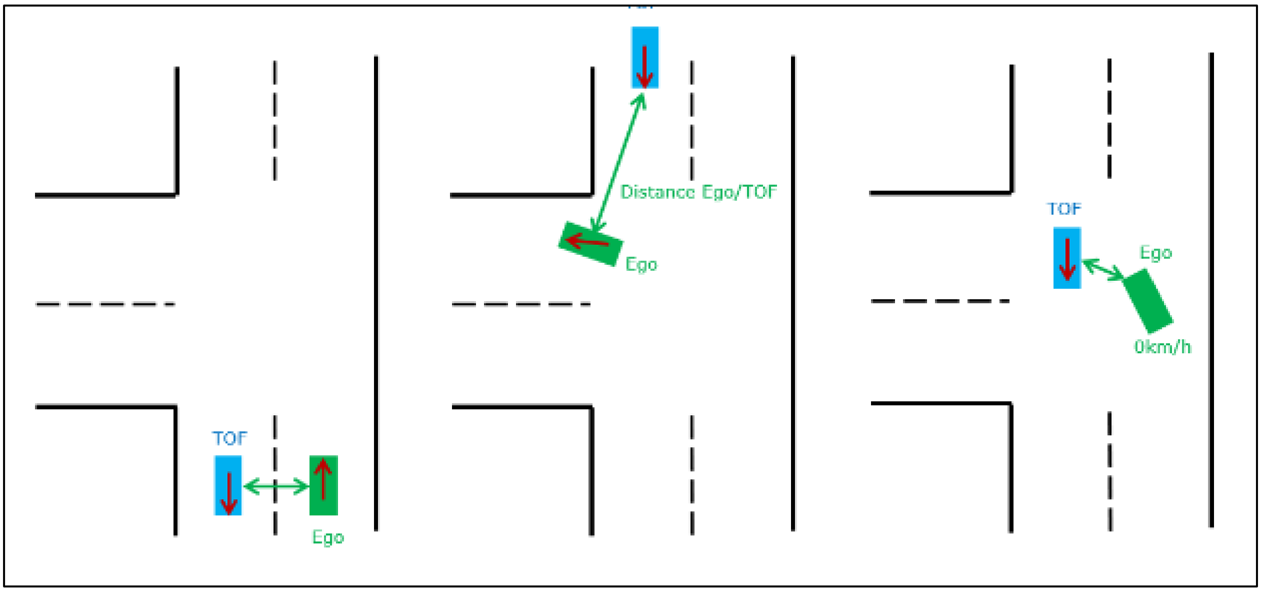


Figure 27: Safe minimum distance Ego/TOF

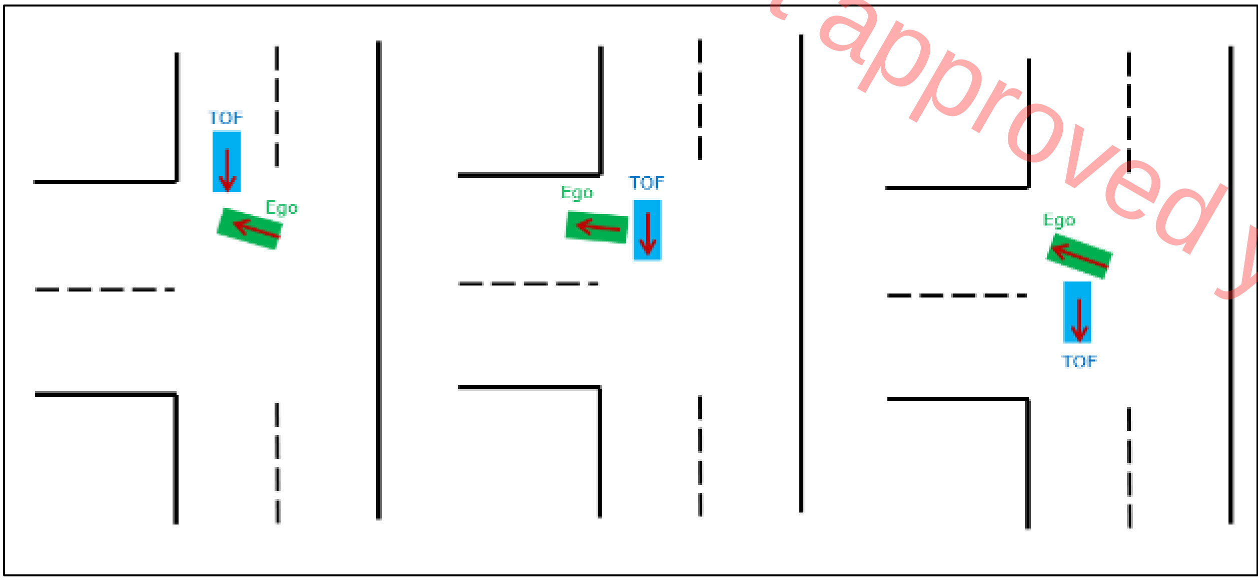


Figure 28: Unsafe minimum distance Ego/TOF

- **Maximum Deceleration:**

During Ego braking, the deceleration increases weakly or strongly depending on the situation of the normal driving or emergency braking. In normal driving, the TTC is higher allowing a smooth braking as shown on the figure 27. In emergency situations, the Ego detects late the front objects involving strong braking and high unsafe deceleration. the Ego For each simulation, the maximum deceleration (minimum of negative acceleration) is computed and then plotted for all simulations.

This output allows to check both decision making and braking models to validate its components and give recommendations for improvement and optimization.

- **Discomfort scale**

The discomfort scale allows to define, based on EN 13452-1 regulation, a safe and comfort range of both acceleration and jerk.

It is computed from as following:

$$Discomfort\ Scale = 2.02 * Jerk + 20.6 * Acceleration - 0.51 * Jerk * Acceleration$$

Figure 29 shows the color map of discomfort scale over acceleration and jerk of Ego. The red zone for high discomfort scale which is corresponding to high acceleration and jerk could be reduced to extend the comfort range. Therefore, an optimum range of discomfort scale allows to define additional criterions based on both acceleration and jerk.

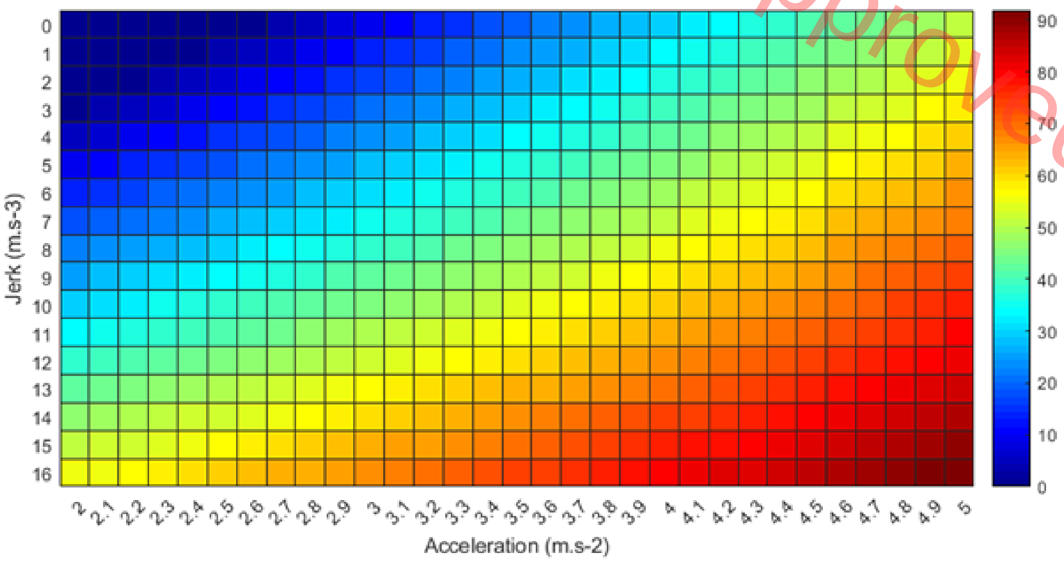


Figure 29: Map of Discomfort scale (%) over acceleration and jerk (CEESAR data)

5 Massive simulations for Safety Evaluation

After having a validated virtual environment, able to cover safety relevant use cases with a sufficient reproducability of real situation behavior, the setup of massive simulation is the last step to allow validating efficiently all critical use cases variations.

