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Scaling autonomous logistics

D4.7 – Safety and SOTIF Assessment Report

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Responsible Author(s)	Marianne Kivikangas (CertX)
Responsible Co-Author(s)	Sami Koskinen (VTT), Mikko Tarkiainen (VTT), Hannes Watzinger (Digitrans), Andrea Dumfart (Digitrans), Niku Gorji (CertX)
Technical Peer Review	Arman Iranfar (CertX)
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CONTACT

Mrs. Magali Cottevieille
Project Coordinator
EasyMile
21 Boulevard de la Marquette
31000 Toulouse
France

Email: magali.cottevieille@easymile.com
www.award-h2020.eu

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List of acronyms

ADAS	Advanced Driver Assistance System
ADS	Autonomous Driving System
ADV	Autonomous Driving Vehicle
ASIL	Automotive Safety Integrity Level
AV	Autonomous Vehicle
FSC	Functional Safety Concept
HARA	Hazard Analysis and Risk Assessment
ODD	Operational Design Domain
RSS	Responsibility-Sensitive Safety
SG	Safety Goals
SOTIF	Safety Of the Intended Functionality
UC	Use Case
VRU	Vulnerable Road User
VUT	Vehicle Under Test

Executive Summary

This report summarizes the outcomes of safety tests, in preparation to perform field tests safely within the AWARD project. The tests will use automated industrial trucks and forklifts to transport goods on predefined routes. The project targets operations in harsh weather conditions.

All the Safety and SOTIF proving ground tests were executed at the Digitrans Test Center for Automated Driving in St. Valentin, Austria. The main areas are the outdoor rain plant, intersection, roundabout, and dynamic area. These tests, designed by evaluating the Operational Design Domain (ODD) of the vehicle, incorporate basic scenarios such as static or dynamic obstacles in the front and on the side. Additionally, the ODD evaluation considers several factors, including roadway types, weather conditions, and obstacles, to anticipate the upcoming field tests and routes. Each element is assessed for severity and exposure, with combinations of these ODD properties compiled into a matrix to filter out impractical scenarios. This process leads to the identification of not only the most critical combinations but also includes essential basic tests as the foundation for safety and SOTIF assessments.

Test scenarios focused on varying parameters like obstacles, vehicle trajectories, and weather conditions critical for safety. Every scenario was repeated approximately 20 times for the evaluation of consistency. Variation means that the same scenario was done with slight changes e.g. left/right, object size but no significant change. Run means that each scenario is done multiple times for evaluation the consistency. Iteration means the progressive numbering during the execution of one scenario with different variations and all runs. Success criteria were defined beforehand for each scenario. These criteria were assessed at the site, by the persons carrying out safety validation. Using the success criteria, vehicle performance in each run was marked as OK or not OK. Vehicle log data and videos were collected to support a detailed analysis of vehicle behaviour in selected runs.

Some scenarios require simulation due to the impracticality to execute them on proving grounds. Furthermore, simulations show complementary information on vehicle behaviour that is not easily accessible for proving ground tests. In simulations, it is possible to do tests that would have been too dangerous to conduct or too difficult to arrange in the real world or could have resulted in costly damage.

This report aims to offer a thorough analysis of safety aspects, with input from earlier risk analyses and test site reviews to select test scenarios. The focus is on analysing whether the vehicles behave safely in tested scenarios that should represent basic accident scenarios and use-case specific aspects. This is done by conducting tests at the proving ground and simulations to analyse the success in avoiding accidents, ensuring smooth and repeatable vehicle control, and maintaining safety margins in various situations.

As a result, this report provides a discussion on the main test results, identified issues, and our recommendations on how the issues should be addressed before operational tests begin. If a certain safety issue is difficult to solve before the tests, test sites must address the topic using specific means, such as infrastructure, access control, or safety operator tasks.

Recommendations are presented for future development of the tested vehicles (e.g. sensor setup, brake control) and their logic (e.g. necessary safety margins), as well as for precautions to take into account during testing. Improvements and further internal testing are required to address the mentioned limitations. Taking these recommendations into account, all AWARD vehicles continue to further internal testing with a safety driver.

1. Introduction

The AWARD project aims to showcase and assess technical enhancements for all-weather capabilities of automated vehicles through specific real-world tests. These tests encompass various challenging environments, ranging from industrial zones to public roadways, utilizing various automated vehicles and accommodating different user requirements.

With a focus on demonstrating automated vehicles operating in challenging weather conditions and addressing deployment hurdles in logistics operations, the AWARD project strategically employs several use cases aligned with market demands, spanning from factory operations to logistics hubs.

The specified use cases within the AWARD project are as follows:

- Use Case 1 (UC1): Loading and transport with an automated forklift. Referred in this report as “Forklift””.
- Use Case 2 (UC2): Hub-to-hub shuttle service from warehouse/production site to logistics hubs. Referred in this report as “Kamag”.
- Use Case 3 (UC3): Automated airport baggage tractor. Referred in this report as “EZTow”.
- Use Case 4 (UC4): Container for transfer operations and automated boat loading. Referred in this report as “EZTug”.

The aim of the safety validation activities is to investigate and assess the level and the performance of the developed automated vehicles from a safety perspective within the project. Potentially identified limitations from the tests form the basis for recommendations and possible mitigation actions at the pilot sites to allow a safe operation during the demonstration.

This public report delineates the Safety of The Intended Functionality (SOTIF) compliance assessment, contributing to achieving Objective 2 in the AWARD project. Objective 2 entails the development of a secure and scalable autonomous driving system capable of managing adverse weather conditions, specifically tailored for heavy-duty vehicles.

Grounded in the SOTIF activities outlined in D4.2 - SOTIF activities [7], this document presents design of the proving grounds, as well as the process of test scenario selection for each use case and evaluation of the test results. Vehicle log data and videos were collected to support later detailed analysis of vehicle behaviour in selected runs. The log data contained mainly the following timed signals maximally at 100 Hz: vehicle location and speed, emergency mode, navigation software speed command for the vehicle to adjust its speed to, nearest edge of a possible object in monitored safety zone, and for monitored large areas such as intersections, information if the monitored area was free or occupied.

Some scenarios were tested through simulation due to the impracticality of executing them on proving grounds. Simulations made it possible to conduct tests that could be too dangerous in the real world, were challenging to organize, or could lead to costly damages.

This report provides a summary of Safety and SOTIF assessment aspects, while the applicability and target platforms are detailed in WP2.

1.1. Purpose and Scope

This Safety and SOTIF assessment report explains the design and selection of scenarios for the safety tests and gives an overview of the proving ground. The safety tests are conducted and evaluated as mandatory requirements for performing the field tests safely. Finally, recommendations are made to ensure the safety of upcoming operational tests.

1.2. Related documents

The relation with the different work packages of the project is shown in Figure 1. The Safety and SOTIF assessment is linked to the concept and product development, as well as the testing. Additionally to the documents in this project, discussion with the contributors, driver logs, vehicle data collected, pictures, and videos are used to develop the outputs.

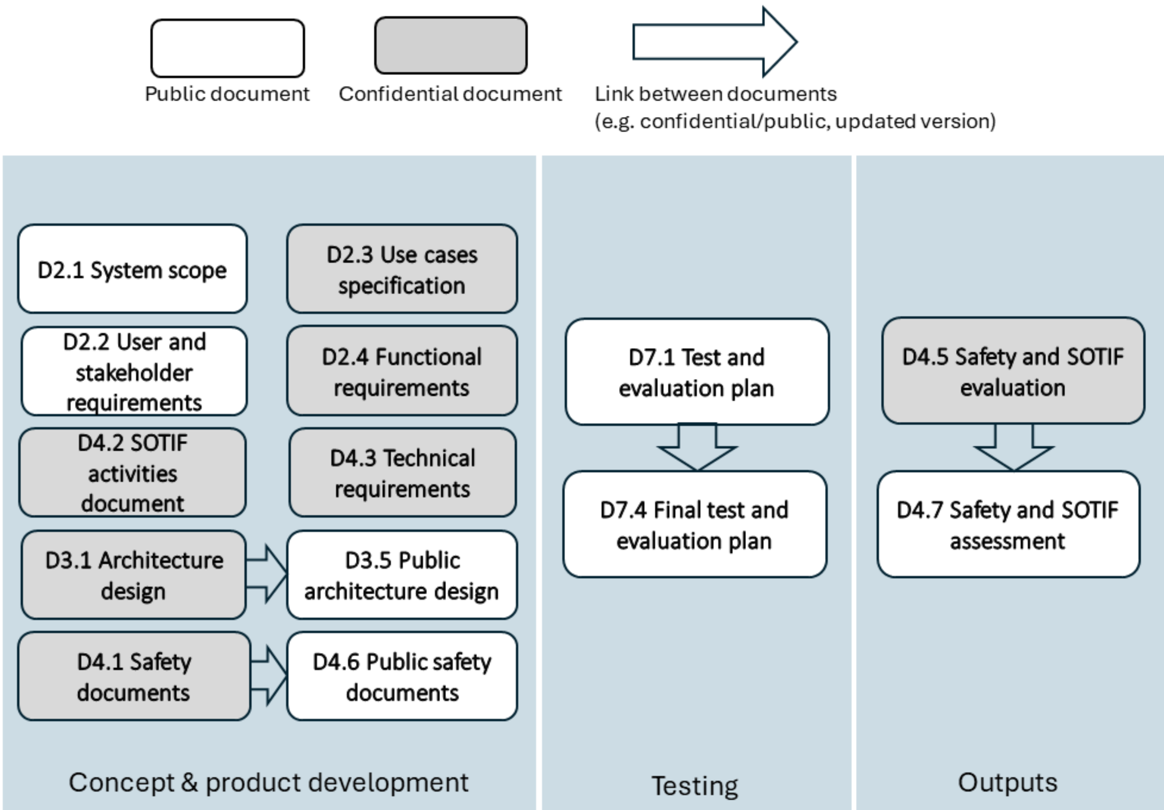


Figure 1. Related documents

1.3. Confidentiality

This document is public, and content aimed to be shared for external use, to all the AWARD consortium partners and extended to anyone else.

2. Defining Safety Validation Scenarios through ODD Analysis

This chapter explains the requirements of operational scenarios and the Operational Design Domain (ODD) within the AWARD project. The relevant operational scenarios are defined for each use case with the dynamic environmental conditions, such as weather conditions, weather-induced road conditions, and visibility. The road environment is categorized with the possible roadway types, geometries, and conditions. The environment can impact visibility, sensor performance, vehicle manoeuvrability, and communications systems.

2.1. Operational Scenarios

This section describes the operational scenarios for each use case. Operational scenarios constitute refined and systematically structured narratives elucidating the functioning of the system and Autonomous Vehicles (AVs) within their environmental context. They serve the crucial role of validating specific use cases. Within the framework of the AWARD project, these scenarios provide strategic guidance for tasks associated with comprehensive system development, precise test case definition, and methodical test development. By intricately refining, formalizing, and organizing the descriptions of system behaviour and AV operations, operational scenarios facilitate the establishment of well-defined test environments. This supports parameterizing these environments and specifying the desired outcomes, contributing to the efficacy of the testing process. A list of Operational Scenarios for the AWARD use cases is presented in D2.3 – Use Case Specification in Chapter 4.2 [5].

For a detailed description of the sites, the reader can refer to document "7.4 – Final Test and Evaluation Plan" which describes the test sites. The following operational scenarios by use case (see Table 1) have been identified in the D2.3 – Use Case Specification [5].

The dynamic environmental conditions for all use cases are weather conditions, weather-induced road conditions, visibility, and connectivity.

