



D3.2 - Automatic Train Operations: implementation, operation characteristics and technologies for the Railway field

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1 Introduction

1.1 Objectives

The ASTRail project contributes to the innovation of the railway sector by supporting research activities related to specific topics such as GNSS localization, hazard analysis of the moving block signalling system, formal methods and autonomous driving. The latter topic is the target of the activities of ASTRail WP3 which aims to provide recommendations about the technological solutions, coming from non-railway sectors, which may be exploited in the next future for enhancing autonomous driving in the railway sector.

The main target of WP3 is to identify which automatic driving technologies from the automotive sector, and from other application fields different from the railway, are the most suited for the implementation in the rail sector for ATO (Automatic Train Operation). To achieve this target, the following objectives can be identified:

- Provide State of the Art of all the technologies for automated driving in the automotive sector and other application fields considering technologies that are already on the market or in the development phase;
- Identification of the basic implementation characteristics of the automotive sector that are compliant for the implementation in the railway sector;
- Identification of the operation conditions that are required for the different level of automation for the autonomous driving of automotive vehicles and for the different Grade of Automation (GoA) in ATO (e.g. driverless or unattended operations);
- Selection of the candidate automated driving technologies to be assessed for the rail sector.

The task T3.1 of WP3 “*Automated driving technologies in the automotive and in other application fields*” was dedicated to the identification of the technologies which are currently employed or under development in the automotive, in the railway and in other application fields, such as agriculture, maritime and industrial, where vehicles with autonomous driving features are already available or addressed. The survey performed in task T3.1 is reported in the deliverable D3.1 [RD.1] – “*State of the Art of Automated Driving technologies*”. Scientific literature, industrial and market solutions have been analysed to provide an overview of all cutting-edge technologies that are available.

The task T3.2 of WP3 “*Analysis of Automatic Train Operations: operation conditions and implementation characteristics*” performed an evaluation of the main features of autonomous driving road vehicles and of ATO focusing on implementation characteristics and required operation conditions for different GoA.

The last task of WP3 is task T3.3 “*Assessment of automated driving technologies for railways*” and it concludes the activity of WP3 providing the results about which autonomous driving technologies can be leveraged in the railway sector for ATO. Task T3.3 received the input from Task 3.1 regarding the currently available automatic driving technologies in different application fields. Task 3.2 indicated which the main requirements are to implement ATO for different grade of automation considering the needed applications. Further input from Task 3.2 is the specification of which basic characteristics of the automotive sector technologies can be implemented also in the rail sector. The base of knowledge created in task T3.2 will be leveraged in task T3.3 to better identify and evaluate the suitability of autonomous driving technologies in the railways.

The selection of the most suited automatic driving technologies to be reused in the railway is the target of task T3.3. The assessment will consider the technologies, extending the evaluation to the related common practices, standards and guidelines. The evaluation will take into account the requirements of different railway segments, mainly focusing on mainlines which represent the more complex scenario for automated driving implementation, (e.g. in conditions of mixed traffic with fitted and non-fitted trains) with the aim to detect potentially fully interoperable solution compatible with ERTMS/ETCS.

This task will first identify which are the requirements and the expected performances of automated driving technologies in the railway sector. In particular, the use cases and the applications (e.g., rail crossing, identification of people along the tracks, etc.) that should be covered by ATO will be specified. Using this outcome, a first selection of the technologies identified in Task 3.1 will be performed to limit the evaluation to those technologies that can be reused.

The suitability assessment of the selected technologies will be performed using a Multi-Criteria Decision Making (MCDM) method. For this scope, a set of criteria concerning several aspects of ATO will be specified. MCDM methods can be a fair procedure to evaluate the automatic driving technologies since they allow to perform qualitative evaluation considering also criteria that may be in conflict of each other. Outcome will consist in a ranking of technologies, for each particular technical domain, that identifies the most suited technologies for the implementation of specific ATO functions requirements.

1.2 Scope

This deliverable aims to identify the most suitable technology to be implemented in the railway field for performing automated driving at different GoA. The assessment of different solutions, proposed in sectors other than railways, will be conducted on the base of the results achieved in ASTRail tasks T3.1 and T3.2. Furthermore, the deliverable will detail the evaluation analysis performed in Task 3.3 to identify which automatic driving technologies, not yet exploited in the railway sector, are the most suited to be reused in the rail field.

To define a framework for the assessment of reusability of technology used for autonomous driving in the automotive sector for Railways, the analysis of the operation conditions and implementation characteristics on both fields shall be performed.

Regarding the railway field, this analysis will be done for ATO in Main line applications. Main line applications present the challenges for ATO due to the complexity of the track layouts, the presence of different operators (both for trains and infrastructure), different train classes, infrastructure fitments, open borders in Europe, etc...

Moreover, functional features of future ATO shall fit with the current ETCS architecture and they shall support an incremental approach during the transition period [1]:

- On-board ATO must adapt itself to current infrastructure fitment;
- Trackside equipment have not to affect the current operation of the existing trains;
- On-board functionality is complete and the level of functions activated depends on the data actually coming from trackside;
- Scalability is required for realistic migration to full ATO features.

ATO interoperability shall be an extension of ETCS interoperability with the following main technical features [1]:

- No difference between "ETCS Interoperability" and "ATO Interoperability".
- ATO communication based on ETCS principles and grammar (add-on).
- ATO not safety related since ETCS always supervises the current speed as today.
- ATO active only in ETCS FS.

1.3 Document structure

The deliverable D3.2 is organised as follows:

- Chapter 2 analyses and compares the implementation characteristics and the operation conditions between the automotive and the railway sector, it reports the activities and the results of task T3.2;
- Chapter 3 describes the ATO functions and it illustrates the use cases where the ATO functions can be deployed; the use cases are then analysed to identify specific requirements of ATO functions that are exploited for the technologies evaluation; a resume of the technologies identified in ASTRail deliverable D3.1 is also introduced in this chapter;
- The assessment of the suitability of the technologies, based on the identified requirements of ATO function, is performed in Chapter 4, using the Weighted Sum Model method;
- Chapter 5 summarizes the achieved results and draws the final conclusions of the WP3 activities.

1.4 Related documents

ID	Title	Reference	Version	Date
[RD.1]	D3.1 - State of the Art of Automated Driving technologies	ASTRail Project	1.0	2017-11-30
[RD.2]	D2.1 - Modelling of the moving block signalling system	ASTRail Project	1.0	2017-11-29

1.5 Terms and definitions

Automatic Train Operation refers to the ability to start/stop a train and opening doors in an automatic way.

Localisation is the determination of the geographical movement state of a certain means of transportation (that means location and speed according to amount and direction in relation to a point of reference of the vehicle) in a spatial reference system.

Navigation is defined as: localisation of a vehicle and its guidance from a location to a destination. Navigation is also defined as the science of getting ships, aircraft, spacecraft or people from place to place; especially: the method of estimating location, course, and distance travelled.

Plane Line is used to indicate a train running along a line, without crossing levels presence or station approaching operation required.

Positioning is a process of putting an object in a place.

Position is the information of a place related to a coordinate system.

Safety: Freedom from unacceptable risk of harm.

Safety Function: A safety function is defined as a function to be implemented by a safety-related system, this system is an Electric/Electronic/Programmable Electronic system, another technology safety-related system or external risk reduction facilities, which is intended to achieve or maintain a safe state for the Equipment Under Control, in respect of a specific hazardous event. A safety function is not part of machine operation: if such a function fails, the machine can still operate normally, but the risk of injury from its operation increases.

Safety Integrity: The safety integrity is defined as the likelihood of a system satisfactorily performing the required safety functions under all the stated conditions within a stated period of time.

Type of Operation of a line: High Speed, Low Traffic/Regional, Urban/Suburban.

2 Automated driving and ATO: implementation characteristics and operation conditions

This chapter corresponds to the main output of Task T3.2 in which operation conditions and implementation characteristics are analysed for both automotive and railway sectors. ***This analysis aims in particular to determine which of the implementation characteristics and of the operation conditions typical of the automotive sector are valid also in the railway field.*** To achieve this goal, the relevance and effectiveness of characteristics from autonomous driving in the automotive sector will be highlighted.

This analysis considers only those characteristics and conditions that are related to ATO and to autonomous driving tasks in the automotive sector.

In this work, indeed, we consider that ATO does not implement functionalities that are already covered by other systems and we consider that ATO implements functionalities identified by the current definition of ATO over ERTMS system [5]. We consider that additional functionalities could be included in ATO system but only if they let ATO to maintain backward compatibility with the ERTMS system.

Concerning autonomous driving in the automotive sector, we refer to the definition of J3016 Recommended Practice [5] as detailed in Sect. 2.2.3. In particular, in the J3016 document it is specified that autonomous driving is related to dynamic driving tasks and it shall not consider strategic functions.

For example, trajectory planning presents differences between the automotive and the railway sector. Indeed, in the railways, trains run following a timetable and they have to respect the indications of clearly defined movement authorities, while on the roads vehicles don't have these constraints (even if they have to be compliant with traffic laws, there are also some restrictions on stopping locations and there are some sort of movement authorities such as the traffic lights). However, in this analysis trajectory planning is not detailed since trajectory planning is a strategic function and, moreover, trajectory planning is already responsibility of Traffic Management System in the railways.