5.1 Methodology

The validation toolchain is used a basis-environment, to simulate a defined set of logical scenario variations, described as following:

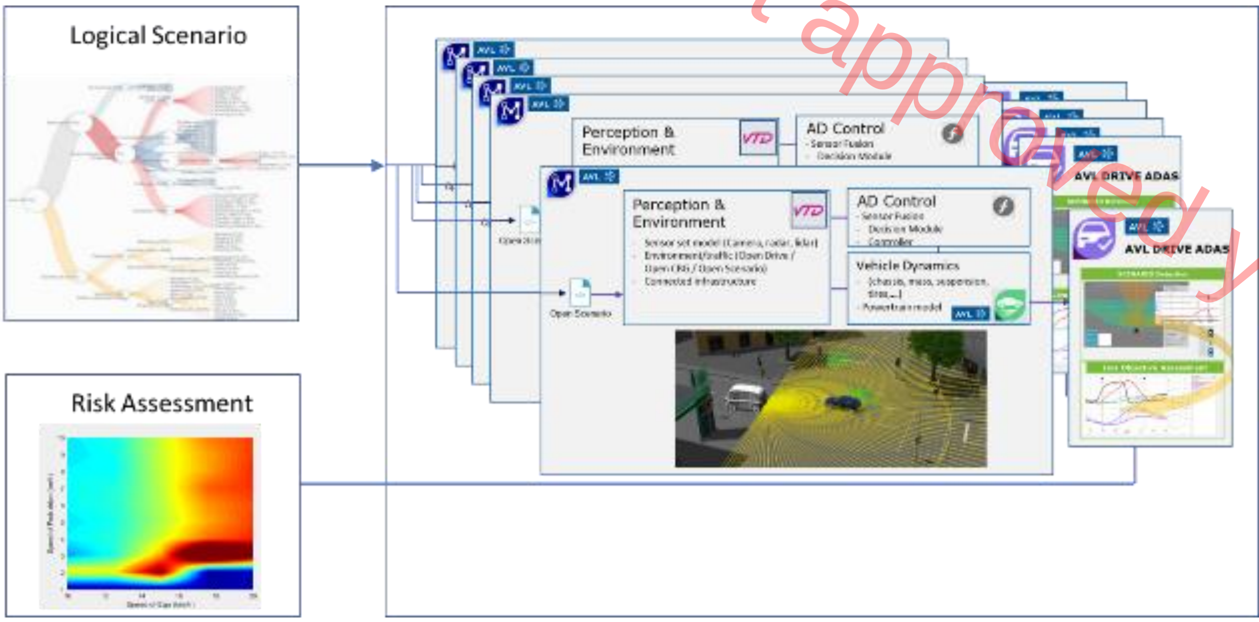


Figure 30: Validation toolchain for massive simulation

Massive simulation allows to run several simulations by varying relevant parameters (inputs) of a use case. The key performance indicators (KPIs) for all simulations are computed and analyzed in a coverage map based on all defined criteria.

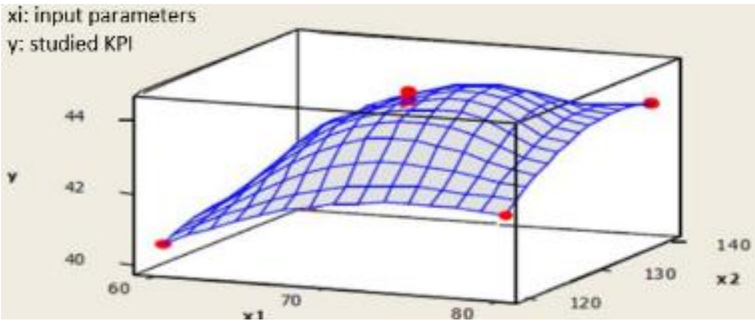


Figure 31: Coverage Map: 3D output over two inputs

When applying safety and comfort related thresholds to the coverage map, unsafe zones and zones of discomfort can be detected as shown on Figure 32. The corresponding input parameters then describe the system limits.

The simulation results also allow to draw up recommendations about actions to increase system performance and can demonstrate to which degree the “safe zone” will be increased by doing so.

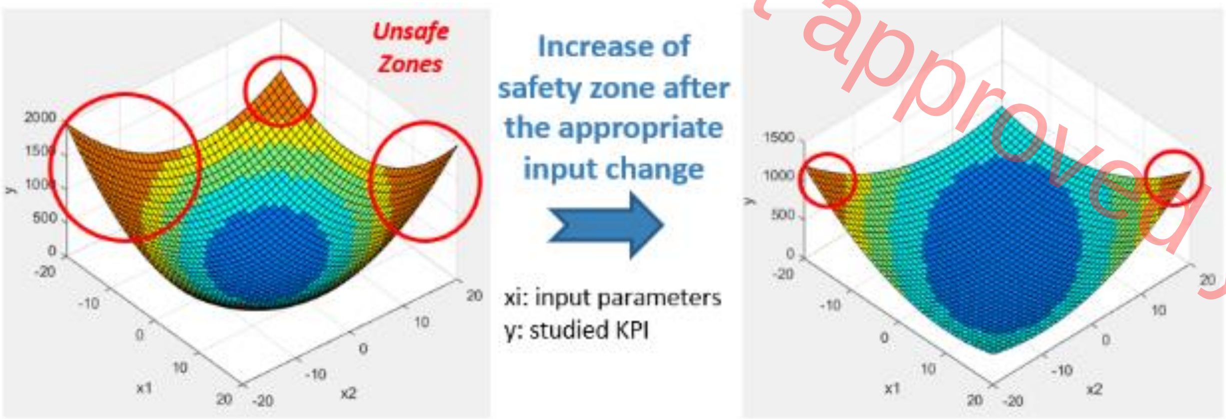


Figure 32: Safe/unsafe and comfort/discomfort zones based on coverage map

5.2 Turn Left use case

5.2.1 Parameters and matrix of simulations

For the "Turn Left" use case, several parameters could be varied to analyze the impact of each on the safety of the system. However, in the first step only more relevant parameters are varied as speed of Ego, speed of TOF and time to collision. Consequently, all other parameters are supposed constant and the initial distance separating both Ego and TOF to the turn left are the same.

Figure 33 shows the "Turn left" use case and its associated parameters.