Table 1. Operational scenarios grouped for every use case

#	Use Case	Relevant Operational Scenarios
UC1	Loading and transport with automated forklift	- Driving straight ahead - Coupling trailers / trolleys - Uncoupling trailers / trolleys - Picking up lattice boxes - Placing lattice boxes - Stopping in front of an obstacle - Passing an obstacle - Uphill drive - Downhill drive - Visibility extension by road-side camera
UC2	Hub-to-hub shuttle service from warehouse/ production site to logistics hubs	- Leaving a compound site - Driving on a public road and approaching an intersection - Driving straight ahead - Passing an intersection - Passing an intersection with turning lane

		- Driving through a tunnel or overpass - Driving through a bottleneck - Reversing at the compound site - Enter and Check-in at a compound site - Exit and Check-out at a compound site - Stopping in front of an obstacle - Passing an obstacle - Performing a safe stop - Uphill drive - Downhill drive - Visibility extension by road-side camera - Approaching a ramp
UC3	Automated baggage tractor on an airport	- Driving straight ahead - Passing an intersection - Passing an intersection with turning lane - Driving through a tunnel or overpass - Coupling trailers / trolleys - Uncoupling trailers / trolleys - Uphill drive - Downhill drive - Stopping in front of an obstacle - Passing an obstacle - Performing a safe stop - Approaching a ramp
UC4	Trailer transfer operations and automated ship loading in a port	- Enter and Check-in at a compound site - Exit and Check-out at a compound site - Driving straight ahead - Driving on a public road and approaching an intersection - Entering deck of vessel - Coupling trailers / trolleys - Uncoupling trailers / trolleys - Stopping in front of an obstacle - Passing an obstacle - Performing a safe stop - Visibility extension by road-side camera - Approaching a ramp

2.2. Scenery, Environment, and Dynamic Elements

In this section, a brief introduction is given to the scenery, environment, dynamic elements, and objects. These topics are described in greater detail in D4.2 – SOTIF activities [7] and D2.3 – Use Case Specification [5].

Every scenario starts with an initial scene. Actions and events, as well as goals and values, may be specified to characterize this temporal development within a scenario [2]. Scenery defines all geo-spatially stationary objects in the ODD of the vehicle. Generally, the scenery can be classified into drivable areas, junctions, zones, fixed road structures, temporary road structures, and special structures. Environmental attributes are wind, rainfall, snowfall, particulates, illumination, and connectivity. Dynamic elements can be divided into scripted traffic and non-scripted traffic. Non-scripted traffic elements are traffic participants and manoeuvres. Scripted traffic elements are the density of agents, volume, intersection manoeuvres, flow rate, and agent type [8].

The ODD has been defined using NHTSA guidelines. The Award ODD has been defined in D2.3 – Use Case. The aim was to define a generic format to the requirements, as well as to identify common elements and subsequently enable uniform technical developments and tests. A hierarchy was defined to cover all the requirements and to identify common elements of the use cases. The main defined categories are:

- physical infrastructure, which is characterized by technical structures, such as roads, bridges, and tunnels. Static and dynamic objects are included as well, such as buildings, other road users, and obstacles (e.g. vegetation).
- operational constraints, which are characterized by traffic, operation area, logistics, and fleet management. It includes elements such as dynamic changes in speed limits, traffic characteristics, and construction.
- environmental conditions, which are characterized by weather and connectivity. These can impact factors, such as visibility, sensor performance, vehicle manoeuvrability, and communications systems.

The method of how the tests were designed within the AWARD project, including an example of the ODD design for a use case, is explained in Chapter 2.3.

The following environmental conditions (see Table 2) have been identified in the D2.3 – Use Case Specification [5] and are considered with the operational scenarios. Within the AWARD project, the operational scenarios will be evaluated with a selection of the dynamic environmental conditions, but not with all combinations. In the document D2.3 – Use Case Specification [5], 28 Operational Scenarios were defined, which would conclude to over 100 Operational Scenarios if combined with all combinations of dynamic environmental conditions. An exhaustive combination of these conditions would result in millions of scenarios. The dynamic environmental conditions include weather conditions, weather induced road conditions, visibility, and connectivity.

Table 2. Dynamic environmental conditions considered for the operational scenarios

	Environmental condition	Values
EC:WE:WC	Weather conditions	normal, rain, snow, fog, wind
EC:WE:RC	Weather induced road conditions	dry, wet, icy
EC:WE:VI	Visibility	day, night, reduced visibility
EC:CO	Connectivity	intact, malfunction

For the different weather conditions, the definitions according to the American Meteorological Society [3] were adopted. The following numeric values for rain, snow, fog, and wind are defined in Table 3, Table 4, Table 5, and Table 6.

Table 3. Rainfall rates

Rain	Rainfall per hour (mean value)	Rainfall rate at the proving ground (peak values)
Light rain	< 2.5 mm/h	20 mm/h
Moderate rain	2.5 – 7.6 mm/h	30 mm/h
Heavy rain	> 7.6 mm/h	100 mm/h

As for the given categorization of the rain intensities, only mean values over a period of one hour are considered, these appear to be quite low. Nevertheless, in real weather events rain intensities can easily go over 100 mm, but usually only for short durations (e.g. a few minutes). To test the performance of the sensor set and of the ADS, these critical peak values of rain fall are relevant and were hence considered in the performed tests.

Table 4. Snow Intensity

Snow	Associated visibility
Light snow	> 1 km
Moderate snow	0.5 – 1 km
Heavy snow	< 0.5 km

Table 5. Fog Severity (adapted from NWS Experimental Fog Severity Index)

Fog severity	Visibility in m
1	> 1609 m
2	1609–805 m
3	805–244 m
4	244–61 m
5	< 61 m

Table 6. Wind classification (adapted from World Meteorological Organization WMO)

Wind classification	Wind (Knots)	Wind (m/s)
Calm	< 1	0–0.2
Light air	1–3	0.3–1.5
Light breeze	4–6	1.6–3.3
Gentle breeze	7–10	3.4–5.4
Moderate breeze	11–16	5.5–7.9
Fresh breeze	17–21	8.0–10.7
Strong breeze	22–27	10.8–13.8
Near gale	28–33	13.9–17.1
Gale	34–40	17.2–20.7
Strong gale	41–47	20.8–24.4
Storm	48–55	24.5–28.4
Violent storm	56–63	28.5–32.6
Hurricane	> 64	> 32.7

2.3. Input to test design

This section explains the method of how the tests were designed. First, the ODD of the vehicle during the use case in public or private areas was evaluated. Different aspects like roadway type, number of lanes, roadway geometry, weather and road conditions, light conditions, road marking, and different obstacles that can occur during the use case were listed. Table 7 presents an example of how the ODD for a use case could look like.

Table 7. Example of an ODD design for a use case

Roadway type			Weather & road conditions		Light conditions	Road marking	Objects
Street	Single lane only (one in each direction)	straight	ideally all weather conditions	Dry	Daylight	Barrier line | Barrier line	Pedestrian
Crossing	Two lane (incl. turning lane)	curvy		Wet	Sunset	Division line | Barrier line	Cyclist
	unregulated crossing (with and without priority)			Icy	Night	Division line | short dashed line	Car
	regulated crossing			Snow covered		Divsion line | Curbstone	Door
	Slope				front- & backlight	Barrier line | Curbestone	small obstacle
	(Short) Tunnel					Curbestone | Curbestone	medium obstacle
						None | None	tall obstacle
						None | Curbestone	Stop line
							Animals

All the listed elements were rated with a value for severity (impact when occurring) and exposure (likelihood/probability of occurrence). Table 8 presents an example table of an exposure and severity rating.

Table 8. Exposure and severity rating

Category	Description	Rating (limited to few values)		
Exposure	likelihood/probability of occurrence	0	0.5	1
Severity	impact when occurring	0	0.5	1

Table 9 presents an example extract of rating the ODD.

Table 9. Example extract of rating the ODD

Roadway type	E	S	Comment
Street	1	0.5	Streets and crossings occur but the probability of collision is higher at a crossing because of the amount of traffic participants.
Crossing	1	1	
Roadway geometry	**E**	**S**	**Comment**
Straight	1	0.5	Straight and curvy elements occur but the front visibility in a curve is lower.
Curvy	1	1	
Road condition	**E**	**S**	**Comment**
Dry	1	0.5	Mostly, the road will be dry or wet, icy and snowy conditions only happen sometimes but are more dangerous, the same applies for wet roads.
Wet	1	1	
Icy	0.5	1	
Snow covered	0.5	1	

In the next step, all the different variations of the ODD parameters were added together to get a matrix of scenarios with all possible combinations of the parameters that could occur during the use cases. This matrix had more than 1000 entries for every use case. During this process, useless combinations that can't occur were removed. For example, given for creating the matrix, the roadway geometry is either straight or curvy and the road condition is either dry, wet, icy, or snowy. Both types of roadway geometry can appear with each of the four different road conditions resulting in eight different combinations.

After creating the matrix with the ODD properties, the individual rating of exposure and severity was combined. The result presents the most safety-critical combinations forming the basis for planning the safety and SOTIF tests. Table 10 shows an example of the created ODD matrix.

Table 10. Extract from the created ODD matrix

Scenario	Description	Roadway type	E	S	Roadway geometry	E	S	Weather	E	S	Road condition	E	S	Light conditions	E	S	Road markings	E	S	Object	E	S	Total E	Total S	Relevance %
127	Unpassable Object	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Pedestrian	1	1	1	1	100
128	Unpassable Object	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Car	1	1	1	1	100
295	VRU Crossing	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Pedestrian	1	1	1	1	100
296	VRU Crossing	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Car	1	1	1	1	100
463	Turn Left	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Pedestrian	1	1	1	1	100
464	Turn Left	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Car	1	1	1	1	100
631	Turn Right	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Pedestrian	1	1	1	1	100
632	Turn Right	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Car	1	1	1	1	100
799	Follow Lane	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Pedestrian	1	1	1	1	100
800	Follow Lane	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Car	1	1	1	1	100
967	Recognize other road user	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Pedestrian	1	1	1	1	100
968	Recognize other road user	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Car	1	1	1	1	100
1135	Passable Object	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Pedestrian	1	1	1	1	100
1136	Passable Object	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Car	1	1	1	1	100
1303	Be Overtaken	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Pedestrian	1	1	1	1	100
1304	Be Overtaken	Crossing	1	1	Straight	1	1	Rainy	1	1	Wet	1	1	Daylight	1	1	Dashed | Solid	1	1	Car	1	1	1	1	100

For the scenarios executed on the proving ground, the test parameters such as obstacles, vehicle trajectories, and road weather conditions relevant for each of the use cases were varied. In this project, a major focus was on rainy weather conditions with wet roads as well as different traffic participants (other cars, pedestrians). Weather conditions such as snowfall, which could not be reproduced in reality were covered by simulation as detailed in Chapter 4.

As a result of the process described above, a test plan was obtained for each of the four use case vehicles.

3. Test setup and preparation

This section introduces the proving ground, the test design methodology of the AWARD project, the test objects used, and outlines the success criteria for safety validation tests.

3.1. Overview of the proving ground

All the Safety and SOTIF proving ground tests were executed at the Digitrans Test Center for Automated Driving in St. Valentin, Austria. The map (see Figure 2) shows the proving ground and the main areas used during the tests. The main areas are the outdoor rain plant, intersection, roundabout, and dynamic area.

Figure 2. St. Valentin, Austria proving ground

Table 11 explains the relevant sections in more detail.

Table 11. Proving ground main areas

Dynamic area	**Outdoor rain plant**
- 450 m x 20 m - 6 lanes - Lane width: 3.5 m and 3.25 m - High performance road markings  ©DigiTrans GmbH	- Generation of natural rain - Length: approx. 80 m - Height: approx. 10 m - Rain intensities: - Light rain: variable between 20 and 30 mm/hour - Heavy rain: 100 mm/hour  ©DigiTrans GmbH

Roundabout	Intersection
- Roundabout diameter: 28 m - Roundabout with 4 junctions - Different confluence angles - Two lanes each 5 m wide  ©DigiTrans GmbH	- Regulated street crossing with 4 junction arms - Intelligent traffic light control – C-ITS interface - Unregulated intersection with 3 junction arms  ©DigiTrans GmbH

3.2. Test objects

The objects that were used in the testing site are shown in Table 12. Objects could have been only used partly in specific test scenarios. A variety of objects may be used in one scenario, for example, to determine the smallest detectable obstacle by the autonomous vehicle (AV).