The main functions of autonomous driving for each sector and level of automation will be determined below, to make clear which of them are responsible of the system and which of the driver.

Here an important clarification about safety must be done. In this work we consider the ATO functions for railway to be complementary to the ATP system, as defined by ERTMS/ETCS European standard. Within this frame, all the safety functions are demanded to the train protection system and to the movement authority evaluation system. The ATP functions will always be prior to the ATO commands, at every time and at any level.

2.1 General description of considered Implementation characteristics and Operation conditions

The following Table 2.1 shows the description of the considered implementation characteristics for autonomous driving. Implementation characteristics aim to characterize aspects concerning environment, vehicle and related aspects. These parameters will serve as a basis for comparison between automotive and railways backgrounds. To simplify the subsequent analysis and to increase understanding, characteristics have been grouped into main classes and each characteristic has a unique ID.

Main class	Specific characteristic		ID	Description
Circulation characteristics	Traffic characteristics	Maximum speed	ICC-1	These and other characteristics may be referred to different types of circulation environment, such as main lines, high-speed lines, suburban lines for the railway case and motorway, urban road for the automotive case.
		Frequency of vehicles		
	Sharing of circulation area with other manned vehicles		ICC-2	Potential presence in the circulation environment of vehicles driven by human drivers.
	Potential presence of vulnerable users		ICC-3	The presence may not be permitted but it is still possible that vulnerable users or, more in general, people are in the circulation environment.

Main class	Specific characteristic	ID	Description
	<i>Regulations</i>	ICC-4	Specific rules that the vehicle has to follow.
Environmental characteristics	<i>Structured or not structured environment</i>	ICE-1	Presence or not of lanes, guides, tracks and other items that define the driving surface.
	<i>Aliasing</i>	ICE-2	Environment perception is the same in different locations, meaning that it is not possible to distinguish features that characterize a given location.
	<i>GNSS availability and reliability</i>	ICE-3	Define more likely characteristics of the environment that can have an impact on the GNSS system, i.e. open-space / restricted/ urban environment.
	<i>Static environment</i>	ICE-4	Define if the environment is subject to dynamic changes. It mainly impact on mapping aspects.
	<i>Weather and other environmental conditions</i>	ICE-5	Specify if driving can be affected by bad weather conditions or by other disadvantageous environmental conditions that can result in degraded driving operations.
Vehicle characteristics	<i>Size and weight</i>	ICV-1	Specify size and weight of the vehicle. These characteristics mainly impacting on vehicle braking distance.
	<i>Passengers on-board</i>	ICV-2	Presence of people not in charge of driving or supervising the vehicle.
Technologies characteristics	<i>Complementarity</i>	ICT-1	Multi-sensors data fusion for increased reliability and accuracy.
	<i>Cooperativeness</i>	ICT-2	Vehicle-to-vehicle and vehicle-to-infrastructure communications for enhanced availability of information.
	<i>Weather and environmental condition sensitiveness</i>	ICT-3	A technology may present different performance according to weather and environmental conditions.
	<i>Performance and operational characteristics</i>	ICT-4	Performance of a technology in a given scenario, for example the range at which a technology can detect an object of a given size.

Table 2.1 – Implementation characteristics selected for the analysis

The following Table 2.2 shows the description of the considered operation conditions for autonomous driving. Operation conditions are intended as the conditions that need to be satisfied to have the automated driving systems properly operating. These conditions will serve as a basis for comparison between automotive and railways backgrounds. To simplify the subsequent analysis and to increase understanding, operation conditions have been grouped into main classes and each condition has a unique ID.

According to the definition, the operational conditions include the environmental conditions and the physical loads experienced by the system during all phases of the life cycle. Functional faults and Hazards can only be predicted and prevented if the operational conditions are known and understood before the design phase.

Therefore, the operational conditions must be described in the requirements specification developed before the design phase.

Type of Condition	Condition	ID	Description
Positioning operations	<i>Periodic vehicle localization</i>	OCP-1	Localization requirements for the driving operations of the vehicles.
	<i>Start of mission</i>	OCP-2	Localization at the start of the journey.
	<i>Stop at the station</i>	OCP-3	Precise stopping at the station.
	<i>Positioning in closed environment</i>	OCP-3	Positioning operations in particular conditions.
Obstacle detection operations	<i>Static obstacles</i>	OCD-1	Operations related to the detection of static obstacles.
	<i>Moving obstacles</i>	OCD-2	Requirements for the detection of moving obstacles.
	<i>Obstacles dimension</i>	OCD-3	Detection of small or large obstacles and related requirements.
	<i>Obstacle type</i>	OCD-4	Detection of "True" obstacles (rocks, cars, people) and "fake" obstacles (fallen leaves, journal papers).
Trajectory planning	<i>Initial trajectory planning</i>	OCT-1	Requirements about the planning of the trajectory at the start of the trip.
	<i>Ongoing trajectory refinement</i>	OCT-2	Trajectory refined according to current localization of the vehicle and obstacles detection.
Vehicle control (Driving)	<i>Definition of actions to implement refined trajectory</i>	OCV-1	Decision to brake, accelerate, steer.
	<i>Implementation of the control actions</i>	OCV-2	Brake, accelerate, steer.
	<i>Passengers management</i>	OCV-3	Requirements and operations related to the management of passengers such as door opening/closure, passengers getting on/off and emergency situations.
	<i>Definition of the level of automated driving</i>	OCV-4	Level of automated driving is set according to the driving conditions (Responsibility of the driver).

Table 2.2 –Operation conditions selected for the analysis

2.2 Implementation characteristics and operation conditions for automotive sector

Table 2.3 and Table 2.4 introduce the implementation characteristics and operation conditions for the automotive sector. This analysis does not cover safety aspects of the automotive sector since up to now no standardization about this aspect has been performed and each automated driving system implements specific safety levels that are not publicly available.

2.2.1 Implementation characteristics

The implementation characteristics of the automotive sector are described in the following Table 2.3.

Main class	Specific characteristic	ID	Values
Circulation characteristics	Traffic characteristics	ICC-1	Motorway
			Rural road
			Urban road
	Maximum speed	ICC-1	Low-speed urban road
			130 km/h
	Frequency of vehicles	ICC-1	90 km/h
Circulation characteristics	Sharing of circulation area with other manned vehicles	ICC-2	50 km/h
	Potential presence of vulnerable users	ICC-3	30 km/h
	Regulations	ICC-4	Medium-High
		ICC-4	Low
Environmental characteristics	Structured or not structured environment	ICE-1	Medium-High
	Aliasing	ICE-2	Medium-High
	GNSS availability and reliability	ICE-3	Medium-High
	Static environment	ICE-4	Medium-High
	Weather and other environmental conditions	ICE-5	Medium-High
		ICE-5	Medium-High
Vehicle characteristics	Size and weight (mainly related to braking distance)	ICV-1	Average weight of 1000 kg and size in the following ranges length 4-5 m, width 1.5 - 2 m, height 1.3 – 1.8 m. From few tens of meters at low speeds (30-50 km/h) to around 100 m at medium speed (90 km/h) and up to 200-300 m at high speed (130 km/h). Stopping distances usually include reaction times and they depend on road conditions (wet or dry), on the tyres status and on the type of car.
	Passengers on-board	ICV-2	Yes.

Main class	Specific characteristic	ID	Values
Technologies characteristics	<i>Complementarity</i>	ICT-1	Multiple sensors are typically used for both positioning and obstacle detection. More than one GNSS positioning systems are used to increase accuracy (e.g., GPS and Galileo) and they are typically complemented with visual positioning methods. Active sensors (e.g., RADAR, LiDAR) and passive sensors (visual, infrared cameras) are jointly used to enhance the perception system.
	<i>Cooperativeness</i>	ICT-2	Vehicle-to-vehicle and vehicle-to-infrastructure communications are both considered to exchange information related to the status of the vehicle (position, direction, speed) and to presence of possible dangers (obstacles, road conditions, etc.). The effectiveness strongly depends on how many vehicles are equipped with the communication system.
	<i>Weather and environmental condition sensitiveness</i>	ICT-3	Visual sensors but also radars and LiDARs can be strongly affected by bad weather conditions. GNSS positioning systems can have a degradation in the performance due to poor signal reception in urban areas and in mountainous areas.
	<i>Performance and operational characteristics</i>	ICT-4	A positioning accuracy in the order of centimetres is required for full autonomous manoeuvres. Along-track positioning accuracy may be more relaxed, while critical is the cross-track positioning accuracy. Obstacle detection at 360° degrees is required. Front detection is typically in the order of few hundred meters. Lateral and rear detection is usually up to 100 m. Short-range detection is jointly used for increase detection performance of close objects.

Table 2.3 – Implementation characteristics for automotive

2.2.2 Operation conditions

Table 2.4 presents the operation conditions for autonomous driving in the automotive sector.