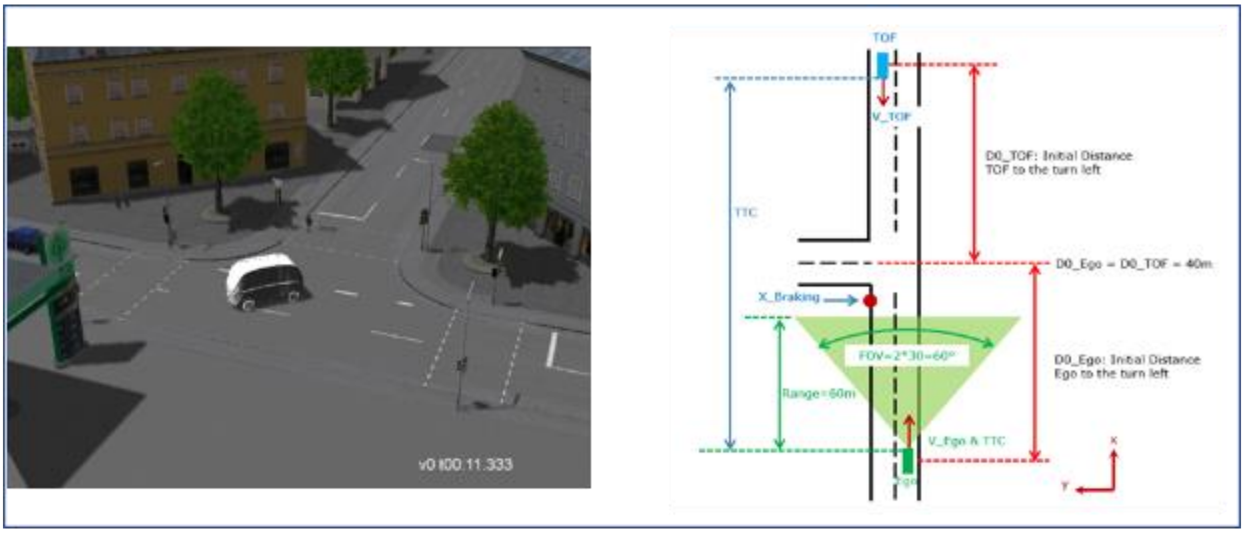


Figure 33: Parameters of the "Turn Left" use case

For the first evaluation, Ego speed is varied from 10 to 20km/h by resolution of 2.5km/h (5 variation levels) and TOF speed from 10 to 50 km/h by the same resolution (17 variation levels). The Time gap is varied from 4s to 6s by 1s as resolution. Sensor inputs are set at default values (range=60m and FoV=2*30=60°).

The total number of simulations with constant for one TTC is 5*17=85 and 85*3=255 with three different TTC. Figure 34 shows the structure of simulations matrix.

	Main Inputs	Main Outputs
Ego	speed Position Radar range Radar Field of View	Deceleration safety Lateral acceleration Jerk Discomfort scale Minimum distance Ego/TOF
TOF	speed position	
Decision making	TTC	

Active	Case	Speed_Ego	Speed_TOF	TTC	Radar_range	FoV_Angle	Position_TOF	Position_Ego
	TTC4_1	10	10	5	60	30	40	40
	TTC4_2	10	12.5	5	60	30	40	40
	TTC4_3	10	15	5	60	30	40	40
	TTC4_4	10	17.5	5	60	30	40	40
	TTC4_5	10	20	5	60	30	40	40
	TTC4_6	10	22.5	5	60	30	40	40
	TTC4_7	10	25	5	60	30	40	40
	TTC4_8	10	27.5	5	60	30	40	40
	TTC4_9	10	30	5	60	30	40	40
	TTC4_10	10	32.5	5	60	30	40	40
	TTC4_11	10	35	5	60	30	40	40
	TTC4_12	10	37.5	5	60	30	40	40
	TTC4_13	10	40	5	60	30	40	40
	TTC4_14	10	42.5	5	60	30	40	40
	TTC4_15	10	45	5	60	30	40	40
	TTC4_16	10	47.5	5	60	30	40	40
	TTC4_17	10	50	5	60	30	40	40
	TTC4_18	12.5	10	5	60	30	40	40
	TTC4_19	12.5	12.5	5	60	30	40	40
	TTC4_20	12.5	15	5	60	30	40	40
	TTC4_21	12.5	17.5	5	60	30	40	40
	TTC4_22	12.5	20	5	60	30	40	40
	TTC4_23	12.5	22.5	5	60	30	40	40
	TTC4_24	12.5	25	5	60	30	40	40
	TTC4_25	12.5	27.5	5	60	30	40	40

Figure 34: parameters and matrix of simulations

Optimization of simulation numbers by DoE

Figure 34 shows additional parameters that could be included in simulation to perform a more complete analysis of use cases.

However, if the number of parameters to vary increases and small resolution of variation is used, the total number of simulations will be factorial increasing the time to run all matrix simulations.

The design of experiment (DoE) could be a solution to deal with this multiparameter use case, using an appropriate optimization algorithm, in order to have, with less parameter variations, the same results as factorial combination.

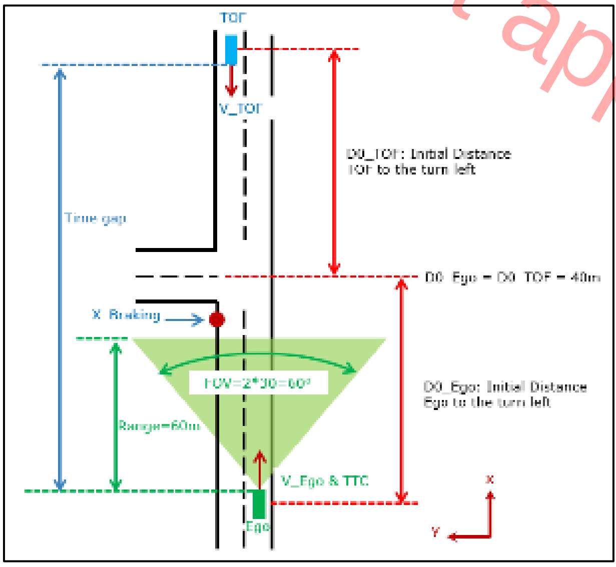


Figure 35: Turn left use case with more parameters

5.2.2 Risk Assessment – example of results

Minimum distance Ego/TOF:

The following figure shows the color map result of EGO DECISION CRITERION, minimum distance Ego/TOF over both Ego and TOF speeds and for three time to collision: 4s, 5s and 6s.