Table 12. Test objects

Object name	Picture	Related test vehicle and operational site
Car dummy		Kamag, EZTow, EZTug
Metal fence		Kamag, EZTow, Forklift
Pedestrian (adult)		Kamag, EZTow, EZTug, Forklift

Pedestrian (child)		EZTug, Forklift
Two Euro-Pallets with plastic box		Kamag
Plastic fence		Kamag, EZTow, Forklift
Suitcase		EZTow
Euro-Pallet with plastic box and traffic cone		EZTug
Euro-Pallet with plastic box		Forklift

Traffic cones		Forklift

3.3. Success Criteria for Safety Validation Tests

Even today, regulations that define safety margins and performance objectives for AVs are sparse. One notable initiative, Mobileye's Responsibility-Sensitive Safety (RSS), proposed assigning specific accelerations to other road users that would be deemed reasonable. For instance, it suggested that a driver should be able to respond to an unexpected event ahead within two seconds at the latest (with one second being the norm for reaction time) and initiate moderate braking with a specified deceleration. Failure to do so largely attributes fault for any ensuing accident to the driver, irrespective of the braking trigger.

The European type approval regulation for automated driving systems (2022/1426) and certain test definitions for ADAS-like systems, including lane-keeping, followed suit by beginning to specify first concrete values for braking tests. These efforts, though significant, remain subjects of debate. After all, increasing safety margins always theoretically enhances safety. Pushing for smaller margins in the pursuit of efficiency – by driving closer and faster to other road users – or imitating human driving style does not necessarily lead to fewer fatalities than in current traffic.

In this report, we synthesize these frameworks to establish our own set of reasonable success criteria for each testing scenario. We must especially consider the expected speeds and accelerations of other road users. The core mathematical principles remain unchanged, whether we base our calculations on their reaction times of 1.5 or 2 seconds or a moderate braking force of 0.3 or 0.4 g. Despite such fine-tuning, the proposed success criteria offer a justified high level of safety.

Few companies openly disclose the values used in their designs and simulations, highlighting a gap in transparency. The difference in speed between a running and a walking person, for example, is significant. If a vehicle can accurately classify objects as humans and track their speeds, it enhances the chances of a timely reaction. Ideally, the system should also distinguish between an adult jogger and a less predictable child, though current technologies do not generally possess this level of sophistication. In a design aimed at absolute safety, every pedestrian is assumed to be a child, leading sometimes to an overly cautious approach that some might criticize. Thus, many manufacturers opt against preparing for the worst-case scenario at all times, moving away from the goal of absolute safety. Doing so, they might not take into account the legislation that requires driving extra carefully near children, intoxicated, and disabled persons.

The debate over safety goals may escalate into a political discourse, especially when fatalities occur and are scrutinized in court. Whether AVs should be designed to avoid even highly improbable scenarios remains a point of contention. With AVs, we can choose the level of safety by programming larger safety margins.

In our work, we use the ISO 13855 standard for factory robotics as a reference for reasonable human movement speeds: 2 m/s for upper limbs and 1.6 m/s for lower limbs. These figures apply to walking and are not meant to represent running, jumping, or falling. Nonetheless, they provide a basis for what automated systems should be capable of handling. Starting from a standstill, the value of 2 m/s covers even small sprints.

When a human approaches at 2 m/s from an obscured angle (from behind a visual obstruction), the situation becomes more complex. Liability in such an accident may need to be assessed on a case-by-case basis: Was the pedestrian violating traffic laws? Could a human driver have anticipated the situation more effectively than an AV? A human might see better, but an AV could be programmed to slow down at such visual obstruction areas.

Defining success criteria extends beyond regulatory compliance, as one aspect is to include the vehicle's designed operational goals for the behaviour of the vehicle. For instance, if the vehicle's software aims to consistently stop 2 meters before a static obstacle but tests show significant variance from this target, it signals potential issues in sensing or brake control. Inadequate brake control or intermittent obstacle detection can impact performance, rendering such a test scenario unsuccessful. Furthermore, erratic brake control that results in excessive deceleration could cause discomfort or damage to cargo.

Sensor setup or calibration issues may lead to blind spots or erratic behaviour, such as trying to speed up when there are still obstacles present, or hitting brakes when there is only free space ahead. Even if short moments do not create a safety problem, they are topics to address in further development.

3.3.1. Examples of analysing test scenarios to define success criteria

Parked Vehicle or Static Object in Path:

- The parked vehicle is detected at the latest at braking distance, preferably earlier. A light braking with 0.3 *g* and e.g. 0.8 s maximal reaction time (input the system's actual tested reaction time, when available) and initial speed of 30 km/h are defined. Braking distance 18.5 meters.
- Target value for stopping distance to object is 2 m as defined by strategy, acceptable variation +/-1 m
- Minimum distance to obstacle after stopping: 1 m
- Smooth brake control and no overshoot in braking deceleration
- Obstacle detected minimally from 18.5 + 1 meters

- Continuous detection with no longer than 0.2 s pauses (choose a value that doesn't yet greatly affect vehicle behaviour)
- Log: speed & deceleration rate and distance to object, continuously. Manually measure final stopping distance, to confirm sensor calibration. Nearest edge coordinates or other object coordinates. Vehicle coordinates and speed command. Photos and videos of the test.

Slow-Moving and Suddenly Braking Vehicle in the front:

- If the vehicle doesn't track objects, objects in front are considered static and AV keeps a rather long safety margin. Cut-ins, however, could cause vehicle to brake hard. Requirements mostly as in case 1, not going closer than braking distance without starting to slow down.
- If the vehicle features tracking, the minimum acceptable gap is defined by the maximum assumed braking of the previous vehicle (0.8 *g*), own reaction time (depending on vehicle specifications), driving speed (20 km/h), and own max deceleration (e.g. 0.3 *g*). With these values: 1.78 seconds (~10 meters). Prove that the AV doesn't go too close to the preceding vehicle.
- Log: both vehicles RTK-GPS (speed, acceleration, coordinates). Distance estimate from sensors. Speed command of the vehicle (intention). Photos and video.

Jaywalking pedestrian:

- When a pedestrian or bicycle violating the priority enters the AV's safety zone, the AV will start decelerating and comes to a complete stop. If the pedestrian enters the AV trajectory very late (stopping distance from 20 km/h for example 5 m, depending on the vehicle) the AV will carry out an emergency braking.
- Without object tracking: Reaction time 0.6 s when a fast target enters the critical zone. The zone size is calculated based on the pedestrian approach speed of 2 m/s, so that the vehicle can stop before contact (or pass the collision point using current speed, so that collision doesn't happen).
- Stop at 2 meters from the target, or as in system specifications (expected variation +/- 1m), if there is no need for full emergency braking. In emergency case, stop before contact but not necessarily 2 m before.
- Hard braking (>0.5 *g*, depending on vehicle type) in true emergency situations.
- The braking deceleration should remain reasonably stable to enable short stopping distances.
- Log: object coordinates, lateral and longitudinal distance to pedestrian dummy, vehicle dynamics and speed command, video. Mark zones with tape on asphalt.

AV entering an intersection:

- Other traffic has priority. We must ensure a free space at least of their reasonable braking distance, based on a slow reaction time of 2 seconds and medium 0.3 *g* braking. This equals 28.5 meters on 30 km/h speed limit roads and 60.5 m on 50 km/h.
- The AV must be able to confidently monitor whether that full intersection area is free, with pauses no longer than 0.2 s in object detection, so that the AV does not meaningfully start to move forward. The test can be performed with AV static all the

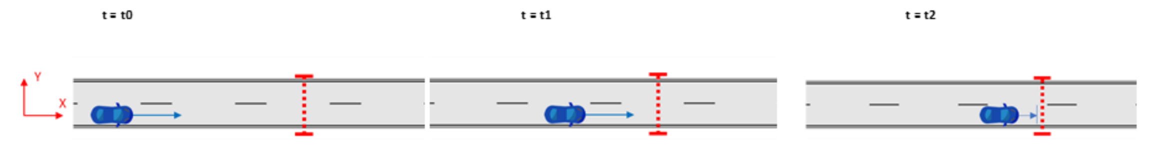
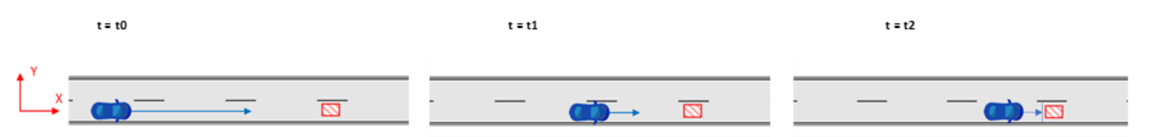
time, monitoring the intersection, or AV on route, requiring synchronized movement of actors.
- Log coordinates of objects moving in the intersection zone and AV estimate regarding if the monitored area is free or not.

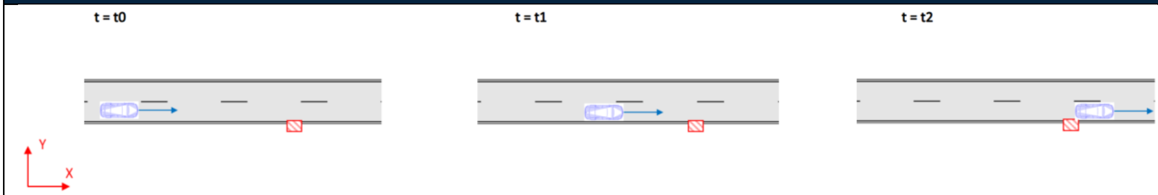
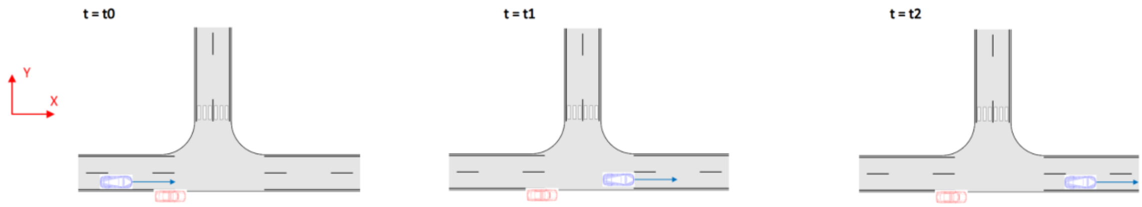
3.4. Test scenarios

In test preparation the vehicle and object must be arranged; accordingly, the area needs to be defined; rain and lighting conditions need to be adjusted before starting.

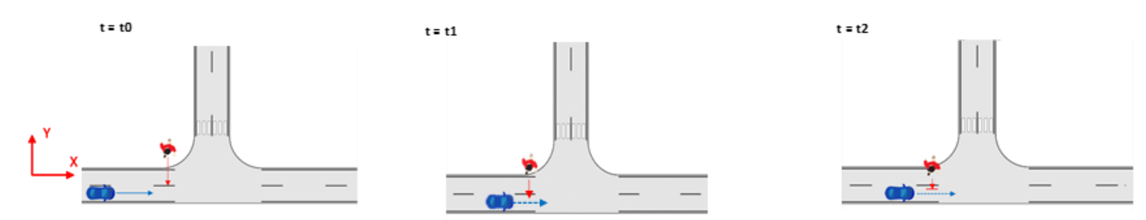
Table 13 shows the scenarios tested in the safety tests and the corresponding vehicles that were tested in the specific scenario. Additionally, optional sensor tests were performed on the Kamag vehicle. The tests were to measure static objects at varied distances, and dynamic objects at varied distances.