Type of Condition	Condition	ID	Impact on automated driving tasks
Positioning operations	<i>Periodic vehicle localization</i>	OCP-1	The required accuracy of the localization is not standardized. Desired target is to reach centimeters-level accuracy, at least few tens of centimeters. This goal seems to be viable considering current research results in the field. The accuracy in the lateral positioning (cross-track direction) is strictly important for autonomous driving decisions related to lanes occupancy (e.g. lane keeping, overtaking). Up to 10 cm of accuracy in lateral positioning can be considered sufficient for autonomous driving manoeuvres [2].

Type of Condition	Condition	ID	Impact on automated driving tasks
			The periodicity of localization is strictly related to the frequency that localization sensors update the information. For example, GNSS sensors can update the measured position with a frequency of ten times per second. However, the periodical update of the information depends also on the multi-sensors data fusion algorithms. These algorithms can update the position at a rate higher than that of specific sensors thanks to the extrapolation of the information.
	<i>Start of mission</i>	OCP-2	No specific positioning application seems to be proposed in the State of the Art to initialize the position of the vehicle at the start of the trip.
	<i>Stop at the station</i>	OCP-3	In the automotive sector, the “Stop at the station” application can be considered equivalent to the parking. Ultrasonic sensors measure short-range distances in order to locate the vehicle with respect to the other vehicles allowing precise parking manoeuvres.
	<i>Positioning in closed environment</i>	OCP-4	Radio signal-based positioning systems and dead reckoning methods can be exploited in tunnels to compensate GNSS system’s unavailability. Other possibility to increase the positioning accuracy is to exploit natural or artificial landmarks positioning methods. Cooperative positioning methods, which are based on exchange of information among vehicles and with the infrastructure, can be also employed.
Obstacle detection operations	<i>Static obstacles</i>	OCD-1	Visual sensors (e.g., cameras) and active sensors (e.g., RADARs, LiDARs) are jointly used to perceive the surrounding environment for potential obstacles.
	<i>Moving obstacles</i>	OCD-2	<p>Detection of vehicles and of other road actors can be eased thanks to communication technologies. Each road actor, which is equipped with an appropriate communication equipment, can broadcast its position, direction and speed in order to prevent any collision. Apart from vehicles, it is likely that bicyclists and motorcyclists will be connected in the vehicular networks. Pedestrians may be connected as well exploiting the widespread of smartphones.</p> <p>The detection of pedestrians and animals is also targeted by exploiting thermal cameras that can well detect warm bodies. This approach loses effectiveness when pedestrians wear heavily insulating clothing.</p>
	<i>Obstacles dimension</i>	OCD-3	No specific information is provided about this aspect in the State of the Art. It is expected that the perception systems of self-driving cars are designed to consider only relevant size obstacles.
	<i>Obstacle type</i>	OCD-4	Visual cameras are used in the obstacle detection systems since they allow to obtain a good spatial resolution of the environment easing the objects recognition. Research effort is also devoted to classify detected object to understand if they represent a true obstacle or not.

Type of Condition	Condition	ID	Impact on automated driving tasks
Trajectory planning	<i>Initial trajectory planning</i>	OCT-1	Related to autonomous driving applications at a strategic level, not inherent to real-time driving tasks
	<i>Ongoing trajectory refinement</i>	OCT-2	Continuous refinement of the trajectory given the information about the position of the vehicle and the presence of potential obstacles.
Vehicle control (Driving)	<i>Definition of actions to implement refined trajectory</i>	OCV-1	Control modules that, considering vehicle dynamics, take decisions to brake, accelerate, steer in order to implement the refined trajectory (i.e. three dimensional working area).
	<i>Implementation of the control actions</i>	OCV-2	Brake, accelerate, steer (i.e. three dimensional working area).
	<i>Passengers management</i>	OCV-3	Not specific focus on this aspect in the State of the Art. Currently, emergency calls in case of crash are automatically performed on vehicles.
	<i>Definition of the level of automated driving</i>	OCV-4	Levels of automated driving are defined based on the tasks that are performed by the human driver or by the driving automation system. In some levels, there is the possibility that the system requests the human driver to intervene in case that the system cannot ensure the proper and safe execution of a driving task.

Table 2.4 – Operation conditions for autonomous driving

2.2.3 Driving operations for the different Levels of Automation

The Recommended Practice J3016 “Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles” published by SAE International [3] provides a taxonomy of automated driving of motor vehicles for roadways operations, including a functional definition of the levels of automated driving and of all related terms. In the following of this subsection, an overview of what defined in the J3016 Recommended Practice is provided. Definitions reported from the document are highlighted in *italics*.

First, it is necessary to recall that the act of driving includes several decisions and actions that can or cannot be strictly related to the vehicle motion. The J3016 takes as reference the document by Michon [4] in which it is introduced that the act of driving can be divided in three different types of functions: strategic, tactical and operational functions. Strategic functions include trip planning, i.e. set the destination and the waypoints and choose the timing. Tactical functions are related to the manoeuvres of the vehicles during a trip, e.g., change lane, overtake a vehicle, select appropriate speed and check mirrors. Operational functions are all these operations, requiring instantaneous reaction, which can be considered pre-cognitive or innate. For example, the micro-corrections of the steering, braking or accelerating to keep the correct vehicle’s position or to avoid some obstacle or hazard.

The J3016 Recommended Practice defines as automated driving the “*performance of part or all of the Dynamic Driving Task (DDT) on a sustained basis*”. The dynamic driving task includes all those real-time operational and tactical functions that are required to operate a vehicle in on road-traffic. Strategic functions are not included. The sustained operation of the vehicle means that part or all of the DDT is performed “*between and across external events, including responding to external events and continuing performance of part or all of the DDT in the absence of external events*”. Figure 1 depicts the schema of driving functions divided by category.

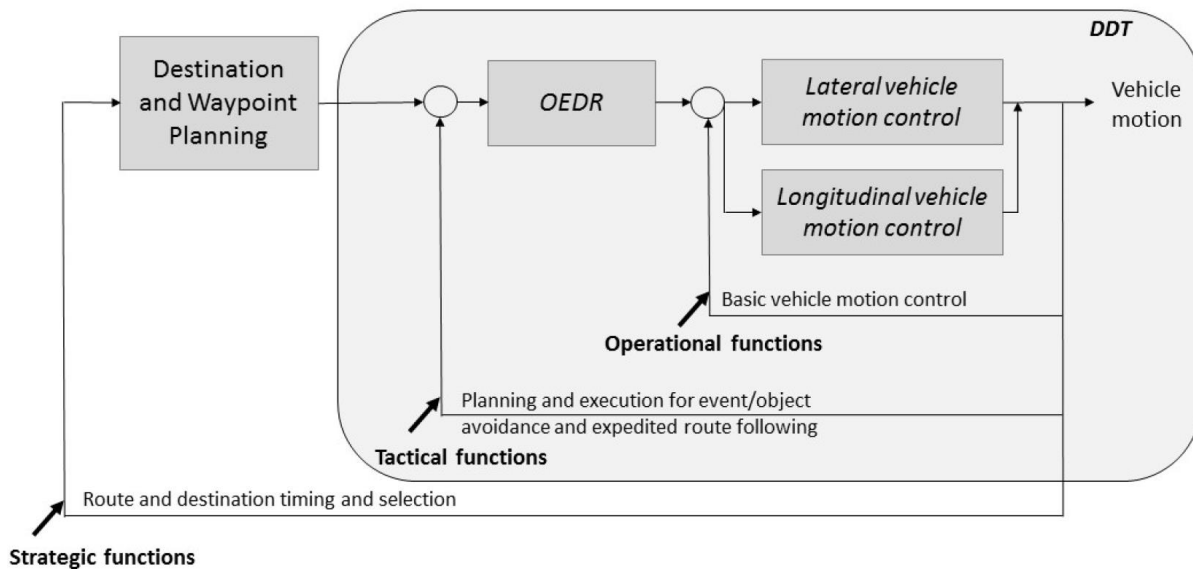


Figure 1 – Driving task overview schema [3]

The J3016 Recommended Practice details that DDT includes without limitations:

- **Lateral vehicle motion control** via steering (operational function), it includes the detection of the vehicle positioning relative to lane boundaries and application of steering and/or differential braking inputs to maintain appropriate lateral positioning;
- **Longitudinal vehicle motion control** via acceleration and deceleration (operational function), it includes maintaining set speed as well as detecting a preceding vehicle in the path of the subject vehicle, maintaining an appropriate gap to the preceding vehicle and applying propulsion or braking inputs to cause the vehicle to maintain that speed or gap;
- **Object and Event Detection and Response (OEDR)** (operational and tactical function), it consists in monitoring the driving environment via object and event detection, recognition, classification, and response preparation together with the object and event response execution;
- **Manoeuvre planning** (tactical function);
- **Enhancing conspicuity** via lighting, signalling and gesturing, etc. (tactical function).

The J3016 Recommended Practice reports a taxonomy of automated driving that consists in six discrete and mutually exclusive levels. Each level is characterized by the roles of the human driver and of the automated driving system in the execution of dynamic driving tasks. These levels are only descriptive and informative. The J3016 Recommended Practice does not intend to legally standardize these levels.