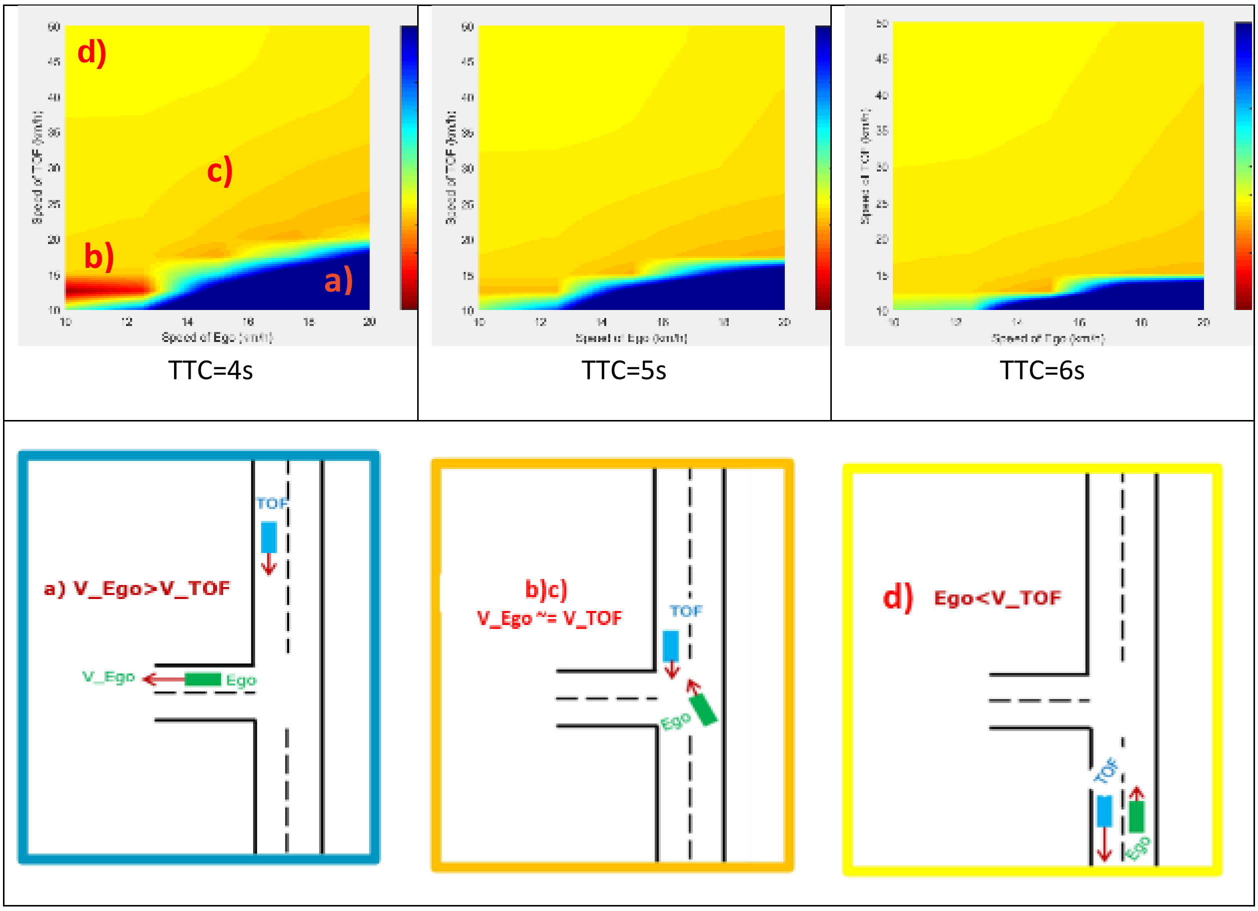


Figure 36: Minimum distance Ego/TOF (scale [0m-10m])

According to the color map, four areas of are identified:

Area a)

This area of use cases corresponds to the situations where Ego speed is higher than TOF speed. TOF arrives later to the conflict point relatively to Ego and keeping high distance to Ego (Minimum Distance Ego/TOF > 6m). This area is not relevant for the safety assessment.

Area b)

The red zone in color map represents the collision cases (Minimum Distance Ego/TOF <2m) where Ego and TOF arrive at the same time on the turn left.

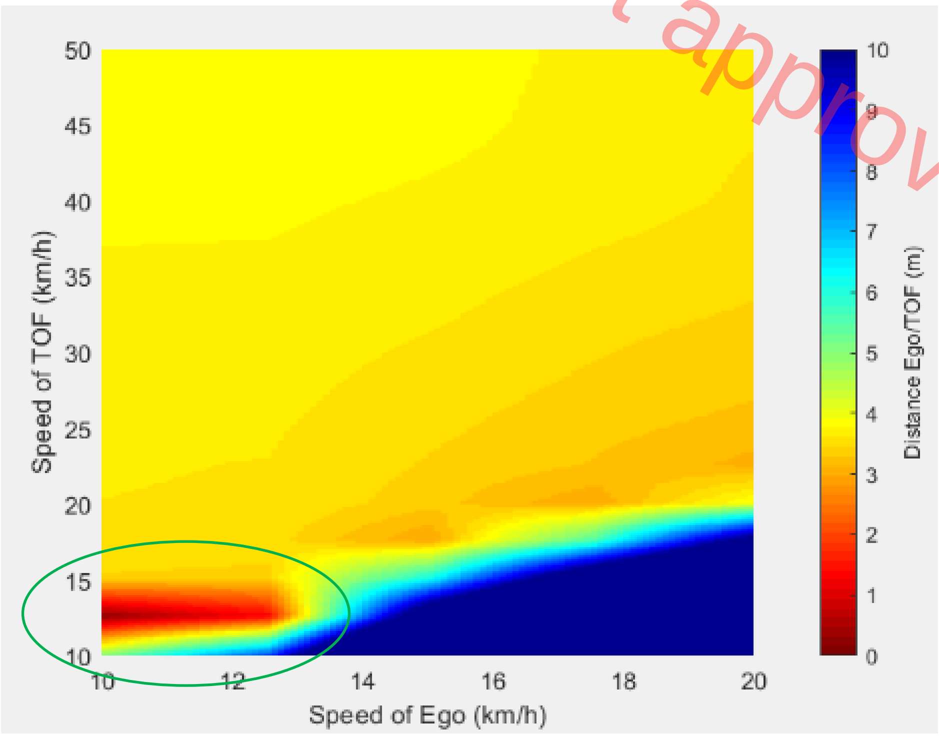


Figure 37: Minimum distance Ego / TOF TTC = 4 s

This unsafe zone appears at low TTC of 4s and mainly at low speed of both Ego and TOF. For this TTC case, Ego is crossing the turn left where its field of view heads for the left as shown on Figure 38.

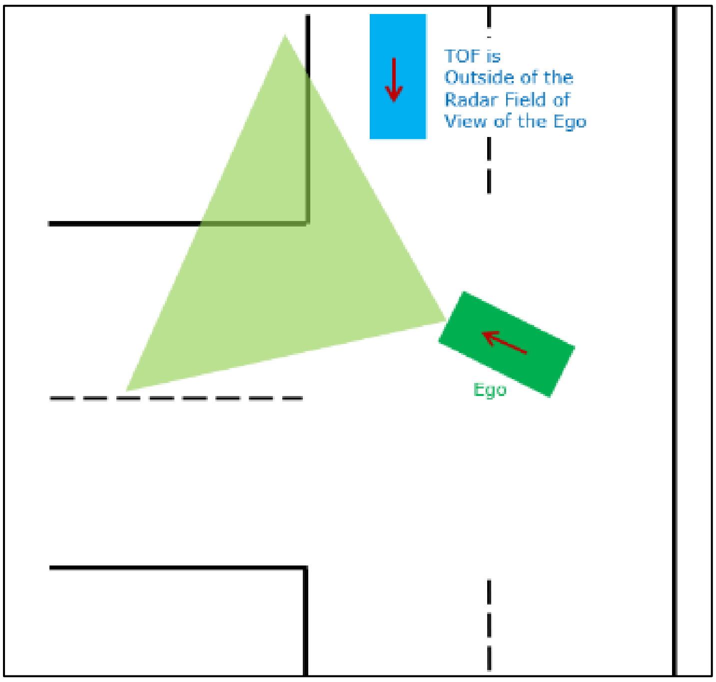


Figure 38: TOF not detected by Ego despite close position to each other

In other words, EGO does not detect the vehicle before starting the cornering maneuver for this parametrization (4s of TTC) and is not able to avoid any collision during cornering.

In addition, current system perception boundaries, used for this study, do not allow to see objects by 360 degrees, which is an additional lever for recommendation. This boundary is also limiting TOF approach during cornering maneuver, that could have helped mitigating collision with an emergency maneuver.

Consequently, TOF is not detected by Ego during the path crossing and causing collision with TOF as shown above.
As a global observation, the perdition with 4s TTC will definitely be too dangerous and generate unsafe situations. EGO shall have more predictive capabilities to cross the road with a smooth maneuver, without any anxious TOF approach.

Area c)

This area corresponds to the cases where both Ego and TOF arrive at the same time on the turn left. The collision risk at the road intersection. Consequently, ego brakes and stops keeping the safe distance (Minimum Distance Ego/TOF ≈ 3m).