Table 13. Combined table of the safety test scenarios

<table>
<tr><th colspan="3">Unpassable Object (gate/barrier)</th></tr>
<tr><td colspan="3">
</td></tr>
<tr><td colspan="3">The vehicle is driving along a straight major road where it has to go straight and continue driving on the trajectory. The vehicle has to stop before a closed gate/barrier.</td></tr>
<tr><td>Test vehicles</td><td>Speed</td><td>Relevant functionalities</td></tr>
<tr><td>Kamag</td><td>20 km/h</td><td rowspan="3">Keeping the lane, braking, and stopping safely in front of the gate or barrier.</td></tr>
<tr><td>Forklift</td><td>10 km/h</td></tr>
<tr><td>EZTow</td><td>15 km/h</td></tr>
<tr><th colspan="3">Unpassable Object (small/medium obstacle)</th></tr>
<tr><td colspan="3">
</td></tr>
<tr><td colspan="3">The vehicle drives along a straight major road and has to stop in front of an obstacle. A small/medium obstacle (box/euro-pallet/traffic cone) is lying on the lane in the defined distance.</td></tr>
<tr><td>Test vehicles</td><td>Speed</td><td>Relevant functionalities</td></tr>
<tr><td>Kamag</td><td>20 km/h</td><td rowspan="3">Recognizing target on the lane, avoiding collision, slowing down, and topping safely in front of the obstacle.</td></tr>
<tr><td>Forklift</td><td>10 km/h</td></tr>
<tr><td>EZTug</td><td>20 km/h</td></tr>
</table>

Unpassable Object (curve)		
		
The AV drives a curvature and has to stop in front of an obstacle. A small/medium obstacle (box/euro-pallet/traffic cone) is lying on the lane in the defined distance.		
Test vehicles	Speed	Relevant functionalities
Forklift	10 km/h	Recognizing the object on the lane; avoiding collision, braking, and stopping safely in front of the obstacle.
Passable Object (small/medium obstacle)		
		
The AV is driving along a straight major road where it has to go straight and continue driving on the trajectory. A small/medium obstacle (suitcase) is lying next to the lane.		
Test vehicles	Speed	Relevant functionalities
EZTow	15 km/h	Recognizing the target next to the lane, avoiding collision, and not slowing down when the target is out of the safety boundary.
Passable Object (car)		
		
The AV is driving along a straight major road and approaches an intersection where it has to go straight and continue driving on the trajectory. A car is parked close beside the lane.		
Test vehicles	Speed	Relevant functionalities
EZTow	15 km/h	Recognizing the target next to the lane, avoiding collision, and not slowing down when the target is out of the safety boundary.

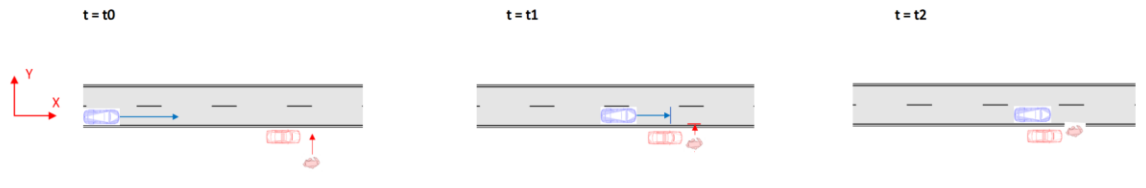
VRU Crossing



The AV drives straight. A pedestrian will cross the road from one side or walk towards the AV.

Test vehicles	Speed	Relevant functionalities
Kamag	20 km/h	Keeping the lane, braking and stopping safely in front of the pedestrian.
Forklift	10 km/h	
EZTug	20 km/h	
EZTow	15 km/h	

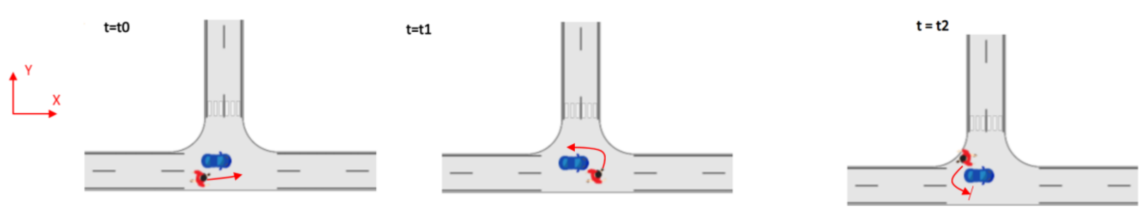
Pedestrian standing/appearing behind a static car



The AV drives straight. A Pedestrian is approaching the road behind a parked car and stops right before the AV's trajectory.

Test vehicles	Speed	Relevant functionalities
EZTow	15 km/h	Keeping the lane, braking, and stopping safely in front of the pedestrian.

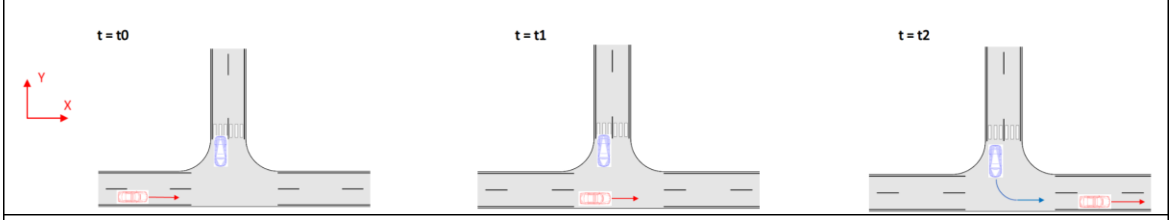
Static VUT



The AV is stationary and a human walks around with the goal to identify blind spots.

Test vehicles	Speed	Relevant functionalities
Forklift	0 km/h	Identifying blind spots.

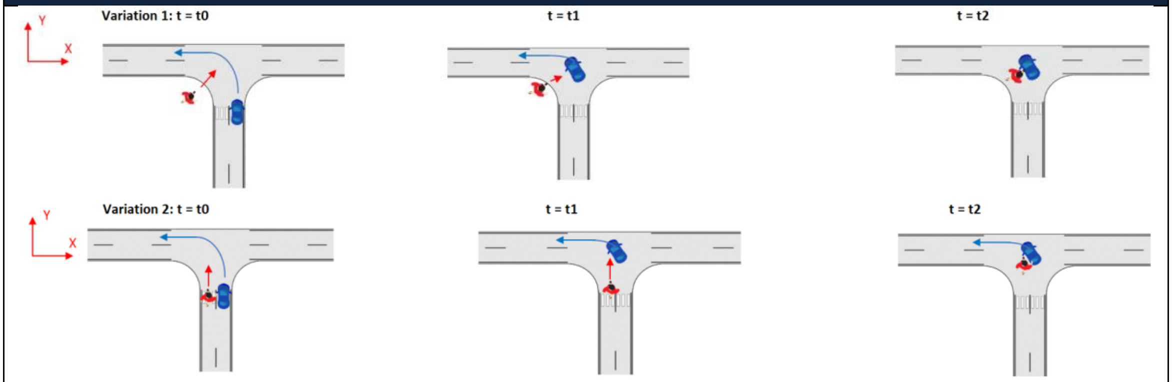
Turn left with cross-traffic



The AV is approaching an intersection where it has to turn left. From the AV's right side there is some cross traffic going straight.

Test vehicles	Speed	Relevant functionalities
Kamag	20 km/h, decelerating to 5 km/h during turning	Turning left, recognizing cross-traffic, and avoiding collision.

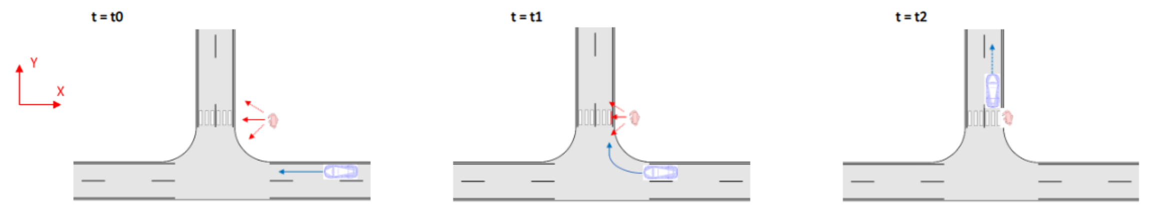
Turn left with pedestrian



The AV approaches an intersection where it has to turn left. A pedestrian approaches the intersection from the AV's left side.

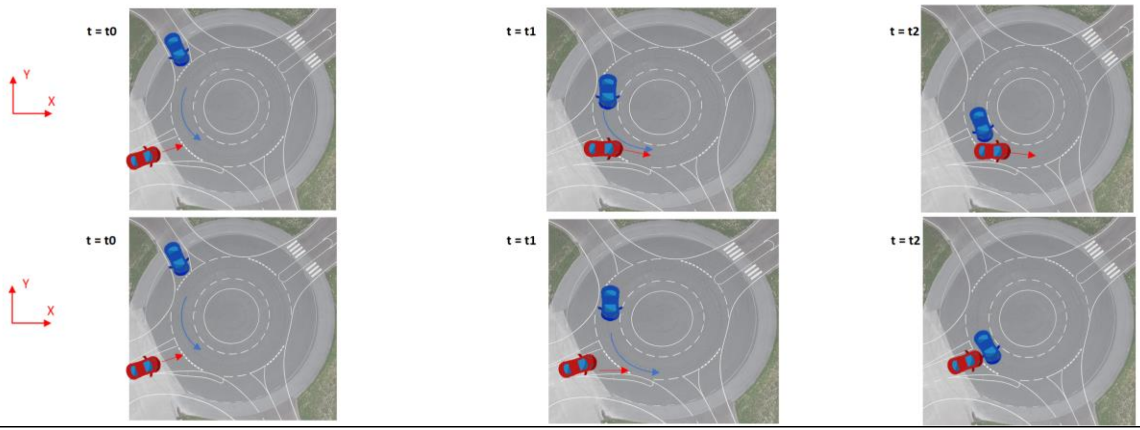
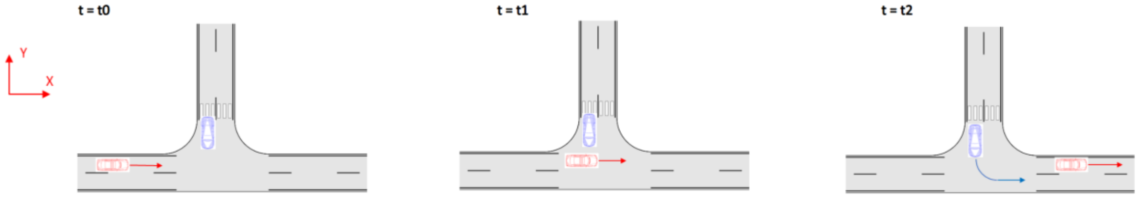
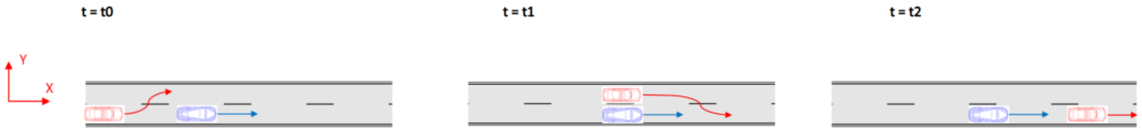
Test vehicles	Speed	Relevant functionalities
EZTug	20 km/h, decelerating to 10 km/h during turning	Turning left, recognizing pedestrian, and avoiding collision.

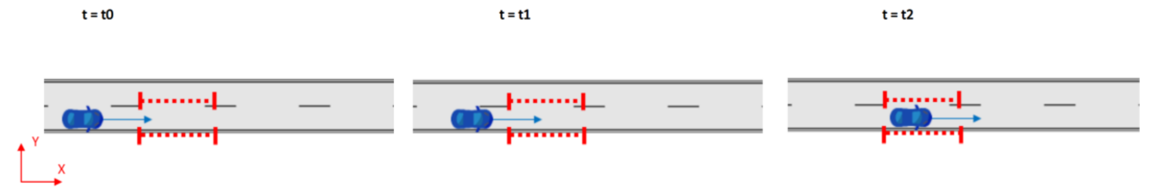
Turn right



The AV drives straight and approaches an intersection where it has to turn right and continue driving. On the crosswalk, a pedestrian wants to enter the road and stops right before the AV's trajectory.