The automated driving systems are differentiated into levels according to the following characteristics:

- the automated driving system performs **either the longitudinal or the lateral vehicle motion control** subtask of the DDT;
- the automated driving system performs **both the longitudinal and the lateral vehicle motion control** subtasks of the DDT simultaneously;
- the automated driving system also **performs the OEDR subtask** of the DDT;
- **the automated driving system is limited by an Operational Design Domain (ODD)**, which corresponds to the conditions in which a given automated driving systems can operate; the driving modes (e.g., expressway merging, high-speed cruising, low-speed traffic jam, etc.) supported are also specified in the ODD; “geographic, roadway, environmental, traffic, speed, and/or temporal limitations” can be specified in the ODD;
- **the automated driving system also performs DDT fallback** that is “the response by the user or by an automated driving system to either perform the DDT or achieve a minimal risk condition after occurrence of a DDT performance-relevant system failure(s) or upon ODD exit”; a DDT performance-relevant system failure occurs when there is a malfunction in the automated driving system that is not anymore able to perform the DDT in a reliable way.

According to these characteristics, the six levels have been defined as follows:

- **Level 0 – No Driving Automation:** *the human driver performs the entire DDT, even when enhanced by active safety systems (e.g., anti-lock brake systems (ABS), electronic stability control (ESC), and lane keeping assistance systems);*
- **Level 1 – Driver Assistance:** *the sustained and ODD-specific execution by a driving automation system of either the lateral or the longitudinal vehicle motion control subtask of the DDT (but not both simultaneously) with the expectation that the driver performs the remainder of the DDT;*
- **Level 2 – Partial Driving Automation:** *the sustained and ODD-specific execution by a driving automation system of both the lateral and longitudinal vehicle motion control subtasks of the DDT with the expectation that the driver completes the OEDR subtask and supervises the driving automation system;*
- **Level 3 – Conditional Driving Automation:** *the sustained and ODD-specific performance by an ADS of the entire DDT with the expectation that the DDT fallback-ready user is receptive to ADS-issued requests to intervene, as well as to DDT performance-relevant system failures in other vehicle systems, and will respond appropriately;*
- **Level 4 – High Driving Automation:** *the sustained and ODD-specific performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will respond to a request to intervene;*
- **Level 5 – Full Driving Automation:** *the sustained and unconditional (i.e., not ODD-specific) performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will respond to a request to intervene.*

Table 2.5 reports in a schematic way the definition of the 6 levels highlighting which functions are operated in each level by the human driver or by the automated driving system. It also specifies for each level if a specific ODD can be applied or not.

Level	Name	Narrative definition	Dynamic Driving Task (DDT)		DDT fallback	ODD
			Sustained lateral and longitudinal vehicle motion control	Object and Event Detection and Response (OEDR)		
Driver performs part or all of the DDT						
0	No Driving Automation	The performance by the driver of the entire DDT, even when enhanced by active safety systems.	Driver	Driver	Driver	n/a
1	Driver Assistance	The sustained and ODD-specific execution by a driving automation system of either the lateral or the longitudinal vehicle motion control subtask of the DDT (but not both simultaneously) with the expectation that the driver performs the remainder of the DDT.	Driver and System	Driver	Driver	Limited
2	Partial Driving Automation	The sustained and ODD-specific execution by a driving automation system of both the lateral and longitudinal vehicle motion control subtasks of the DDT with the expectation that the driver completes	System	Driver	Driver	Limited

		the OEDR subtask and supervises the <i>driving automation system</i> .				
ADS performs the entire DDT (while engaged)						
3	Conditional Driving Automation	The <i>sustained</i> and <i>ODD-specific</i> performance by an <i>ADS</i> of the entire DDT with the expectation that the <i>DDT fallback-ready user</i> is <i>receptive</i> to <i>ADS-issued requests to intervene</i> , as well as to <i>DDT performance-relevant system failures</i> in other vehicle systems, and will respond appropriately.	System	System	<i>Fallback-ready user (becomes the driver during fallback)</i>	<i>Limited</i>
4	High Driving Automation	The <i>sustained</i> and <i>ODD-specific</i> performance by an <i>ADS</i> of the entire DDT and <i>DDT fallback</i> without any expectation that a <i>user</i> will respond to a <i>request to intervene</i> .	System	System	System	<i>Limited</i>
5	Full Driving Automation	The <i>sustained</i> and unconditional (i.e., not <i>ODD-specific</i>) performance by an <i>ADS</i> of the entire DDT and <i>DDT fallback</i> without any expectation that a <i>user</i> will respond to a <i>request to intervene</i> .	System	System	System	<i>Unlimited</i>

Table 2.5 – Definition of automated driving levels by J3016 Recommended Practice [3].

2.3 Implementation characteristics and operation conditions for ATO

Table 2.6 and Table 2.7 contain an analysis of implementation characteristics and operation conditions for the railway sector. The focus of this analysis is on mainlines.

2.3.1 Implementation characteristics

The main implementation characteristics of autonomous driving on Railways are highlighted in the Table 2.6.

Main class	Specific characteristic		ID	Values			
Circulation characteristics	Traffic characteristics	Type of Railway	ICC-1	Mixed a	Mixed b	Mixed c	Dedicated
		Maximum speed		Less than 80 km/h	80-120 km/h	120-200 km/h	More than 200 km/h
		Type of vehicles		Pass+ Freight	Pass+ Freight	Pass+ Freight	HSL
	Sharing of circulation area with other manned vehicles		ICC-2	At least during the transition period there is high probability of sharing the railway line between autonomous and manned vehicles.			
	Potential presence of vulnerable users		ICC-3	Presence may not be permitted but it is still possible. The best practice consists in eliminating of level crossings, nevertheless a random presence of vulnerable users shall be considered.			

Main class	Specific characteristic	ID	Values
	<i>Regulations</i>	ICC-4	Railway Traffic Regulations.
Environmental characteristics	<i>Structured or not structured environment</i>	ICE-1	Vehicles movement is conditioned by track geometry. The vehicles shall follow and comply the time-schedule provided by TMS.
	<i>Aliasing</i>	ICE-2	Environment perception is the same in different locations, it is not possible to distinguish features that characterize a given location.
	<i>GNSS availability and reliability</i>	ICE-3	Open-space / restricted/ urban environment.
	<i>Static environment</i>	ICE-4	It mainly impact on mapping aspects.
	<i>Weather and other environmental conditions</i>	ICE-5	Normal or degraded operations.
Vehicle characteristics	<i>Size, weight and configuration (mainly related to braking distance)</i>	ICV-1	ATO on-board shall be configurable to be fitted in any rolling stock type: control of brakes, doors and performance. <i>Braking distance for type of railway: Mixed a: 250m, Mixed b: 550m, Mixed c: 1500m, Dedicated: 1600m.</i>
	<i>Passengers on-board</i>	ICV-2	Passenger and freight trains, maintenance trains and engineering vehicles.
Technologies characteristics	<i>Complementarity</i>	ICT-1	Multi-sensors data fusion for increased reliability and accuracy. Gathering and fusion of data from track sensors.
	<i>Cooperativeness</i>	ICT-2	Vehicle-to-vehicle and vehicle-to-infrastructure communications for enhanced availability of information.
	<i>Weather and environmental condition sensitiveness</i>	ICT-3	A technology may present different performance according to weather and environmental conditions.

Main class	Specific characteristic	ID	Values
	<i>Performance and operational characteristics</i>	ICT-4	<p>A positioning accuracy in the order of centimetres is required for ATO for precise stopping, while for running trains it can be relaxed to meters range (e.g. horizontal accuracy required for HSL is 1 m, and for medium density lines is 10m). Cross-track positioning accuracy can be discretized since it is sufficient to provide information about which track the train occupies.</p> <p>Obstacle detection may be limited to the front direction with limited detection angle, nevertheless, flank protection (against the collision with another train on switches) shall be assured for the operation when Full Supervision by ETCS is not available (<90°). The front detection strongly varies according to required braking distance that can range from few hundred meters up to few kilometres for high speed trains (at least 400m to 1600m).</p> <p>Also, ATO system shall be able to detect some defined markers (e.g. ETCS stop marker) at distance enough to brake the train with limited speed operation.</p>

Table 2.6 – Implementation characteristics for ATO

2.3.2 Operation conditions

In the Table 2.7 the main operation conditions considered for autonomous driving in the railway sector are presented.

Type of Condition	Condition	ID	Impact on ATO
Positioning operations	<i>Periodic vehicle localization</i>	OCP-1	ATO function shall allow to localize ATO- fitted trains in mixed lines.
	<i>Start of mission</i>	OCP-2	Localization at the start of the journey.
	<i>Stop at the station</i>	OCP-3	Precise stopping at the station.
	<i>Positioning in closed environment</i>	OCP-4	Positioning operations in particular conditions.
Obstacle detection operations	<i>Static obstacles</i>	OCD-1	ATO on-board shall have interfaces to external obstacles detection and railway supervision systems.
	<i>Moving obstacles</i>	OCD-2	Other trains on line. Responsibility of the safe headway distance management is out of the scope of ATO.