Area d)

This area corresponds to the cases where TOF speed is higher than Ego speed. TOF arrives fast on the straight road in the opposite lane of ego keeping a safe distance equal to the lane with (Minimum Distance Ego/TOF = lane width = 3.8m).

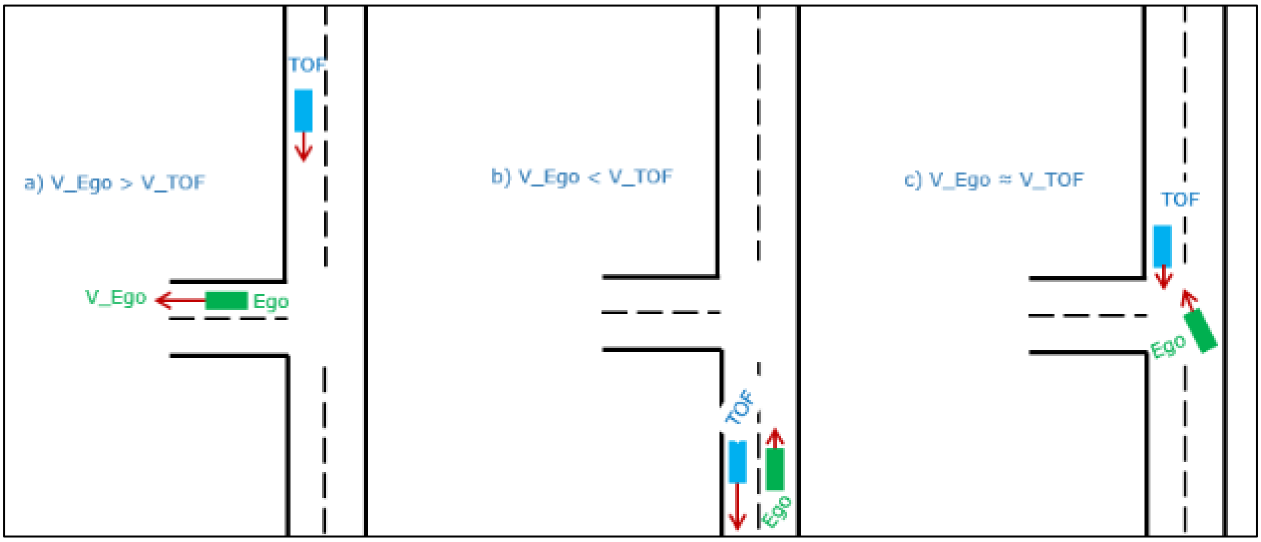
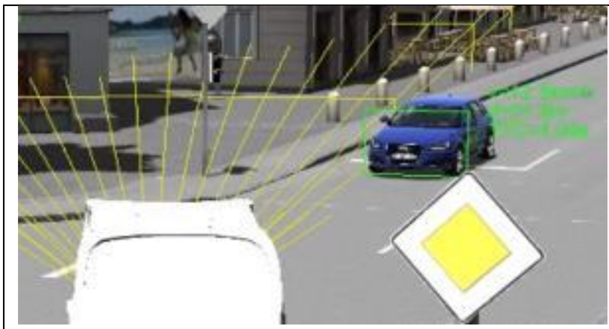


Figure 39: Different scenarios based on the speed of Ego relative to TOF



Ego crossing the turn left at TTC=4.1s

Ego/TOF collision

Figure 40: Collison due to low TTC(4s) and low radar FOV

Maximum deceleration:

Figure 41 shows the color map of the maximum deceleration. This plot allows to identify four different zones (example for TTC=4s):

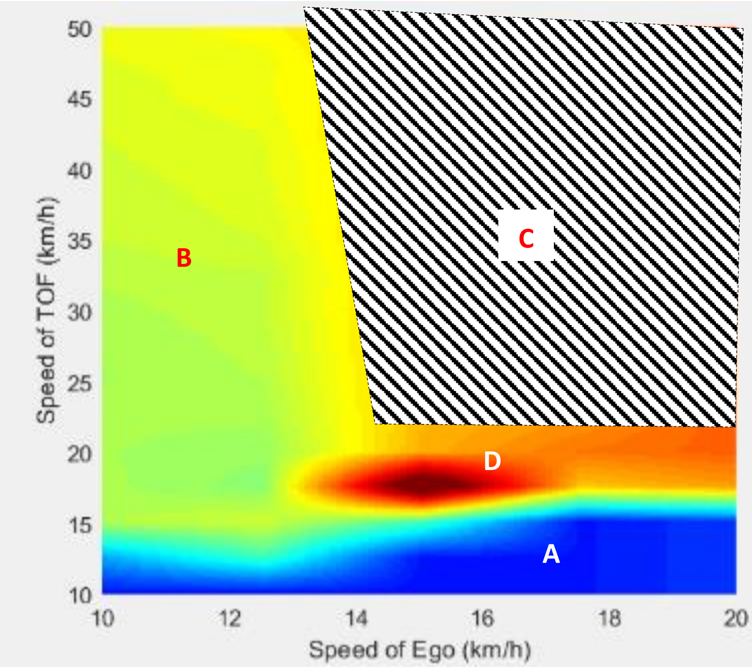


Figure 41: Color map for max. deceleration

Area A:

This blue area corresponds to the case of turn left crossing without any braking, considered as a safe area for Ego, No Ego deceleration due to the low speed of TOF, allowing EGO to perform its maneuver without any reaction on TOF.

The variation of TTC parameter has an impact on this safe area.

TTC=4s:

At low TTC (=4s), the braking action is delayed allowing to the Ego to cross the turn left before TOF approaching, no anticipation as TOF not considered by EGO (too slow and far away to request any action).

TTC=6s:

Ego considers TOF vehicle as TTC configuration allows more prediction for EGO decision module. Indeed, EGO starts to brake early and stops safely on its lane waiting the crossing of TOF before to turn left.

We will see below that whereas reducing EGO safe area without any braking action, increasing TTC parameter will help avoiding critical safety situations explained in Area D.

Area B:

This area corresponds to the situation where Ego moves with low speed and brakes at TOF detection with a safe deceleration (> $-2m/s^2$).

We assume here a correct anticipation of trajectory conflict point between EGO and TOF. The more the TTC parameter is high, the more variation of the driving situation is safely managed by EGO, with a minimum deceleration peak at $-2m/s^2$, which is considered as comfortable.

Area C:

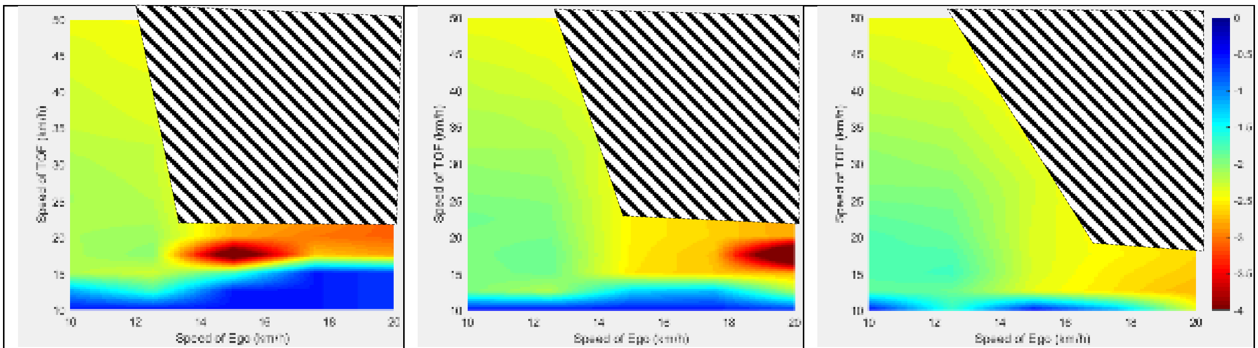
The hatched area located in the top right corner corresponds to the high speed of Ego and TOF.