Test vehicles	Speed	Relevant functionalities
Kamag	20 km/h	Turning right, braking, and stopping safely in front of the pedestrian.
EZTow	15 km/h	

<table>
<tr><th colspan="3">Roundabout</th></tr>
<tr><td colspan="3">
</td></tr>
<tr><td colspan="3">The AV approaches and enters a public roundabout and executes a half revolution in the roundabout.</td></tr>
<tr><td>Test vehicles</td><td>Speed</td><td>Relevant functionalities</td></tr>
<tr><td>EZTug</td><td>5.4 km/h</td><td>Entering roundabout, turning right, avoiding collision.</td></tr>
<tr><th colspan="3">Crossing intersection with cross traffic</th></tr>
<tr><td colspan="3">
</td></tr>
<tr><td colspan="3">The AV is approaching an intersection where it has to turn left and continue driving on the trajectory. From the AV's left side, there is some cross traffic going straight.</td></tr>
<tr><td>Test vehicles</td><td>Speed</td><td>Relevant functionalities</td></tr>
<tr><td>EZTow</td><td>15 km/h</td><td>Turning left, recognizing of cross traffic, avoiding colision</td></tr>
<tr><th colspan="3">Be overtaken</th></tr>
<tr><td colspan="3">
</td></tr>
<tr><td colspan="3">The AV is driving straight and has to continue driving on the trajectory. The AV is being overtaken by a car.</td></tr>
<tr><td>Test vehicles</td><td>Speed</td><td>Relevant functionalities</td></tr>
<tr><td>Kamag</td><td>20 km/h, decreasing to 5 km/h</td><td>Recognizing target vehicle, avoiding collision, not slowing down when target is out of the safety boundary.</td></tr>
<tr><td>EZTow</td><td>0 km/h</td><td>The scenario was carried out with a static vehicle due to safety reasons and varied lateral distances. The focus was on evaluating the detection zone of the vehicle when being overtaken by another car.</td></tr>
</table>

Reverse parking		
		
Reverse parking, Pedestrian walking in from different angles.		
Test vehicles	Speed	Relevant functionalities
Kamag	10 km/h	Driving reverse, recognizing pedestrian, and avoiding collision.
Side barriers		
		
The AV drives along a straight and has to pass barriers.		
Test vehicles	Speed	Relevant functionalities
Forklift	5 km/h	Recognizing side barriers, and avoiding collision.

The test scenarios were performed as planned for each use case. Some planned scenarios were omitted as they were rated with lower priority and due to time constraints during the tests. The scenario could be omitted if similar relevant functionality was covered already by one or multiple other scenarios combined, or if observing and validating certain behaviour was already assessed from other scenarios. That leads the scenario to be rated with lower priority and would be thus skipped. The scenario could also be omitted if prior findings prove that the scenario would not occur often. An example of such a scenario is that Kamag was not tested to be overtaken since the speed of the vehicle decreases to 5 km/h when there is another vehicle driving in the other lane next to it. Overtaking another vehicle with 5 km/h was not considered a scenario that would occur often and thus the scenario was omitted.

3.4.1. Port operations – EZTug

During the test week of the EZTug (see Figure 3), the focus was on a different size range of obstacles, and rain conditions to test the most safety-critical scenarios. The size of the EZTug is 5,4 m (length), 2,53 m (width), and 3,26 m (height). The maximum speed of the EZTug was set to 20 km/h. The automated EZTug tug differs from its human-driven counterparts mainly in two aspects. Firstly, it has been equipped with advanced environmental sensors. Secondly, the vehicle is not planned to be driven in reverse. Whereas human drivers reverse when picking up and occasionally otherwise, the current safety validation plans for the vehicle include driving forward, only. This is to ensure visibility.

Figure 3. EZTug

Figure 4 shows the perception sensors of the EZTug.

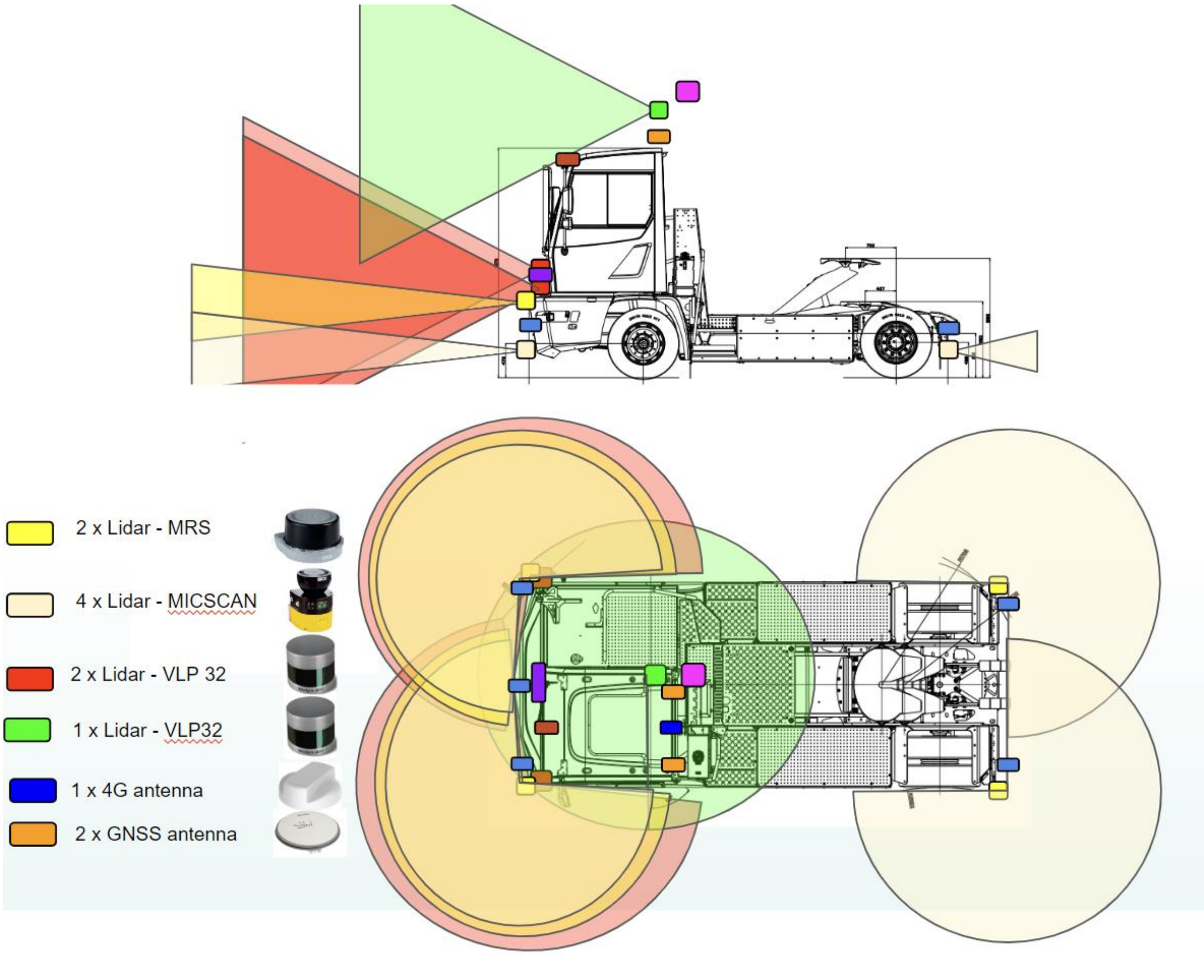


Figure 4. EZTug sensors

The test plan includes different scenarios developed for the validation of the EZTug vehicle.

Table 13 shows the tested scenarios. All scenarios were tested in the dynamic area, the nearby junction, or the roundabout.

3.4.2. Hub-to-hub shuttle service – Kamag

During the test week of the KAMAG PM swap body transporter (Figure 5 and Figure 6), the focus was on a different size range of obstacles, and rain conditions to test the most safety-critical scenarios. The size of the KAMAG is 9,07 m (length), 2,48 m (width), and 2,27 m (height). The vehicle speed is set to 20 km/h.

Figure 5. Kamag

Figure 6 shows the perception of the Kamag.

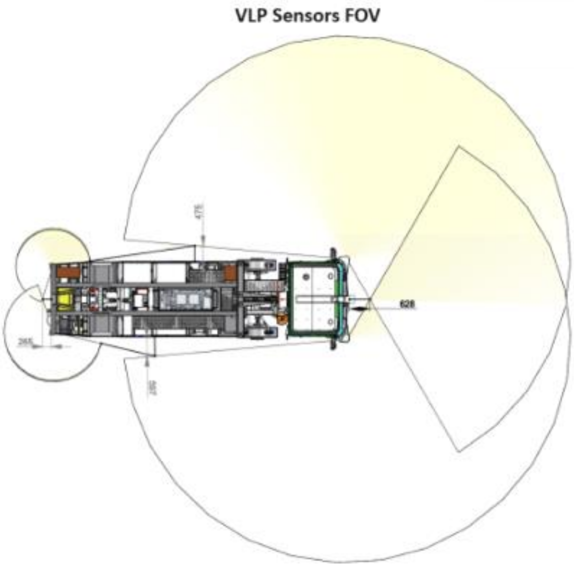


Figure 6. Kamag sensors (VLP)

The test plan includes different scenarios developed for the validation of the Kamag.

Table 13 shows tested scenarios. All scenarios were tested in the dynamic area, or the nearby junction.

3.4.3. Airport baggage tractor – EZTow

Having been utilized for an extended period, the EZTow (Figure 7) platform has provided EasyMile with ample opportunities to tune its parameters, making it the most advanced test vehicle in this aspect. During its test week, the focus was on a different size range of obstacles, and rain conditions to test the most safety-critical scenarios. The size of the EZTow is 3,16 m (length), 2 m (width), and 2,09 m (height). The vehicle speed is set to 15 km/h. Maximum speed is 30 km/h.

Figure 7. EZTow

Figure 8 shows the perception sensors of the EZTow.

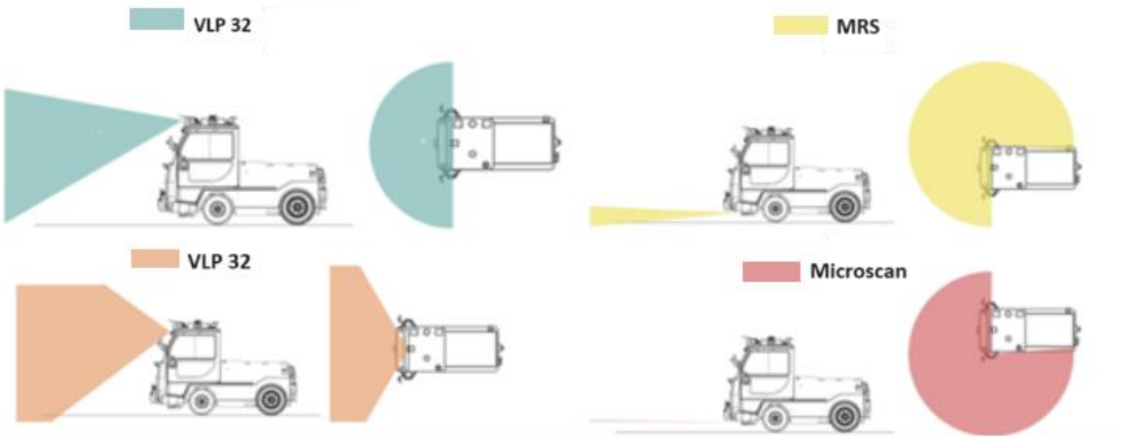


Figure 8. EZTow sensors

3.4.4. Automated forklift – Forklift

The size of the Forklift is 4,1 m (length) including forks, 2 m (width), and 2,6 m (height), which increase with fork height. The maximum speed of the Forklift (see Figure 9) was set to 10 km/h. The sensor system consisted of one stereo camera with three lenses which was mounted on the engine-bay-sided end of the vehicle. Several other sensors, such as the

AWARD sensor set, were mounted on the vehicle, but they were neither used for the anti-collision system nor the object detection system yet in these tests. The forklift is the most recent addition as one of the vehicles, therefore it has limitations and will be evaluated accordingly with the information that is available at the time of writing this report.