Type of Condition	Condition	ID	Impact on ATO
	<i>Obstacles dimension</i>	OCD-3	Small or large obstacles.
	<i>Obstacle type</i>	OCD-4	“True” obstacles (rocks, cars, people) and “fake” obstacles (fallen leaves, journal papers).
Trajectory planning	<i>Initial trajectory planning</i>	OCT-1	Out of the scope of ATO. Planned by TMS according to time schedule. Indeed, trains run according to timetables and they must respect the movement authorities.
	<i>Ongoing trajectory / Speed profile refinement</i>	OCT-2	Speed profile refined according to current localization of the vehicle and obstacles detection.
Vehicle control (Driving)	<i>Definition of actions to implement refined trajectory</i>	OCD-1	Decision to brake, accelerate (i.e. two dimensional working area).
	<i>Implementation of the control actions</i>	OCD-2	Brake, accelerate (i.e. two dimensional working area).
	<i>Passengers management</i>	OCD-3	<ul style="list-style-type: none"> – Door opening/closure (trains) – Passengers getting on/off (automotive) – Emergency situations.
	<i>Definition of the level of automated driving</i>	OCD-4	Level of automated driving is set according to the driving conditions (Responsibility of the driver).

Table 2.7 – Operation conditions for ATO

Autonomous driving systems for railways shall be able to comply Operational Requirements in any Operational Condition.

ATO over ETCS Operation Requirements are found in the ERA document [5] and they are grouped according to 10 principles:

- ATO Principle 1: Performance and Energy Efficiency;
- ATO Principle 2: Supervision and Regulation;
- ATO Principle 3: Yards, Depots and Stabling Areas;
- ATO Principle 4: Ensure safe movement of trains;
- ATO Principle 5: Operate Train;
- ATO Principle 6: Control Traction Power;
- ATO Principle 7: Supervise railway;
- ATO Principle 8: Supervise loading and unloading;
- ATO Principle 9: ATO status and failures;
- ATO Principle 10: Detection and management of emergency situations.

2.3.3 Train operations for the different Grades of Automation (from ASTRail Deliverable D2.1 [RD.2])

Basic functions of train operation		GoA0	GoA1	GoA2	GoA3	GoA4
		<i>On-sight train operation</i>	<i>Non-automated train operation</i>	<i>Semi-automated train operation</i>	<i>Driverless train operation</i>	<i>Unattended train operation</i>
Ensuring safe movement of trains	<i>Ensure safe route</i>	X (points command/control in system)	system	system	system	system
	<i>Ensure safe separation of trains</i>	X	system	system	system	system
	<i>Ensure safe speed</i>	X	X (partly supervised by system)	system	system	system
Driving	<i>Control acceleration and braking</i>	X	X	system	system	system
Supervising guideway	<i>Prevent collision with obstacles</i>	X	X	X	system	system
	<i>Prevent collision with persons on track</i>	X	X	X	system	system
Supervising passenger transfer	<i>Control passengers' doors</i>	X	X	X	X	system
	<i>Prevent person injuries between cars or between platform and train</i>	X	X	X	X	system
	<i>Ensure safe starting conditions</i>	X	X	X	X	system
Operating a train	<i>Set in/ set off operation</i>	X	X	X	X	system
	<i>Supervise the status of the train</i>	X	X	X	X	system
Ensuring detection and management of emergency situations	<i>Perform train diagnostic</i>	X	X	X	X	System and/or staff in OCC

Table 2.8 – Train operations for the different Grades of Automation

2.4 Comparison analysis of implementation characteristics, operation conditions and automation levels between automotive and ATO

Table 2.10 and Table 2.11 contain a comparison of implementation characteristics and operation conditions between automotive and railways. Visual matching symbols are used to provide a quick indication of the amount of overlapping between the two sectors. See Table 2.9 for a legend of the adopted symbols.







Symbol	Description
	Good overlap
	Partial overlap
	No overlap

Table 2.9 - Comparison symbols

In railways vehicles movement is conditioned by track geometry. Additionally, the vehicles shall follow and comply the time-schedule provided by TMS. These conditions allow to relax the requirements regarding navigation and trajectory planning which are critical in the autonomous vehicles of other transportation sectors.

This comparison is performed to constitute a knowledge basis that will be exploited during the evaluation of the autonomous driving technologies. Understanding which implementation characteristics are similar or not in the two sectors can help in the evaluation of the suitability of a given technological solution. The analysis of the operation conditions can help as well in identifying which the needs are for an automated driving system easing the definition of which requirements the automated driving system should sustain.

2.4.1 Analysis of "Implementation characteristics" in the automotive and in the railway sector

ID	Specific characteristic	Values	Matching
ICC-1	Traffic characteristics	<p>Maximum speed is the only characteristic that can be compared between the two sectors. Cars can reach typically up to 130 km/h, while trains can exceed this speed in specific types of railways (e.g., HSL). However, significant differences between automotive and railway sectors are present for what concerns speed and braking distance, having typically larger braking distances for trains with respect to cars running at the same speed.</p> <p>An automotive technological solution, whose proper operation is related to the speed of the vehicle (i.e., visual-based technological solution), may be reused just for the trains running at the same speed at which cars are expected to run by the considered solution. In the specific of obstacle detection solutions, it is required to take into account the different braking distance required.</p>	
ICC-2	Sharing of circulation area with other manned vehicles	In both automotive and railway sectors it is expected that manned and automated driving vehicles will circulate during a transition period.	
ICC-3	Potential presence of vulnerable users	In the automotive sector the presence of vulnerable users is admitted. In the railway sector it is not admitted, but presence of users is still possible. Solutions implemented in the automotive and concerning the detection of pedestrians, animals or other vulnerable users can be evaluated for a possible reuse in railways.	

ID	Specific characteristic	Values	Matching
ICC-4	Regulations	Specific regulations are present in both cases. Due to the peculiarity of regulations, it is not likely to have any synergies on this aspect.	✗
ICE-1	Structured or not structured environment	In both cases there is a structured environment. Main difference is that the railway vehicles' movement is physically constrained by the tracks, while cars' movement is typically bounded by road markings in a virtual way. Automotive solutions exploiting this characteristics may inspire similar solutions for the railway sector.	≈
ICE-2	Aliasing	Aliasing is present in both sectors. Solutions mitigating this issue may be considered for a reuse in the railway environment.	✓
ICE-3	GNSS availability and reliability	In both sectors vehicles can circulate in open-space / restricted/ urban environments. Solutions, exploited in the automotive sector to improve the reliability of GNSS system, may be of interest also in the railway sector.	✓
ICE-4	Static environment	More likely impact in the automotive, while limited in the railway sector. This aspect may impact on map-based positioning applications and solutions of the automotive sector may be reused in the railway if there is the interest.	≈
ICE-5	Weather and other environmental conditions	Degraded operations due to bad weather conditions are possible in both sectors. Railway sector can benefit from solutions in the automotive that concern automated driving in degraded conditions.	✓
ICV-1	Size and weight (mainly related to braking distance)	Not comparable as specified in the "Traffic characteristics" analysis (first row of the table).	✗
ICV-2	Passengers on-board	Passengers are present on cars and on passengers' trains. Not focus on passengers handling in the automotive sector. Not many solutions to be analysed for possible reuse in the railways.	≈
ICT-1	Complementarity	Multi-sensors data fusion is exploited in both sectors.	✓
ICT-2	Cooperativeness	Vehicle-to-vehicle and vehicle-to-infrastructure communications can be exploited in both sectors.	✓
ICT-3	Weather and environmental condition sensitiveness	Weather conditions can impact operations in both sectors.	✓
ICT-4	Performance and operational characteristics	The required performance and working characteristics are likely to be different between the two sectors, however sensors may be reused for the same scope if sensors are properly designed to meet railway requirements and characteristics.	≈

Table 2.10 - Implementation characteristics comparison

2.4.2 Analysis of "Operation conditions" in the automotive and in the railway sector

ID	Condition	Impact on automated driving tasks	Matching
OCP-1	Periodic vehicle localization	Localization is required in both sector. Cross-track accuracy is important in both cases since it is required to be able to distinguish the position of the vehicle in the lane or track.	✓
OCP-2	Start of mission	In the automotive sector, no significant importance is given in the literature to this operation.	✗
OCP-3	Stop at the station	The automotive parking functionality may provide some inputs to the precise stopping at the station.	≈
OCP-4	Positioning in closed environment	Required in both automotive and railway sector.	✓
OCD-1	Static obstacles	Required in both automotive and railway sector. Obstacle detection in railway sector is more challenging since braking distances of trains are longer and consequently obstacles have to be detected earlier.	≈
OCD-2	Moving obstacles	Detection of moving obstacles is more challenging in the automotive sector since vulnerable road users can be present. In railway sector the ATO is not responsible for managing the distances between trains. The presence of people is not admitted, however it is still possible. This requires trains to be able to detect people. Possible to leverage on knowledge from the automotive sector.	≈
OCD-3	Obstacles dimension	Obstacles of different sizes can be present in both sectors.	✓
OCD-4	Obstacle type	Obstacles of different types can be present in both sectors.	✓
OCT-1	Initial trajectory planning	Not considered as part of the required automated driving capabilities in both automotive and railway sector. In any case, substantial differences are present since in the railways trains run according to a specific timetables and they have to respect the indications of movement authorities.	✗
OCT-2	Ongoing trajectory refinement	Both trains and cars require to refine their trajectories according to the localization and obstacle detection responses. In the specific, trains require only to adjust their speed (i.e. two-dimensional working area).	✗
OCV-1	Definition of actions to implement refined trajectory	Control action is required in both cases, but it is strictly related to specific driving characteristics of each environment and to the available information from sensors.	✗
OCV-2	Implementation of the control actions	Strictly dependent on the actuators that are available.	✗
OCV-3	Passengers management	In the automotive insights on this aspect are not provided in the literature, while in the railway sector is an actual matter.	✗
OCV-4	Definition of the level of automated driving	In both cases the level of automated driving is defined according to which operations are executed by the driver and which ones by the automated driving system. Different definitions of levels are	≈

provided in the automotive and in the railway sector. More detailed analysis is provided in the following.