This area is not relevant for safety evaluation, EGO is able to manage these situations respecting safe deceleration.
Currently the results are dashed due to simulation limitations.

Area D :
TTC=4s:
For 1 parameter set: Ego_Speed=15km/h, TOF_speed=17km/h, there is a conflict point between TOF and EGO trajectory inducing a strong brake request from EGO. This deceleration is no respecting a safe minimum deceleration criteria (< $-4m/s^2$).
All other scenario variations around this set are compliant with this safety criteria. Indeed, only 1 situation is considered as unsafe on all variation for this TTC value.

TTC=5s:
For 1 parameter set: Ego_Speed=20km/h, TOF_speed=17km/h, there is a conflict point between TOF and EGO trajectory inducing a strong brake request from EGO. This deceleration is no respecting a safe minimum deceleration criteria (< $-4m/s^2$).
All other scenario variations around this set are compliant with this safety criteria. Indeed, only 1 situation is considered as unsafe on all variation for this TTC value.
Compared to the previous results with TTC=4s, we can see that the critical situation occurs for a higher EGO speed. It is the limit between TTC and EGO anticipation capability with the current perception configuration.

TTC=6s:
At TTC=6s, all deceleration cases are safe (<$2m/s^2$) except values at the top right corner. EGO is able to manage all situation respecting minimum deceleration criteria safely.
Increasing TTC parameter up to 6s, allows to suppress some critical situations detected with lower TTC values.



TTC=4s | TTC=5s | TTC=6s

The quadrilateral zones correspond to high decelerations due to a numerical issue: the initial TTC which is reached at the beginning of simulation

Figure 42: Maximum deceleration ([$-4m/s^2$; $-0m/s^2$])

<u>Discomfort scale:</u>
Figure 43 shows the discomfort color map over Ego and TOF speeds. As it depends to both deceleration and jerk, its high values (> 50%) are located on the zones where the deceleration is higher. These zones correspond the emergency braking situations happens for TTC < 6s.

To avoid these unsafe situations, the decision-making function shall anticipate early the front collision using long range front radar or infrastructure information.

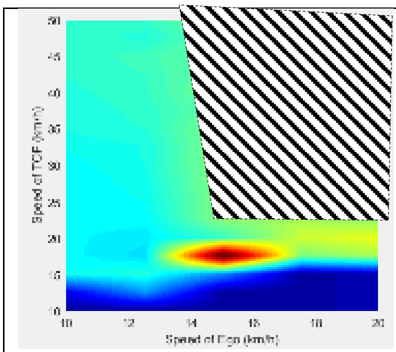
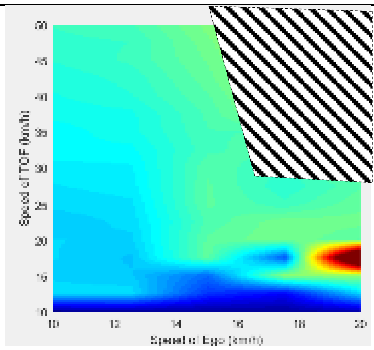
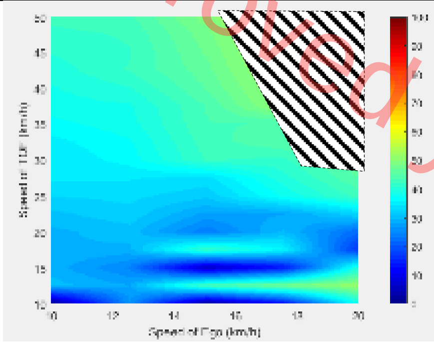
		
TTC=4s	TTC=5s	TTC=6s
The quadrilateral zones correspond to high decelerations due numerical issue: the initial TTC which is reached at the beginning of simulation		

Figure 43: Discomfort scale (%) (scale 0%-100%)

5.2.3 Safety Recommendations

1. The first issue related by this use case corresponds to scenarios where Ego and TOF are located at the same time (TTC) to the Turn Left. In this case, Ego shall reduce gradually its speed to increase the TTC and shall keep a safe deceleration waiting for TOF crossing the turn left.

   TTC parameter must be considered as one main design constrains to ensure deceleration capabilities. The more the vehicle will be capable of high TTC (6 second for this use case) the more it will be allowed to respect smooth and comfortable deceleration, these two properties have a direct link.

   For sure, improving the TTC will give more anticipation capabilities to the vehicle, but on board sensors have limitation. The way how TTC should be used could be the following:

   a. Target deceleration smoothness performances will define level of TTC the system should be capable of (TTC Target).

   b. Simulation activities to evaluate maximum TTC reachable with on borad sensors (TTc on bard)

   c. Remaining Gap will define the request of environment perception of the infrastructure: TTC Target – TTC on board = TTC Infrastructure

2. The second issue happens when the critical TTC is reached during the path crossing and TOF exits the FoV of Ego exactly in the middle of TOF lane. Consequently, the collision is unavoidable if TOF keeps the same constant low speed. To avoid the collision, the first solution is to use an additional

set of corner radar with mid-range allowing to keep TOF inside Ego environment. The second solution concerns the decision making which could be adapted for safe TTC values at low TOF speeds: increase the TTC by additional seconds. The methodology set up based on the tool chain allows to optimize TTC value for all TOF/Ego speeds.

At low speed and in cornering situations, a combination of two parameters shall be considered as design criteria:

- Field of view (FoV)
- TTC

These parameters will help in the definition of EGO decision making process, and could be considered as follow:

a. Target FOV will define the perception capability of the system while target is beside EGO. Perfect target would be 360° FOV with 100% of good detection for each kind of objects (car, Pedestrian, …)

b. FOV capabilities on board may be assessed by simulation / test activities

c. Verify that infrastructure could compensate all situations where on board sensors are not covering all requirements of the Target FOV

d. TTC is considered as set (based on previous recommendation)

e. Real FoV will define minimum distance between EGO and Target to avoid a collision with defined TTC

f. The binomial balancing (FOV;TTC) will allow some calibration to find the best setup via massive simulation.

5.3 Pedestrian use case

5.3.1 Parameters and matrix of simulations

The second use case studied by simulation is shown on Figure 44 is corresponding to a pedestrian crossing Ego’s road. The pedestrian is masked initially by a font parked vehicle. The lack or delay of detection of the pedestrian by Ego represents a complicated and unsafe situation.

This scenario was retained following a ranking by operators.

Several parameters could be varied in the massive simulation of this use case:

- Speed of Ego
- Speed of pedestrian
- Radar field of view
- Radar range
- Initial position of Ego
- Initial position of pedestrian

- Distance pedestrian/Parked vehicle
- Hight of parked vehicle
- Hight od Initial position of pedestrian
- Direction of pedestrian crossing

In this report, only the more relevant parameters are varied: radar field of view and speed Ego and speed of pedestrian as shown in Figure 45Figure 44.