Figure 9. Forklift

The test plan includes different scenarios developed for the validation of the Forklift. During the test week, the focus was on obstacles of different sizes and appearance, and rain conditions and to test the most safety-critical scenarios that are expected in the demonstration.

Figure 10 shows the perception of the Forklift. For safety tests the Collision Detection Camera FOV was used.

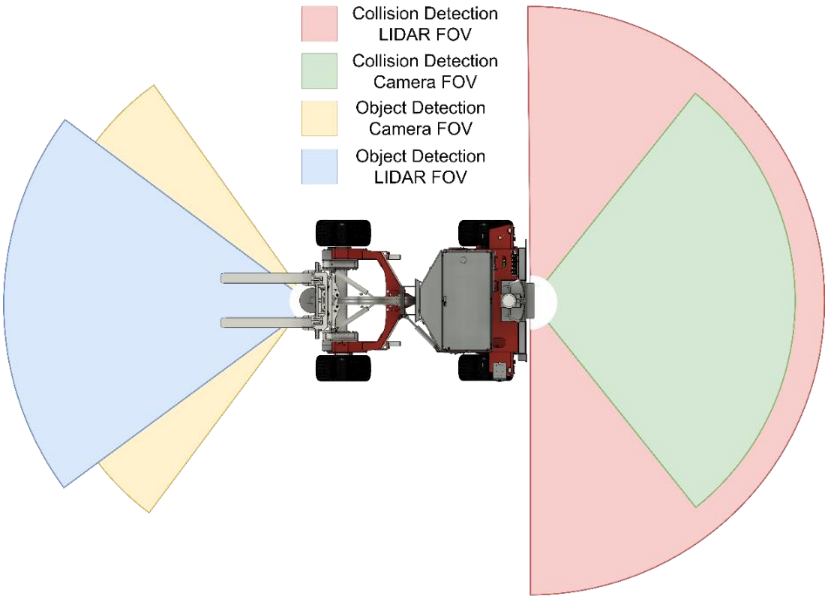


Figure 10. Forklift sensors

4. Simulation for complementing the results

In this chapter, the simulation tests performed within the project during the safety validation activities are described. Simulations for the EZTow platform were used to test selected critical scenarios that could not be tested during the tests on the proving ground as they would have been too dangerous to conduct in real-world, too difficult to arrange (e.g. vehicle with heavily loaded trailer) or could have resulted in costly damage, for example to vehicle sensors. In addition, the simulation provided an option to replicate snow, which was not possible on the test track. To allow a comparison of the ADS' behaviour and performance during the simulation and the real-life tests, some scenarios with identical parameters were conducted virtually and on the test track. Consequently, a different logic and behaviour of the ADS in simulation and in real life could be excluded.

The simulations were done by EasyMile with their proprietary simulator, which used the same automated driving system (ADS) software that was used in the vehicles tested on the proving ground. The output of the simulations was a set of video clips which included a screen recording of the simulation runs. The simulation video included multiple camera views of the scenario (in-vehicle and external camera view), vehicle controls, warnings, and some measurement graphs (e.g. vehicle speed command, odometer speed, etc.), see Figure 11.

Figure 11. Example view of the Easymile simulation of EZTow vehicle with trailer

4.1. Simulated scenarios

Simulations were used to test the following scenarios with listed parameters:
EZTow - Pedestrian appearing behind static object, see Figure 11.

- Weather conditions: cloudy
- Pedestrian speed: 10 km/h, pedestrian starting distance from the street: 3 m
- Vehicle distance to pedestrian crossing when pedestrian starts to move: 2.5 m, 5 m, 7.5 m, 10 m, 15 m
- Additional simulations with full load (6 tons) of the TractEZ with trailer (i.e. the actual load from the airport use case)
    - 10 m distance in dry conditions, in rain (20 mm and 100 mm) and snow
    - 20 meters (in dry weather conditions only)

EZTow - Turn right, see Figure 12.

- Pedestrian walking direction: +/- 45 deg, 0 deg
- Vehicle distance to pedestrian crossing when pedestrian starts to move: 2.5 m, 5 m
- Additional simulation with full load
    - -45° and 2.5 m in dry conditions, in rain (20 mm and 100 mm) and snow

Figure 12. EZTow - Turn right, simulation in 100mm rain with a fully loaded trailer.

EZTow - Crossing intersection with cross traffic, see Figure 13**.**

- Target vehicle distance from the crossing: 30 m, 50 m, 60 m, 100 m
- Additional simulation with full load
    - 30 m distance in dry conditions, in rain (20 mm and 100 mm) and snow

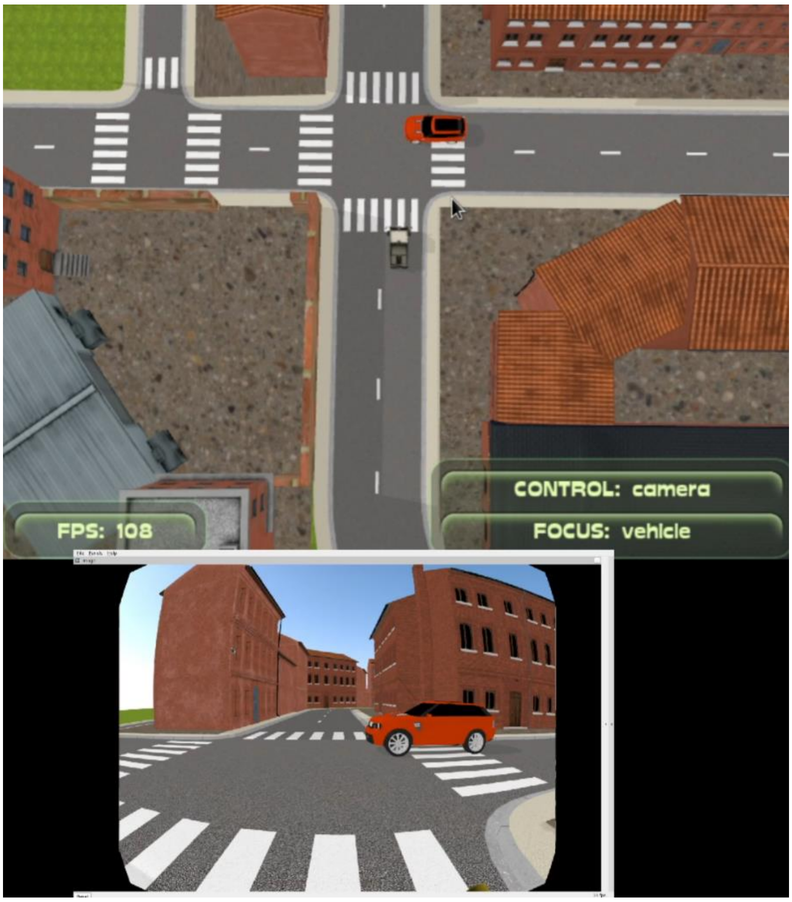


Figure 13. EZTow - Crossing intersection with cross-traffic simulation without trailer

4.2. Findings

This section describes the findings from the simulation. Comparison of the results of the safety tests is discussed in Chapter 7.

The obstacle detection and anti-collision behaviour of EZTow in simulation can be described as follows: The anti-collision system monitors only safety zones in front and sides of the vehicle, objects outside this zone are not considered or tracked. The crossing area monitoring was not used in the simulations, which is the same in the field tests (regarding the selected scenarios). The anti-collision system of the vehicle is monitoring obstacles only in the AV path and 1.2 m distance from the side of the vehicle.

EZTow – Scenario pedestrian appearing behind a static car

- Without the trailer – starting distances 7.5 meters or below from the AV to the jaywalking pedestrian, a collision could not be avoided anymore. For 10 m and above the vehicle stopped safely before the pedestrian. The pedestrian speed was set to 10 km/h (very fast).
- With the fully loaded trailer – starting distances 10 meters or below from the AV to the jaywalking pedestrian, a collision could not be avoided anymore because of longer braking distances with bigger mass.

EZTow – Scenario Turn Right

- Without the trailer – due to the reduced speed of the AV during turning manoeuvres, the vehicle could stop safely and avoid collisions in all variations of this scenario.
- With fully loaded trailer
    - In 100 mm/h rain and snow conditions, due to the reduced speed of the AV due to disturbances caused by the heavy rain or snow, the vehicle could stop safely and avoid collisions in all variations of this scenario.
    - In dry and 20 mm/h rain conditions the vehicle used the normal driving speeds and collision with the pedestrian occurred when the starting distance was only 2.5 meters from the AV to the “jaywalking” pedestrian walking 45 degrees across the intersection, see Figure 12.

EZTow – Intersection with cross-traffic

- Monitoring area was set to allow the AV to cross the intersection. If there is an obstacle in this area, the AV can't automatically validate it and so is waiting at the intersection. In the video, the AV is doing the validation, but a new obstacle is detected just after, so the validation process is "rebooting". For a standard driving situation, obstacles are constantly appearing/disappearing in front of the AV at random distances. The speed command is considered erratic because of that. Due to the AV inertia and the fact that the obstacle is never at the same position, it's able to manage that and still drive.
- Both 20 mm/h and 100 mm/h rain as well as snow disturbances prevented the ego vehicle from driving after stopping at the intersection.

Weather effect in the simulation

- 20 mm of rain and snow caused slight disturbances to the vehicle sensors and the speed command went up and down. This made the vehicle accelerate very slowly and the target vehicle speed was not always reached.
- 100 mm of rain caused heavy disturbances and the vehicle could only drive at a strongly reduced speed.

5. Safety Goals and assessment

This Chapter introduces the safety goals and HARA, and the results of test scenarios from the previous chapter are combined to evaluate each safety goal. The result of the safety and risk assessment determines if the tests provide sufficient proof of safety to continue to the operational tests.

The purpose of the evaluation of known scenarios is to achieve the following objectives [2]:

a) identified potentially hazardous scenarios shall be evaluated if they are hazardous or not
b) the functionality of the system and its elements shall behave as specified for known hazardous scenarios and reasonably foreseeable misuse
c) the potentially hazardous behaviour due to the specified behaviour at the vehicle level shall be evaluated concerning its acceptability
d) known scenarios shall be sufficiently covered according to the verification and validation strategy
e) the verification results shall demonstrate that the validation targets are met.

The purpose of the evaluation of unknown scenarios is that the validation results shall demonstrate that the residual risk from unknown hazardous scenarios meets the acceptance criteria with sufficient confidence [2].

Functional safety concepts were performed through an iterative process in D3.1 – Architecture Design Report [6] and D4.1 – Safety Documents [4]. To identify the risk related to the different AWARD use cases, the list of the operational situations has been analysed. This list of operational situations has been defined and summarized in the D2.3 – Use Case Specification in Table 4 [5].

In the document D4.1 – Safety Documents [4] the following safety goals were identified (see Table 14). The safety goals were identified during the HARA. For each safety goal, the related integrity level and the list of the applicable use cases are defined.