Table 2.11 - Operation conditions comparison

2.4.3 Taxonomy and definitions of Levels of Automation and Grades of Automation: similarities and differences

In this section a comparison between the definitions of the Levels of Automation (LoA) and the GoAs is provided. In addition, the two approaches to the taxonomy and to the definitions are analysed to detect main similarities and differences. Firstly, the focus is devoted to which concepts of the automotive sector can find correspondences or differences in the ATO practices. Further analysis has been then performed considering the ATO requirements and principles currently defined with respect to what specified for the automotive sector.

The scope of this analysis is to constitute a first basis of information to be leveraged in the future for a possible knowledge transfer between the automotive and the railway sectors.

2.4.3.1 Definition of LoA and of GoA levels

Three main categories of levels can be identified in both automotive and railway sectors. These are:

- **No driving automation** with active protection systems (GoA1 and LoA0); in GoA1 the train is driven manually, but it is protected by the ATP system; this level can correspond to LoA0 in which the human driver performs the entire DTT, but active safety systems can be present and they can alert the human driver about possible dangers or they can directly intervene in case of a high risk event;
- **Partial automated driving systems** (GoA2-GoA3 and from LoA1 up to LoA4); not all operations are performed by the automated driving system or the human driver may or has to intervene and take back the control;
- **Fully automated driving systems** (GoA4 and LoA5); in both cases the automated driving system performs all driving related function without requiring the intervention of a human driver.

2.4.3.2 Matching of automated driving concepts in the automotive with respect to ATO definitions

The analysis focused on four automotive related concepts that have been considered as the most significant for the current scope of the analysis. These are:

- **Dynamic Driving Task**; it can correspond, as defined in the J3016 Recommended Practice, to “Driving”, “Supervising guideway” and “Operating a train” basic train functions. The functions of the Dynamic Driving Task of automotive sector differ from the basic functions of train operations, but the final purpose, which is to control the vehicle movements, is the same. Furthermore, the Dynamic Driving Task of the automotive takes only into account functions related to tactical and operational aspects, while ATO principles consider also performance and efficiency aspects;
- **Dynamic Driving Task fallback**; this concept can correspond to the requirements described in ATO Principle 9 “ATO Status and Failures” [5], in the specific to requirements specified in ATO 9.1 “Management of degraded operations”;
- **Driving Mode**; the definition of Driving Mode is not explicitly introduced in the railway sector; the Driving Mode is a specific type of vehicle operation that is characterized by some particular driving requirements; for example, in the automotive sector, driving modes can include *expressway merging*, *high-speed cruising*, *low-speed traffic jam*; similarly, possible driving modes of ATO can be high-speed line operations, station approaching or leaving; in the definition of ATO the requirements for several operations have been specified, but they have not been related to specific driving modes;
- **Operational Design Domain**; it is the definition of the conditions under which an automated driving system is designed to operate and this concept seems to not be used in ATO approach; it seems that

in ATO each GoA is defined to operate some specific functionalities in general and not considering just some specific conditions; in particular, the requirements of a GoA are not detailed for some specific driving modes.

2.4.3.3 Matching of ATO over ETCS requirements and principles with respect to automated driving taxonomy in the automotive sector

The ATO over ETCS requirements have been grouped in ten main ATO principles [5]. These principles have been analysed to detect if similar aspects have been identified also in the automotive sector. The comparison analysis is presented in Table 2.12.

ATO Principle	
ATO Principle 1 – <i>Performance and Energy Efficiency</i>	Performance, energy efficiency and related aspects are not explicitly detailed in the automotive sector as part of the functions to be implemented by the Dynamic Driving Task.
ATO Principle 2 – <i>Supervision and Regulation</i>	Not considered as part of the automated driving system in the automotive sector.
ATO Principle 3 – <i>Yards, Depots and Stabling Areas</i>	There is not a specific corresponding function in the automotive sector.
ATO Principle 4 – <i>Ensure safe movement of trains</i>	In ATO this operation is performed by centralized control system, while no control from a centralized entity is performed in the automotive sector; in the automotive each car is responsible for its own movement, road-side infrastructure can however provide information to each vehicle.
ATO Principle 5 – <i>Operate Train</i>	This ATO principle can correspond to the execution of the Dynamic Driving Task, as it is defined by the J3016 Recommended Practice, in the automotive sector; more functions seem to be required by ATO Principle 5 with respect to what it is expected to be performed in the Dynamic Driving Task.
ATO Principle 6 – <i>Control traction power</i>	The requirements of this ATO principle have not specific correspondences in the automotive sector.
ATO Principle 7 – <i>Supervise railway</i>	There are not specific similar requirements in the automated driving systems of the automotive sector.
ATO Principle 8 – <i>Supervise loading and unloading</i>	<p>The functions described by this ATO principle are not considered in the automotive sector as operations related to the automated driving system.</p> <p>The J3016 Recommended Practice focuses on all functionalities concerning the Dynamic Driving Task; also in the literature and in the research efforts most of the attention is devoted to the performance of the driving task and related actions, no major focus is provided to the vehicle departure or to the supervision of passengers, that are instead aspects well highlighted for what concerns the railway sector.</p>

<p>ATO Principle 9 – <i>ATO Status and Failures</i></p>	<p>The requirements of ATO Principle 9 are similar to the execution of DTT fallback in the automotive sector.</p>
<p>ATO Principle 10 – <i>Detection and Management of Emergency situations</i></p>	<p>It not considered in the automotive sector as operations related to the automated driving system. Automatic vehicle diagnostic for road vehicles are however already available.</p> <p>For what concerns the management of emergency situations, the automated driving system is not explicitly taking into account these features, however the eCall service [6] is expected to be shortly available in all cars for emergency situation calls.</p>

Table 2.12 – Comparison analysis between ATO principles and automated driving definitions in the automotive

3 Autonomous driving technologies for railway applications

In this work a **qualitative analysis** of which technologies, and related sensors, are the most suited to be employed in the railways has been performed. Today's sensors for autonomous driving technologies have been mainly designed for use in application fields different from railways. ***Their working characteristics and performance have been defined to meet the requirements of specific application sector, such as the automotive, the maritime and the avionics.*** A quantitative analysis of these sensors for their employment in the railways would not be fair for this reason.

For example, a RADAR-based detection system presents detection ranges that significantly vary depending on the application field. As detailed in the ASTRail deliverable D3.1 [RD.1], the RADARs employed in autonomous driving cars have ranges that are typically in the range of 100 to 200 m, while marine RADARs can have range up to 12 km.

If we consider for the technologies' evaluation the RADARs employed in the automotive sector, it is clear, due to inadequate performance, that these automotive sensors are not suited to be re-used in the railways. Instead, if we consider marine RADARs it seems that they could provide an adequate range performance for the railway needs.

However, marine RADARs can achieve this range performance in the maritime environment that, likely, do not present the same characteristics of the railway environment. It is necessary to develop RADARs that can provide the required range of performance but in the railway environment.

We decide to perform a qualitative evaluation of the technologies since, as shown in the above example, it is not possible to take as reference a precise sensor based on a given technology. This does not mean that in the evaluation we do not consider technical characteristics or parameters of the technologies. We evaluate the technologies taking into account the relevant technical characteristics and parameters of the technologies considering the performances that can be achievable by sensors developed for the various application fields. For example, the range performance of RADARs in the maritime field can suggest that RADAR technology may provide an adequate detection range for the railways needs.

The evaluation is performed considering several criteria that are detailed in Sect. 4.2. The relevant technical characteristics and parameters, which have been considered for the evaluation, are related to given criteria and they are specified for each respective criterion within Sect. 4.2.

Keeping in mind the aforementioned considerations, advantages and drawbacks of the autonomous driving technologies, which have been identified in the survey of the ASTRail deliverable D3.1 [RD.1], have been evaluated considering their potential application in the railway field. This evaluation has to consider the characteristics and the applications that are specific for the railway field. In this analysis functional similarities from the automotive and from other considered application sectors have been considered.

As outlined in the survey that has been provided in the ASTRail deliverable D3.1 [RD.1], the autonomous driving operations of trains mainly requires that trains regularly define their position and that they detect possible obstacles on the tracks or nearby. However, particular needs for positioning or obstacles detection can be present for some specific use case scenarios.