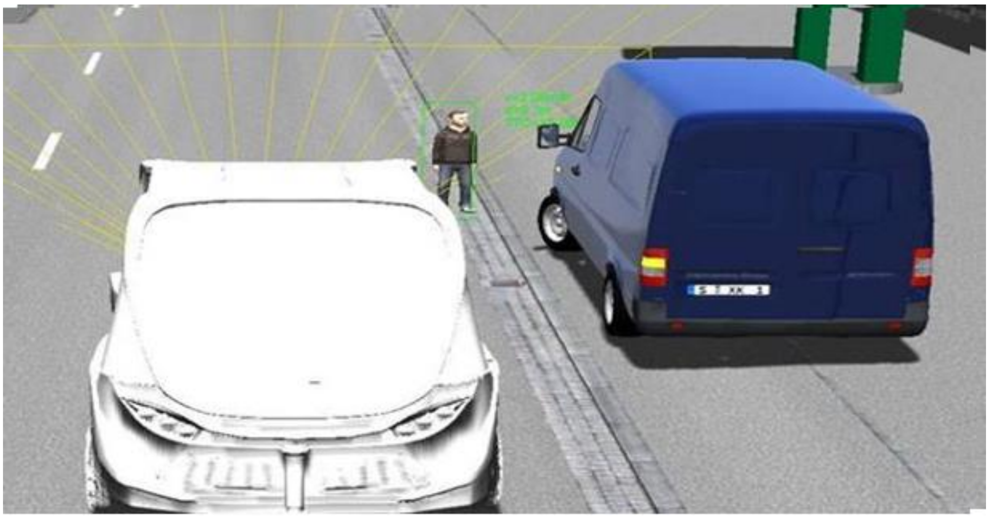


Figure 44: Pedestrian suddenly crossing the road in front of ego vehicle

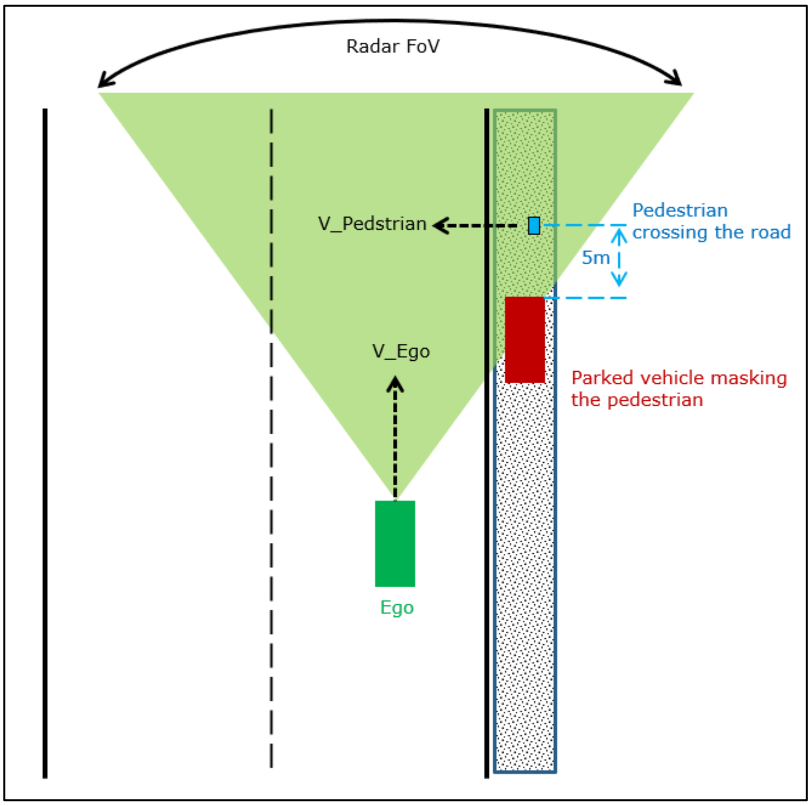


Figure 45: 2nd use case: Detection of pedestrian

Figure 46 shows the matrix of simulations where Ego speed is varied from 10km/h to 20km/h by resolution of 2.5km/h (5 variations), the pedestrian speed is varied from 1km/h to 10km/h by resolution of 1km/h (10 variations).

The FoV is varied from 60° to 100° by resolution of 20° (3 variations of half of FoV angle: 30°, 40° and 50°). The radar range is constant and set to 60m leading to a total of 150 simulations.

For the decision making, all simulations are made with the same TTC of 5s.

	Main Inputs	Main Outputs
Ego	speed Position Radar range Radar Field of View	Deceleration safety Jerk Discomfort scale Minimum distance Ego/Pedestrian
Pedestrian	speed position	
Decision making	TTC	

Active	Case	FoV_Angle	Speed_Ego	Speed_Pedestrian	Radar_range
	uc2_fov50_ 1	50	10	1	60
	uc2_fov50_ 2	50	10	2	60
	uc2_fov50_ 3	50	10	3	60
	uc2_fov50_ 4	50	10	4	60
	uc2_fov50_ 5	50	10	5	60
	uc2_fov50_ 6	50	10	6	60
	uc2_fov50_ 7	50	10	7	60
	uc2_fov50_ 8	50	10	8	60
	uc2_fov50_ 9	50	10	9	60
	uc2_fov50_ 10	50	10	10	60
	uc2_fov50_ 11	50	12.5	1	60
	uc2_fov50_ 12	50	12.5	2	60
	uc2_fov50_ 13	50	12.5	3	60
	uc2_fov50_ 14	50	12.5	4	60
	uc2_fov50_ 15	50	12.5	5	60
	uc2_fov50_ 16	50	12.5	6	60
	uc2_fov50_ 17	50	12.5	7	60
	uc2_fov50_ 18	50	12.5	8	60
	uc2_fov50_ 19	50	12.5	9	60
	uc2_fov50_ 20	50	12.5	10	60
	uc2_fov50_ 21	50	15	1	60
	uc2_fov50_ 22	50	15	2	60
	uc2_fov50_ 23	50	15	3	60

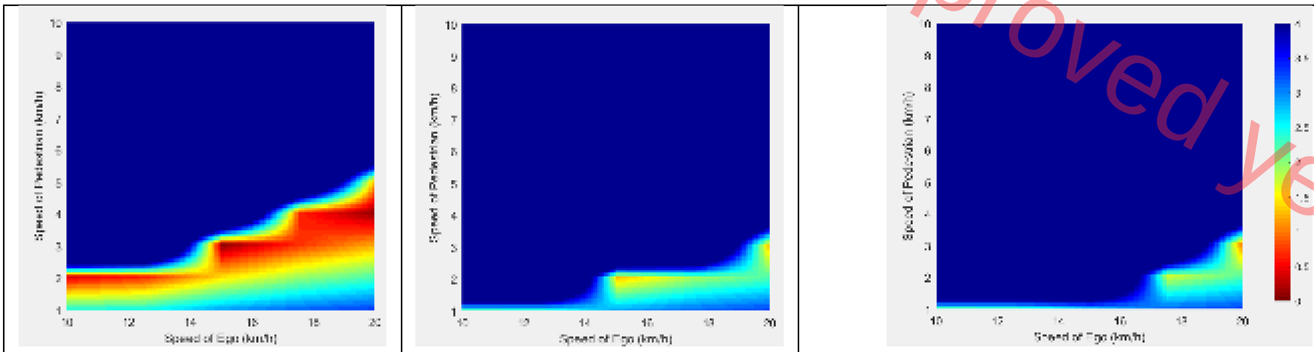
Figure 46: parameters and matrix of simulations Results

5.3.2 Risk assessment – example of results

Figure 47 shows the colour map of the minimum distance Ego/Pedestrian over Ego speed and pedestrian speed at different radar field of views.

The distance Ego/Pedestrian is defined as distance between pedestrian and centre of Ego and the risk of collision happens at critical distance of 2m.