Table 14. Safety goal list

ID	ASIL	Safety Goal	UC
		Collision with massive and static object	
SG01-1	A	ADV shall avoid collision with massive and static object on the trajectory when driving at 20 km/h on a company site	2/4
SG01-2	B	ADV shall avoid collision with passenger car stop on the trajectory when driving on a public road at 20 km/h	2/4
SG01-3	C	ADV shall avoid collision with passenger car stop on the trajectory when driving on a public road at 40 km/h	2/4
SG01-4	A	ADV shall avoid collision with other road users stop on the trajectory when driving at 10 km/h on a private road	1/2/3/4
SG01-5	B	ADV shall avoid collision with passenger car stop on the trajectory when driving through a tunnel at 20 km/h	2/3

	Collision with pedestrian		
SG02-1	C	ADV shall avoid collision with pedestrian on the trajectory when driving at 10 km/h on a company site	2/4
SG02-2	C	ADV shall avoid collision with pedestrian crossing a public road when driving at 20 km/h or 40 km/h	2/4
SG02-3	C	ADV shall avoid collision with pedestrian crossing a private road when driving at 10 km/h	1/2/3/4
	Collision with another vehicle		
SG03-1	QM	ADV shall avoid collision with another truck stop on the trajectory when driving at 10 km/h on a company site	2/4
SG03-2	A	ADV shall avoid collision with passenger car stop on the trajectory when driving at 10 km/h on a company site	2/4
SG03-3	A	ADV shall avoid collision with forklift on the trajectory stop on the trajectory when driving on a company site	2/4
SG03-4	C	ADV shall avoid collision with other road user stops on the trajectory when driving on a public at 40 km/h	2/4
SG03-5	A	ADV shall avoid collision with other road user stops on the trajectory when driving at 10 km/h on a private road	1/3
	Lateral deviation		
SG04-1	D	ADV shall avoid lateral deviation from the navigation lane when driving on a company site at 10 km/h	2/4
SG04-2	D	ADV shall avoid lateral deviation from the navigation lane when driving at 20 km/h on a public road	2/4
SG04-3	C	ADV shall avoid lateral deviation from the navigation lane when driving at 10 km/h on a private road	1/2/3/4
	Crossing intersection		
SG05-1	D	ADV shall decelerate and reach standstill before intersection with public road and other road users driving at 50 km/h	2/4
SG05-2	D	ADV shall not cross intersection with public road if there is oncoming vehicle on the path and other road users driving at 50 km/h	2/4
SG05-3	D	ADV shall decelerate and reach standstill before intersection when the connected traffic light is red and other road users driving at 50 km/h	2
SG05-4	D	ADV shall not cross intersection if the connected traffic light is red and other road users driving at 50 km/h	2
SG05-5	A	ADV shall decelerate and reach standstill before intersection with private road	3
SG05-6	A	ADV shall not cross intersection with private road if there is oncoming vehicle on the path	3
SG05-7	C	ADV shall decelerate and reach standstill before intersection with priority given on a public road	2
SG05-8	C	ADV shall not cross intersection with public road if there is oncoming vehicle on the path	2
SG05-9	A	ADV shall decelerate and reach standstill before intersection with priority given on a private road	3
SG05-10	A	ADV shall not cross intersection with private road if there is oncoming vehicle on the path	3
	Unexpected braking leading to rear collision		

SG06-1	C	ADV shall avoid unexpected deceleration when driving at 20 km/h on a public road	2/4
SG06-2	A	ADV shall avoid unexpected deceleration when driving at 10 km/h on a private road	1/2/3/4
SG06-3	A	ADV shall avoid unexpected deceleration when driving at 10 km/h on a compound site	2/4
	Uncoupling trailer		
SG07-1	B	ADV shall not uncoupling trailer when driving on a private road	3
SG07-2	D	ADV shall not uncoupling trailer when driving on a public road	3
	Approaching the ramp		
SG08-1	C	ADV shall avoid lateral deviation when approaching the ramp	2/3/4
SG08-2	C	ADV shall avoid collision with pedestrian when approaching the ramp	2/3/4
	Passing an obstacle		
SG09-1	A	ADV shall determine correct path and correct timing to pass an obstacle on a private road	1/2/3/4
SG09-2	C	ADV shall determine correct path and correct timing to pass an obstacle on a public road	2/4
	Active status emergency		
SG10-1	A	ADV shall abort the mission and stop in case of Active status emergency safe	1/2/3/4
SG10-2	A	ADV shall abort the mission and drive to a safe zone in case of Active status emergency safe	1/2/3/4

Due to operational situation and use cases modification, following safety goals are not applicable anymore to AWARD project:

- uncoupling trailer (SG07-1/SG07-2)
- passing an obstacle (SG09-1/SG09-2)
- active status emergency (SG10-1/SG10-2).

Each safety goal shall be covered by a safety concept, but a safety concept can mitigate several safety goals 8 [1]. The safety goals can be covered by three main functional safety concepts (Table 15): collision avoidance, trajectory following, and crossing intersection with tragic light [4].

Table 15. HARA coverage table

Safety Goal	SG ID	FSC
Collision with massive and static object	SG01-1/SG01-2/SG01-3/SG01-4/SG01-5	Collision avoidance
Collision with pedestrian	SG02-1/SG02-2/SG02-3/SG02-4	Collision avoidance
Collision with another vehicle	SG03-1/SG03-2/SG03-3/SG03-4/SG03-5	Collision avoidance
Lateral deviation leading to collision	SG04-1/SG04-2/SG04-3	Trajectory following
Crossing intersection	SG05-1/SG05-2/SG05-3/ SG05-4/ SG05-5/ SG05-6/ SG05-7/ SG05-8/ SG05-9/ SG05-10	Crossing intersection with traffic light

Unexpected braking leading to rear collision	SG06-1/SG06-2/SG06-3	Collision avoidance
Uncoupling trailer	SG07-1/SG07-2	Non Applicable
Approaching the ramp	SG08-1	Trajectory following
Approaching the ramp	SG08-2	Collision avoidance
Passing an obstacle	SG09-1/SG09-2	Non Applicable
Active status emergency	SG10-1/SG10-2	Non Applicable

5.1. Collision avoidance

As a system, AWARD ADS shall perceive and detect obstacles on the vehicle trajectory to mitigate and avoid any risk of collision.

The FSC: Collision avoidance allows to mitigate all the situation related to the risk of collision and cover the following safety goals [4]:

- Collision with massive and static object (SG01-1/SG01-2/SG01-3/SG01-4/SG01-5)
- Collision with pedestrian (SG02-1/SG02-2/SG02-3/SG02-4)
- Collision with another vehicle (SG03-1/SG03-2/SG03-3/SG03-4/SG03-5)
- Unexpected braking leading to rear collision (SG06-1/SG06-2/SG06-3)
- Approaching the ramp (SG08-2).

According to the risk analysis, the collision avoidance feature shall be compliant with the higher ASIL of the safety goals list. The ADV shall avoid collision with an obstacle – ASIL C.

Table 16 presents the use cases and scenarios of identified limitations concerning the collision avoidance safety goal. Recommendations to further improve the safety of these scenarios are mentioned in Chapter 6 and Chapter 7.

Table 16. Use case evaluation of safety goal collision avoidance

Situation	SG ID	ASIL	UC	Vehicle	Scenario
Collision with pedestrian	SG02-3	C	4	EZTug	VRU Crossing
Collision with pedestrian	SG02-3	C	4	EZTug	Turning left
Collision with another vehicle	SG03-5	A	4	EZTug	Roundabout
Lateral deviation leading to collision	SG04-3	C	3	EZTow	Pedestrian appearing behind parked car
Collision with massive and static object	SG01-1	A	1	Forklift	Unpassable object (fence)
Collision with massive and static object	SG01-1	A	1	Forklift	Unpassable object (lane)

Collision with pedestrian	SG02-3	C	1	Forklift	VRU Crossing lane

5.2. Trajectory following

The FSC: Trajectory following allow to mitigate all the situation related to the risk of trajectory deviation and cover the following safety goals [4]:

- Lateral deviation (SG04-1/SG04-2/SG04-3)
- Approaching the ramp (SG08-1).

According to the risk analysis, the trajectory following feature shall be compliant with the higher ASIL of the safety goals list. AV truck shall avoid lateral deviation from the navigation lane - ASIL D.

Table 17 presents the use cases and scenarios of identified limitations concerning the trajectory following safety goal. Recommendations to further improve the safety of these scenarios are mentioned in Chapter 6 and Chapter 7.

Table 17. Use case evaluation of safety goal trajectory following

Situation	SG ID	ASIL	UC	Vehicle	Scenario
Lateral deviation	SG04-3	C	1	Forklift	Unpassable Object Lane (small/medium obstacle)

5.3. Crossing intersection

The FSC: Crossing intersection allow to mitigate all the situation related to the risk of unexpected intersection crossing and cover the following safety goals [4]:

- Crossing intersection (SG05-1/SG05-2/SG05-3/ SG05-4/ SG05-5/ SG05-6/ SG05-7/ SG05-8/ SG05-9/ SG05-10).

According to the risk analysis, the trajectory following feature shall be compliant with the higher ASIL of the safety goals list. AV truck shall avoid lateral deviation from the navigation lane - ASIL D.

Based on the performed safety tests, success criteria, and evidence, it can be assumed that there was not a situation where crossing an intersection would have proposed risk. The crossing intersections scenario was only tested by EZTow. Further testing shall be conducted. The test results of pedestrian crossing concluded that intersection logic shall be applied. Recommendations to further improve the safety of these scenarios for EZTow are mentioned in Chapter 6.3.

5.4. Safe interaction with road users

An important aspect of road safety and the test cases is the interaction of AV with other road users. The Operational Scenarios and Interactions have been identified in the D2.3 – Use Cases Specification [5]. Depending on the use case, many operational scenarios involve such situations, especially when AV operates on public roads (UC2 and UC4).

Based on the performed safety tests, success criteria, and evidence, it can be assumed that there was not a situation where there would have been an immediate risk of interaction with other road users. However, certain limitations occur, such as EZTug not detecting vehicles approaching from the side in the Roundabout test scenario. Another detail recommended to consider is the slow speed on public roads and sudden stops. These actions do not propose direct risk but can cause hostile behaviour with other road uses.

5.5. Weather Conditions

The definitions of operational scenarios are used to align the design of the technical components with the environmental parameters. The formal description of the physical infrastructure elements provides the framework for the technical specification. Furthermore, the more dynamic aspects, covered by the elements within “environmental conditions” and “operational constraints” need to be addressed in the design and development process. For this purpose, this report describes the main weather parameters and includes a categorization of these parameters in the Chapter 2.2. Data collection was performed in WP3, including data collection in Finnish Lapland. Considering the visibility, sensors are not affected by the darkness. Further sensor data fusion work will be reported in the D7.2 - Technical Evaluation.

Certain weather conditions of rain and fog (see Figure 14) were tested during the safety tests. First tests were conducted in cold temperatures, then continued to fog testing.

Figure 14. Pictures of tested weather conditions

The SOTIF test could not be performed in snow conditions. Snow conditions were tested in the simulation described in Chapter 4.1 and as part of WP3 data collection. Weather-induced road conditions of dry and wet were tested. Tests were conducted only above zero degrees Celsius. Wind conditions were not considered relevant for the safety tests.

The vehicles generally performed well in light rain. Heavy rain was challenging to overcome since multiple vehicles detected rain as small obstacles, and water started to accumulate on sensor racks faster (Figure 15) than it drained away, disturbing measurements. In many scenarios, the testing could not be continued because of the heavy rain and sudden emergency stops caused by it. Further testing is recommended.

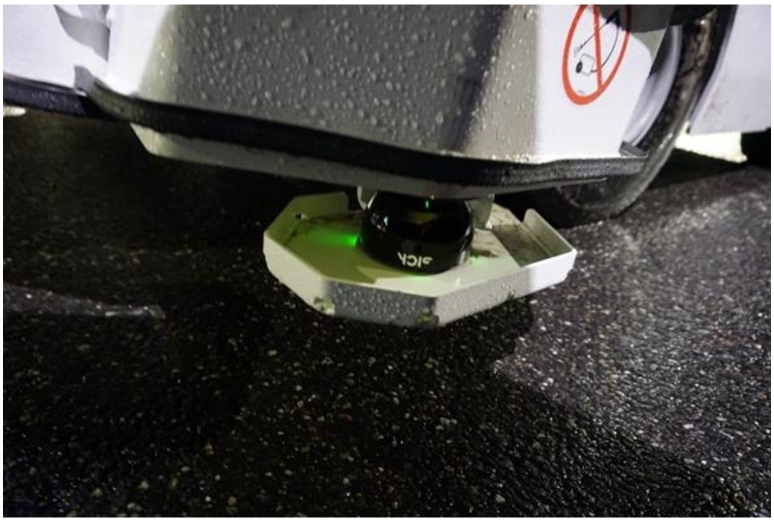


Figure *15*. EZTow sensor rack

6. Results and recommendations

This chapter presents the results and recommendations for each tested vehicle. The combined conclusion is in Chapter 7.