It is well known that metro lines have already adopted autonomous driving solutions, up to GoA 4, with many examples in Europe and all over the world [8]. There are numerous reasons why higher GoA levels are easier to implement in metro lines than in mainline railways. Table 3.1 shows a quick comparison that highlights the major complexity of a main line compared to a metro line.

Despite the greatest difficulties, the introduction of technologies for autonomous driving in mainlines would bring benefits, especially in terms of energy efficiency and savings and compliance with timetables. This work is focused on mainline railways, where the technology gap is more noticeable.

Metro	Mainline
Single Operator	Multiple Undertakings
Limited types of train	Different types of trains (interoperability needed)
Single vendor for signalling (trackside/on-board)	Multiple vendor for signalling
Closed infrastructure	Open infrastructure
Limited track layout	Not limited track layout

Table 3.1 – Metro vs Mainline complexity

The assessment of the suitability of the technologies for railways is based on their evaluation of satisfying specific requirements of ATO functions in the context of selected use cases of interest. The main current and foreseen ATO functions have been firstly identified and they have been matched to most relevant use cases. Analysing the application of the ATO functions to the selected use cases, specific requirements of the ATO functions have been identified.

Furthermore, in deliverable D3.1 [RD.1], the technologies were identified based on specific function categories (i.e. positioning, obstacle detection ...). In the following evaluation, the same approach will be used and ATO requirements will be analysed by category of functionality.

3.1 ATO functions

The main functions that could be ensured by ATO are identified in the following of this Section. The considered ATO functions are both the functions, which have been identified according to the current definition of ATO over ERTMS system [5], and the functions that could be implemented in ATO, while maintaining backward compatibility with the ERTMS system.

Railway is a complex system with numerous interfaces, the responsibilities and safety functions are allocated to diverse subsystems.

Concerning the ATO on board, which is the objective of the current analysis, main responsibilities are:

- To respect Journey profile;
- To adjust accelerations and braking;
- To receive and process the necessary data from external system;
- To stop at precise locations.

No safety function is assigned to ATO on-board, since the emergency braking is the responsibility of ATP system, Journey profile is defined by Transport Management system, routes are assured by Route Management System, functions related to signalling and train positioning are the responsibility of ERTMS.

This approach aims to comply with strict Railway requirements and to assure the backward compatibility with existing systems, so the relevant interfaces shall be considered.

ATO is primarily on-board system that requires trainborne interfaces to traction and braking systems, ETCS European Vital Computer (EVC) and DMI in the driving cab (for GoA2- GoA3).

On the other side, to be compliant with Interoperability specifications, ATO sensors installed on board (object of this deliverable) will require highly reliable interfaces to ATO control module that will perform the evaluation of information about the track clearance behind the train, in this case the evaluation of sensors information shall be done independently from ERTMS/ETCS functions. For this reason, no interface from the sensors to EVC is foreseen.

Regarding the ATO- EVC interface, the following harmonised rules for ATO over ETCS are under development:

- The ATO System Requirements Specification (SRS) (future Subset-125);
- The ATO Onboard solution shall be able to communicate with the ATO trackside using the ATO track/train interface specification (future Subset-126);
- The ATO Onboard solution shall include the ATO/ETCS Onboard Form Fit Functional Interface Specification (FFFIS) defined in future Subset-130.

For the trackside part, some additional fitting may be needed for correct ATO operation, due to the strict requirements for stopping precision (+/- 0,5m in main lines and +/- 10 cm in metros). These fitting could include additional balise groups or other passive sensors installed in stopping points proximities. These additional components also must be managed independently from ERTMS/ETCS system implementing own interfaces (e.g. by means of radio communications) to ATO system on board. The reliability of the interfaces shall be at least 99.99% depending on the required safety and availability level.

Regarding the ATO control functionalities, an example of a new ATO function can be the start of the mission of a train (GoA3- GoA4). Indeed, a train at the start up is not aware of its position and it is not yet protected by the ETCS system. Currently, a human driver has to navigate until the train goes over a physical balise, which provides the required position information to the on-board module, so the ETCS system is activated.

Table 3.2 lists the main functions that ATO can implement in the framework of the ETCS system. Each function can be related to control, object detection and positioning aspects. The functions related to control are introduced for sake of completeness, but they will not be considered during the technologies evaluation since the scope of this activity is to identify technological solutions that can be reused from the automotive sector. Due to the intrinsic peculiarities of control functions, no reuse can be foreseen and for this reason these functions will not be further considered.

The ATO functions concerning positioning aspects are strictly related to high-precision positioning, such as the stopping of the train at the station. The general positioning of the train is assumed to be provided to the ATO system by the ETCS system whose scope is to determine the train position and ensure the compliance of the train movements. This is a main difference with respect to the automotive sector in which automated driving systems are expected to take care of vehicles' positioning aspects.

Function ID	Description	Commentaries	Type
F1	<i>Acquire (receive or request) the necessary data from externally interfaced systems</i>	This data includes, but not limited to: train positioning, Segment Profile, Journey Profile, train data and train running number.	<i>Control</i>
F2	<i>Comply with Journey Profile timing</i>	To respect provided by trackside data (arrival time, dwell time, departure time).	<i>Control</i>
F3	<i>Control the deceleration to stop at required position without emergency breaking</i>	Taking into account the compliance to the Journey Profile, a train should comfortably slow down while entering the station until the complete stop at the expected position.	<i>Control</i>
F4	<i>Precise train localization</i>	The precise positioning function can concern train doors opening or for initial train localization at the train start up. For example, the train doors opening shall match with precision (< 10 cm) the platform doors opening.	<i>Positioning</i>
F5	<i>Calibration of the odometry</i>	Odometry needs to be calibrated to avoid positioning errors. Different calibration methods will be evaluated as well as other relative positioning methods that can complement the odometry.	<i>Control, positioning</i>

F6	<i>Detection of unexpected obstacles on track</i>	Obstacles can be fixed or moving (i.e. people, animals ...), this function is significantly influenced by specific situations characteristics (e.g., speed of the trains, likelihood of the presence of people ...).	<i>Detection</i>
F7	<i>Manage interfaces to external systems</i>	Platform doors, loading system for freight trains, passenger information, surveillance system, alarms.	<i>Control</i>
F8	<i>Detect the next safe location to stop</i>	In case of receiving an alarm from passenger device on-board. The safe location has to avoid ERTMS non-stopping areas.	<i>Control, positioning</i>
F9	<i>Doors opening/closing</i>	Automatic management of opening and closing of vehicle doors.	<i>Control</i>
F10	<i>Trackside detection signals</i>	Detection of signals when running at sight.	<i>Detection</i>

Table 3.2 – ATO main functions

3.2 Use cases in railway applications

The identification of specific requirements of ATO functions for railway applications was performed considering possible use cases of interest. In the remaining of this section the selected use cases are described and the main ATO functions required for each use case are identified.

The ATO functions can be related to *control*, *positioning* and *detection* aspects. Functions related to the two latter aspects are the focus of this work. The technologies, which will be considered in the evaluation, are indeed related to positioning and obstacles detection functionalities. The positioning and detection functions, which will be considered as basis for the requirements identification, are highlighted using *italics* in the following of this section.

3.2.1 List of use cases

Selected use cases for ATO implementation are presented in the following.

3.2.1.1 Plain line running

The “*Plain line running*” is a general use case in which the train is moving along the line. This scenario is applicable in the sections between stations where no level crossings are present. In this use case a main ATO function is to comply with Journey Profile assigned by trackside through the calculation of the ATO Operational Speed Profile.

The main criticality to be considered is the case when the track segment is not protected against the presence of unexpected obstacles (person, animals, fallen rocks or equipment, etc.). Emergency braking in front of unexpected obstacles implies the recognition of such obstacles, in particular it is essential to distinguish real obstacles from not relevant ones.

ATO functions to be implemented are:

- F1, Acquire the necessary data from externally interfaced systems;
- F2, Comply with Journey Profile timing;
- *F6, Detection of unexpected obstacles on track (check of clearance);*
- *F8, Detect the next safe location to stop.*

3.2.1.2 Approaching a station

The use case “*Approaching a station*” refers to the situation in which a train is arriving at a station where it stops. The Journey Profile received by ATO will include the Stopping Points (position, arrival time, dwell time, departure time). In this use case the train is required to stop in a specific and accurate position. Furthermore, the presence of people on tracks or too close to the tracks is more likely with respect to other tracks’ segments. The train has to detect people in dangerous positions and take proper actions to minimize risks. This case also includes track buffer stop approaching and precise dock approach.

ATO functions to be implemented are:

- F1, Acquire the necessary data from externally interfaced systems;
- F2, Comply with Journey Profile timing;
- F3, Control the deceleration to stop at required position without emergency braking;
- *F4, Precise train localization;*
- *F5, Calibration of the odometry;*
- *F6, Detection of unexpected obstacles on track;*
- F7, Manage interfaces to external systems.

3.2.1.3 Leaving a station

The use case “*Leaving a station*” assumes that doors are already closed in passengers train and that loading operations are terminated in case of freight trains. Main function required is the detection of people in dangerous positions. Indeed, similarly to the “*Approaching a station*” use case, there is a higher possibility that people are not in safe positions in the surrounding of a station.