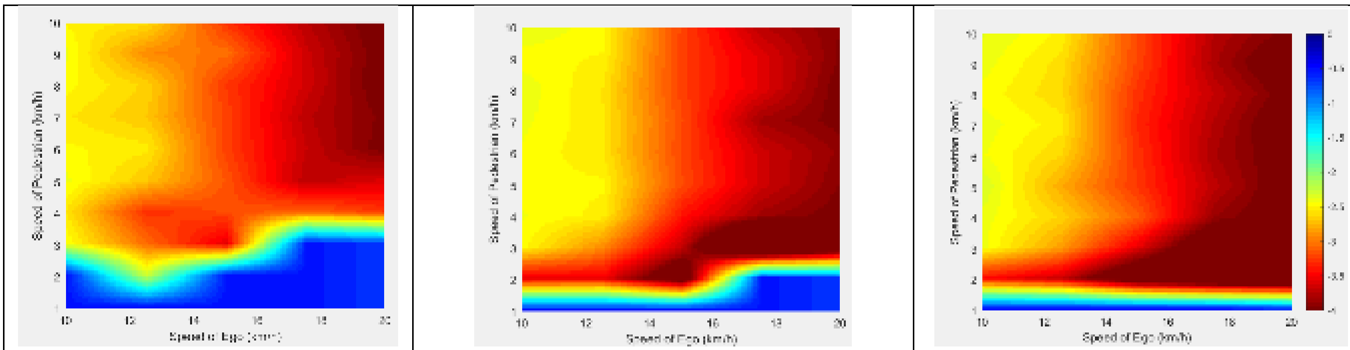
For wider field of view, the collision zone is reduced ensuring safe situations of pedestrian.



FoV= 60° | FoV= 80° | FoV= 100°

Figure 47: Minimum distance Pedestrian/Ego

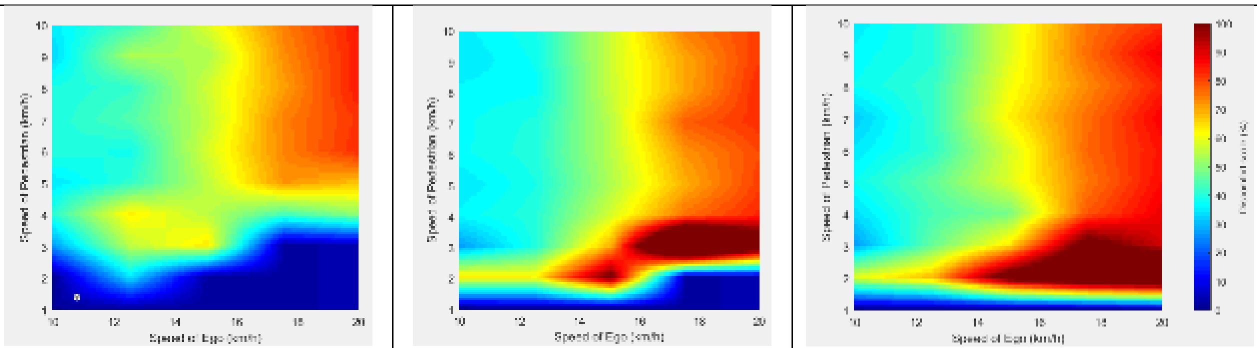
However, and based on Figure 48, the large Ego field of view increases the zone of the maximum of Ego deceleration (<-3m/s²) due to the emergency braking. These unsafe decelerations are disastrous for Ego and mainly for their passengers.



FoV= 60° | FoV= 80° | FoV= 100°

Figure 48: Maximum deceleration

Figure 49 shows the discomfort scale which is increased also at high Ego field of view. The most of simulated scenarios of this criteria is exceeding the safe threshold of 40%.



FoV= 60° | FoV= 80° | FoV= 100°

Figure 49: Discomfort scale (%) (scale 0%-100%)

5.3.3 Safety Recommendations

Based on these results, it seems that the only front radar is not enough to ensure safe behavior of Ego and security of pedestrian. Despite wider field of view of the front sensor, the risk of pedestrian collision is minimized at the cost of passenger safety.

It seems mandatory to complete the perception of Ego by an external information source to warn Ego about any pedestrian standing near to Ego lane or trying to cross it. This additional information allows to anticipate the deceleration when any masked pedestrian tries to cross Ego lane. Ego could decelerate reducing its speed to a minimum threshold and then accelerate when it overtakes the pedestrian area.

The additional information could be provided directly by the infrastructure or by the cloud. Connected cameras or presence sensors could equipped the infrastructure near pedestrian crossing areas to detect and inform about any static or moving objects on the sidewalk and around Ego environment.

This current use case on example of the previous recommendation about FoV and TTC with an extension:

a. Target FOV and range is set for this use case

b. FOV a range capability on board is assessed

==> Impossible to detect hided objects with on board sensors

c. Verify that infrastructure could compensate all situations where on board sensors are not covering all requirements of the Target FOV

d. TTC is considered as set (based on previous recommendation)

e. Real FoV will define minimum distance between EGO and Target to avoid a collision with defined TTC

f. The binomial balancing (FOV;TTC) will allow some calibration to find the best setup via massive simulation.

==> In that case, lets assume that infrastructure is not able to compensate on board FOV to meet Target FoV and TTC can also not be increased.

g. If binomal (FOV;TTC) not matching target safety request, EGO Speed has to be reduced to Vmini (parameter to be defined as acceptable minimum speed) in this specific area until binomial (FoV,TTC) is able to meet the target autonomously.

h. If Vmini is not sufficient to secure the system, this use case should be removed from the list considered scenarios. The design of the bus line should consider all levers to guarantee this use case will never occur.

6 Conclusions

The aim of *WP6 - Safety Evaluation* is to define a method to assess and measure the vehicle behavior with regards to safety aspects, both for passengers and surrounding road users. The safety evaluation in T6.1 builds on several metrics and KPIs provided by the injury risk evaluation performed in T6.2. It includes safety metrics as well as relevant thresholds for safety acceptance.

T6.1 created a virtual environment toolchain and deployed a live safety evaluation solution. In order to provide flexibility to AVENUE, two different virtual environments have been assessed; an open-source simulation environment (CARLA Simulator) and a proprietary Vires VTD (Virtual Test Drive) simulation tool.

The validation toolchain based on Vires VTD is fully operational and used as a base for AVENUE safety evaluation.

A correlation with available test data has allowed to refine a representative solution capable to assess and quantify safety metrics. The different simulation results presented on this report shows the ability of the tool chain to identify and validate associated recommendations to improve vehicle and environment safety.

Based on a correlated validation toolchain, critical scenarios have been selected with relevant parameter set to evaluate limiting parameters and potential levers to improvement global safety for each scenario variation.
A deployment of massive simulations on several input parameters (environment, vehicle perception, …) has been performed. The safety criteria previously detailed have been analyzed to extract some ways of safety improvement.
In that way, for each use cases considered, quantified and concrete recommendation to improve safety have been identified and proposed in this report.

Based on the simulation environment and associated hypothesis, the current safety evaluation methodology has allowed to define several safety improvement recommendations, considering both Safety for vehicle passengers and external environment (vehicles, pedestrian, infrastructure).
These recommendations are focusing on the capability to improve embedded technology (sensor performances, vehicle decision, trajectory planner) and quantify their limitations. Therefore, additional levers have been identified to complete global system design with infrastructure technical recommendation (road design limitations, infrastructure perception solutions, global test sites rules).

Finally, the proposed safety evaluation methodology, allows evaluating virtual and real tests on board safety of the global autonomous system (vehicle + infrastructure). This method can be used as a basis to cover all range of critical scenarios, assess their impact, and quantified the benefits of each technical levers to improve system global safety.