6.1. Kamag safety test results

The major part of the conducted test runs with the KAMAG was completed satisfactorily. During the performed tests the vehicle did not cause any threatening situations for surrounding traffic participants. The vehicle showed an overall good performance in dry weather conditions, with some space for improvement.

The test scenarios revealed a certain behaviour of the vehicle and its safety concept:

- An object inside an area of 1.2 meters in a lateral direction triggered a slowing down of the AV to 5 km/h. As an example, by driving in a lane next to another vehicle, the AV decreased its speed from 20 km/h to 5 km/h.
- When turning, the AV decreased its speed to 5 km/h and accelerated again after the manoeuvre.
- A static small object with a height of 14.4 cm (euro-pallet) was not recognized by any sensor and therefore the vehicle did not react to it. As pallets may appear in the operating domain, this is a topic for further development. A medium-sized object with a height of 44 cm was detected correctly by the safety sensors, resulting in an emergency stop of the AV. Another object with a height of 60 cm was recognized by the other sensors leading to a soft stop.
- The vehicle's max. speed of 20 km/h can be problematic for public roads with higher speed limits as is the case at the pilot site. Here, further infrastructure measures are required to ensure safe operation.

In rainy conditions, the AV showed satisfactory behaviour only for the reverse parking scenario as the sensors at the back of the AV were better protected against rain. When driving forward in moderate and heavy rain, the AV did multiple emergency brakes because of the rain. Furthermore, reduced rain intensities were tested as well without success. In heavy rain, none of the scenarios could be tested due to the immediate emergency stops. The worse performance in rain than with the other tested vehicles was later identified to be a difference in software setup, practically a missing rain filter.

6.2. EZTug safety test results

During the tests, the vehicle showed an overall good performance in dry weather conditions and also in moderate rain with some space for improvement. No threatening situations for surrounding traffic participants could be observed.

The test scenarios revealed a certain behaviour of the vehicle and its safety concept:

- Objects inside an area of 1.2 meters in lateral direction around the AV caused the vehicle to slow down.

- When turning, the AV decreased its speed to 10 km/h and accelerated again after finishing the turning process.
- A medium-sized object with a height of 32 cm and 43 cm was detected correctly by the safety sensors resulting in an emergency stop of the AV if it is lying close to the vehicle, i.e., within the stopping zone. The object lying within the AV's slowing zone, however, was not recognized. Another object with a height of 78 cm was recognized by the non-safety sensors leading to a soft stop.
- Certain sensor blind spot areas were suspected and they are to be checked further.

The vehicle's max. speed of 20 km/h might be seen as a disturbance to the traffic flow on public roads with higher speed limits.

In heavy rain, the AV performed multiple emergency brakes. Therefore, none of the scenarios could be tested under these conditions due to immediate emergency stops. In contrast, all scenarios, except for the roundabout scenario (due to the unavailability of a rain plant), were successfully tested under moderate rain. Here, the vehicle was decreasing its speed to approximately 10 km/h but continued driving along its trajectory.

6.3. EZTow safety test results

This is the vehicle that is closest to a working product and EasyMile has long experience with it. All test scenarios were completed satisfactorily. During the tests, the vehicle did not cause threatening situations for the surrounding traffic participants. The vehicle showed good performance, also in moderate rain and dark. Operating in heavy rain was not yet possible. Mainly so because of water accumulation near the lidar sensors rather than software limitations.

The applied safety concept mainly worked well and fits for operation on public roads with a speed limit of 30 km/h under the predefined ODD. Without rain, the test results indicate that operation could be possible up to 50 km/h speed limits.

Some critical parameters need special attention when setting up new routes or test scenarios: the exact definition of the observation zone and the decision point in the setup for approaching intersections. The tests proved that with a large enough intersection monitoring area being defined in the navigational map, the vehicles can well handle intersections with traffic.

The safety zone configuration and maximum deceleration of the vehicle are already close to being safe concerning normal pedestrian behaviour. However, based on test results and safety zone calculations, it is recommended to set a higher maximum braking deceleration for the EZTow vehicle, raising it from the current 3.5 m/s2 to around 5.6 m/s2. Alternatively, the lateral safety zone could be slightly increased by about 10 cm, or the vehicle could start to drop speed, when objects appear near the current safety zone, depending on their tracked speed.

A reaction time of 0.3 seconds is observed, as that was the measured time it took for the speed to start to drop. If the time reserved for braking is 0.84 s (before pedestrian on the route, safety margin distance 1.35 m divided by human speed 1.6 m/s), this translates to braking deceleration of a little over 4 m/s2. In practice, the maximum value would have to be set a bit higher to achieve that level of deceleration, on average. From of Pedestrian appearing behind a static car, we note that it took 2 seconds for the vehicle to come to a full stop, from the moment of a pedestrian entering the safety zone. This translates to roughly 2.5 m/s2 with a reaction time 0.3 s. Considering that level was achieved with a configuration up to 3.5 m/s2, it would probably require a maximal value of 5.6 m/s2 to reach an average deceleration of 4 m/s2. This should be an acceptable increase, considering the type of cargo and operation of the vehicle. A harder maximal braking would decrease the chance of any pedestrian accident.

With regards to pedestrian crossings, the test results show that interaction with the vehicle and pedestrians could be improved by defining an area to monitor, using the existing intersection logic. Currently in the tests, the vehicle acted only based on its lateral safety margin. When an extended area of the pedestrian crossing is occupied, the vehicle should slow down earlier than currently, thereby communicating intentions better to the pedestrian.

Small blind spots were observed with the sensor setup. A person was able to approach the vehicle from the sides in specific angles and not be detected by the sensors. This could lead to potentially dangerous situations during turning manoeuvres or with pedestrians near when the vehicle starts moving.

Positioning accuracy during the tests, including rain tests, was found to be as high as +/- 5 cm. This deviation was measured from tyre track marks.

6.4. Forklift safety test results

The forklift is the most recent addition to the fleet of vehicles, and it uses different software. The behaviour of the vehicle could be significantly enhanced in almost every scenario by defining a new and larger safety zone around the vehicle for deceleration when objects are detected within that zone. Currently, the vehicle only engages in abrupt and hard braking when an object is detected in a critical zone. Such behaviour can be perplexing to nearby workers, who may be uncertain whether the vehicle has detected them and whether it will eventually brake, especially when it is already close. If the vehicle has indeed not detected them, an accident becomes imminent. Even a vigilant safety operator would find it challenging to control dangerous situations unless a two-phase safety zone is established. A larger zone designated for slowing down would improve interactions from every perspective.

A wider lateral safety zone for slowing down would improve safety in cases where pedestrians, unaware of the vehicle for any reason, approach from the side. There were a couple of hit or near-miss cases. A slowing down zone would reduce the danger. Even if the vehicle moves at a maximum of 10 km/h, it is very heavy.

Probably the current lateral stopping zone is only the width of the vehicle, which calls for further safety strategy (object tracking for estimating future collisions or slowing down when there are objects near the path). Even though such a strategy would slow the vehicle when passing narrow gates, that type of behaviour would also be preferable, as the vehicle is not able to classify which type of objects actually are near.

Unless a two-phase zone definition is not used, max speed could also be relative to remaining free distances. This type of setup would enable even following objects, e.g. a car or walking pedestrian ahead.

The current hard braking design leads to load moving unnecessarily. The approach should be smoother, instead of “hitting the brakes”. Average deceleration is approximately 3.3 m/s2 based on data, during the 0.5 seconds needed to stop. This is a reasonable average. Still, the previous phase of slowing down would be preferable even to avoid dropping or damaging the carried load.

The rain filter in use works reasonably well in all rainy conditions, leading to only a few unnecessary stops. However, the actual camera protection fails to keep drops off the lens.

7. Conclusion

This document provides a summary of the safety validation process on a proving ground and in simulation for selected prototype functionalities regarding environmental sensing and driving manoeuvres of four automated industrial vehicles in the AWARD project. The evaluation of the results served as the foundation for conducting Safety and SOTIF assessments.

One goal of this work is to contribute to the ongoing extension of SOTIF-like analyses for Level 4 automated driving across the entire automated vehicle industry. Furthermore, the controlled proving ground tests and simulations documented in this report formed the final verification step before proceeding to field operational tests at the four pilot sites.

Real tests on proving grounds provide invaluable practical insights that surpass those obtainable from simulation steps in software development. For instance, proving grounds allow for the evaluation of brake smoothness and control, reaction times, blind spot detection, the impact of weather, cumulation of rain/snow, and real-world reliability. However, testing selected scenarios under exceptional conditions like natural snowfall poses challenges for reproducibility in real life. Simulation is a valid and necessary complement to real-world tests, as it enables the detailed examination of specific edge case scenarios, as demonstrated in this report.

The selected test scenarios aimed to cover a variety of situations: 1) basic accident scenarios involving frontal or side-approaching objects, 2) scenarios relevant to the operational test routes, including complex environments like roundabouts or likely overtaking situations, and 3) common obstacles anticipated at the test site. Each scenario was carefully designed with specific initial speeds and success criteria, incorporating variations in speeds and weather conditions.

The outcomes of the proving ground tests indicate satisfactory performance across all vehicles, permitting the continuation of tests under human supervision at operational sites. Specifically, in scenarios involving frontal obstacles, the vehicles demonstrated commendable stopping capabilities, with notable exceptions such as the forklift's inability to detect low-lying objects (29 cm and 39 cm) below a certain size threshold. Thresholds for small objects and possible object identification and classification should be considered for further testing.

The vehicles generally performed well in medium rain, but testing in heavy rain was challenging due to the immediate emergency stops. KAMAG’s performance in rain, worse than the other tested vehicles, was later identified to be a difference in software setup, essentially a missing rain filter.

All the vehicles drive rather slowly, ensuring reasonable safety with the current small safety margins. The reaction time for EZTow was approximately 0.3 seconds, depending on the definition used. This is clearly faster than the average human reaction time of approximately one second. However, humans are generally able to anticipate dangerous situations earlier than the tested vehicles, which monitor whether their safety zone is occupied.

Regarding obstacles approaching from the side, the vehicles safely slow down speed. However, certain extreme tests show that there remains a possibility for an unobservant pedestrian to walk or run under the vehicle. This risk primarily stems from two factors: either the lateral safety zone (for slowing down or stopping) is slightly too small, or the vehicle does not brake as forcefully as it should, given the time it takes for a pedestrian to traverse its safety zone. Recommendations have been made to slightly increase the current braking levels or, alternatively, to slightly expand the lateral safety zone.

Object tracking was not enabled in the test vehicles, as the feature hasn't yet achieved such reliability that it could be trusted in long operations. Such tracking features would also contribute to improvements in lateral safety by enabling the autonomous vehicle (AV) to start decelerating earlier when a collision risk is identified based on intersecting trajectories. In the absence of the object tracking feature, we recommend that safety drivers exercise increased vigilance towards road users like runners or cyclists who may approach quickly from either side of the automated vehicle. Although the automated vehicle might not be at fault in such a potential accident, this precaution is advised to prevent any such incidents.

The same behaviour of the AV from the proving ground tests could be as well observed in simulation, such as collision risk with a pedestrian when turning right and weather-induced disturbances. Also, for the additional critical scenarios (e.g. AV with trailer and full load, snowfall) the overall performance was as expected. Further constraints, however, could be observed during rain tests on the proving ground due to water accumulation at selected sensors appearing as obstacles in the AV's field of view. The design of the sensor housing as the causal reason for this observation was not present in the simulation.

8. References

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[8] SAE international, "System Theoretic Process Analysis (STPA) Recommended Practices for Evaluations of Automotive Related Safety-Critical Systems," 2022.