ATO functions to be implemented are:

- F1, Acquire the necessary data from externally interfaced systems;
- F2, Comply with Journey Profile timing;
- *F6, Detection of unexpected obstacles on track;*
- F7, Manage interfaces to external systems.

3.2.1.4 Supervision of loading and unloading

Passengers’ safety supervision on platforms includes the interface with surveillance system. Passengers’ supervision is needed for doors closing automation.

ATO functions to be implemented are:

- F7, Manage interfaces to external systems (surveillance systems, passengers information systems);
- F9, Doors opening/closing.

3.2.1.5 Level crossing

The necessary protection of the level crossing should be performed by safety related system external to ATO (e.g. interlocking). Indeed, the interlocking functions are responsible for a safe overrunning of level crossing: a train is not allowed to move toward a level crossing that is not “closed”.

ATO has to manage security hazards such as vandalism, unexpected behaviours of users of the level crossing and other rules violation. The presence of people, cars or other vehicles on tracks or too close to tracks is

indeed possible even in the case of protected level crossing. ATO function to check if any obstacle is present in a dangerous position is then required.

The overrunning of an **unprotected** Level Crossing (not supervised by interlocking) must always be managed by the driver in GoA2 and the requirements are similar to the “*Running at sight*” use case that is introduced in the following of this Section. For the unprotected level crossing the ATO function “Trackside signals detection” (F10) is then required. Further details about this function are provided in the “*Running at sight*” use case.

ATO functions to be implemented are:

- F3, Control the deceleration to stop at required position without emergency braking;
- F6, *Detection of unexpected obstacles on track*;
- F7, Manage interfaces to external systems;
- F10, *Trackside signals detection*.

3.2.1.6 *Shunting and other special operations*

This scenario concerns train forming and operations at yards, depots and stabling areas according to Journey profile. Train's operation to move the train in and out of the depot, that can be implemented using ATO functions, can be also included in this case. Main requirements are related to people safety and clearance check.

ATO functions to be implemented are:

- F1, Acquire the necessary data from externally interfaced systems;
- F6, *Detection of unexpected obstacles on track*;
- F7, Manage interfaces to external systems;
- F10, *Trackside signals detection*.

3.2.1.7 *Management of emergency situations*

The ATO is required, starting from GoA3, to react to possible alarms detected and manage passenger requests. In particular, ATO should be able to manage emergency situations and perform proper actions, such as stop the train in the most suitable location to minimize risks.

ATO functions to be implemented are:

- F7, Manage interfaces to external systems;
- F8, *Detect the next safe location to stop*.

3.2.1.8 *ERTMS equipped train start-up*

ATO and even ERTMS could benefit of an automatic first localisation of trains at start up. ERTMS system cannot be enabled until the train overrun a first ETCS balise. In this situation running at sight operation is needed and manual localization of the train is required. The ATO can replace the driver implementing the required functions to drive the train until the train overrun the first ETCS balise.

ATO functions to be implemented are:

- F4, Precise train localization;
- F6, *Detection of unexpected obstacles on track*;
- F7, Manage interfaces to external systems;

- *F10, Trackside signals detection.*

3.2.1.9 Running at sight

The “*Running at sight*” use case refers to all the situations in which the driver must rely solely on his capabilities, without the aid of dedicated protection systems. The driver has thus the complete responsibility to drive the train. Examples of these situations are ERTMS shunting mode, ETCS override, signals passed at danger and unprotected level crossing overrun. Particular safety responsibilities of the driver are to check that the tracks are clear, not to damage people or other objects and to check the switching points’ status. ATO should help the driver to manage required manual operations.

ATO functions to be implemented are:

- F1, Acquire the necessary data from externally interfaced systems;
- *F6, Detection of unexpected obstacles on track;*
- F7, Manage interfaces to external systems;
- *F10, Trackside signals detection (switching point ground signals in particular).*

3.2.1.10 Vehicles joining / splitting

The train forming operations may rely on automatic couplers requiring that the vehicles speed falls in a well-defined range. These operations may be performed within the ATO framework.

ATO functions to be implemented are:

- F3, Control the deceleration to stop at required position without emergency breaking;
- *F4, Precise train localization;*
- *F5, Calibration of the odometry;*
- *F6, Detection of unexpected obstacles on track.*

3.2.2 Railways use cases and ATO functions

Table 3.3 provides the resume of the selected railways use cases and of the corresponding required ATO functions to be implemented for each use case.

The columns of the table concerning ATO functions related to positioning and detection functionalities are highlighted in the table and specifically they are:

- *F4, Precise train localization;*
- *F5, Calibration of the odometry;*
- *F6, Detection of unexpected obstacles on track;*
- *F8, Detect the next safe location to stop;*
- *F10, Trackside signals detection.*

In the next Section 3.3, these ATO functions are analysed with respect to the selected use cases in order to identify specific requirements of the ATO functions that arise when applying these ATO functions to a given use case. These requirements of the ATO functions will then be used in the Section 4 for assessing the suitability in the railway domain of the autonomous driving technologies that are currently in use in the automotive sector.

Use cases	ATO Functions									
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Plain line running	x	x				x		x		
Approaching a station	x	x	x	x	x	x	x			
Leaving a station	x	x				x	x			
Supervision of loading and unloading							x		x	
Level crossing			x			x	x			x
Shunting and other special operations	x					x	x			x
Management of emergency situations							x	x		
ERTMS equipped train start-up				x		x	x			x
Running at sight	x					x	x			x
Vehicles joining / splitting			x	x	x	x				

Table 3.3 – Railways use cases and ATO functions

3.3 Requirements of ATO functions

The evaluation of the selected autonomous driving technologies from the automotive sector will be performed considering specific requirements that the ATO functions should sustain. In this section the requirements for each of the selected ATO functions are resumed in Table 3.4.

The requirements are derived evaluating what the scopes of ATO functions are and considering the previously introduced railway use cases.

The “*Precise train localization*” function needs to provide accurate train positioning for stopping operations in the “*Approaching a station*” use case. Indeed, the precise positioning in this case concerns the interface between platform doors and train doors. The train doors opening should match with precision (i.e. less than 10 cm) the platform doors opening. In case of mismatching the doors will not be opened. Similar accuracy in train positioning is also required in “*Vehicles joining / splitting*” since joining/splitting operations require to exactly know where vehicles are. These use cases highlight then the need to the ATO function of achieving a centimetre-level accuracy for specific operations.

Other requirements of the “*Precise train localization*” ATO function can be further envisaged. Indeed in the “*ERTMS equipped train start-up*” use case the train is not aware of its position and it needs to understand where it is located, in particular it requires to discriminate the track where it is. This results in the requirement of localizing the train at the start up.

The ATO function “*Calibration of the odometry*” involves two main requirements. The first is to use one or more **absolute** localization methods to calibrate the odometry. The second requirement concerns the possibility to exploit other **relative** localization methods to complement the odometry for achieving an improved system performance.

Several requirements can be identified by “*Detection of unexpected obstacles on track*” function. In this case requirements are characterized considering

- the **type of obstacles**, i.e. moving or fixed ones;
- the **size of obstacles** to be detected;
- the **detection distance** at which the obstacles are required to be detected, the distance is strictly correlated to the speed and to the vehicles characteristics such as the size, the weight and the configuration of the trains;
- the **area where obstacles may be**, i.e. along the line or in specific areas such as stations.

These distinctions are also made to better evaluate the technologies for obstacles detection. Indeed, according to type, the size of the obstacles and the detection area, a technology may perform differently. First requirement regards the identification of fixed obstacle on tracks. This requirement mainly applies to “*Plain line running*” use case.

Distinction between fixed and moving obstacles has been made since moving obstacles present typically size and behaviour features different from fixed obstacles. The size of the obstacles can significantly vary depending on the type of the obstacles. We differentiate the obstacles in **moving** and **fixed** obstacles in order to take into account the size aspect. These aspects are reflected in the following use cases *detection of fixed obstacles on tracks*, *detection of moving obstacles along the line* and *detection of moving obstacles at stations, level crossing, yards and other special areas*. We consider as fixed obstacles any object whose size can represent a danger for the train (it is not in the scope of this document to define a danger threshold size), while we consider as size for moving obstacles those of people and large animals as moving obstacles to be detected.

Furthermore, the size of an obstacle has to be related to the distance at which the obstacle has to be detected in such a way that the train can safely stop.

The detection distance is strictly related to the braking distance which in turn strictly depends to the train size, train type and weight. Here we can assume that the weight range between the different train types is not so relevant when considering the braking distance. A simple kinematic formula, which in turn only takes into account the deceleration parameter, can be used to estimate the braking distance without going into the details of the weight of the train. As a mean estimation, the most suitable value for the applied deceleration is 1 m/s^2 . With this assumption, we can consider the following values for different braking distances at specific speed:

- At 80 km/h a complete stop requires 250 m;
- At 120 km/h a complete stop requires 550 m;
- At 200 km/h a complete stop requires 1500 m.

The obstacle location (i.e. the area where obstacles may be) defines the requirements: *detection of moving obstacles at stations, level crossing, yards and other special areas*. The latter requirement has been introduced since **the presence of people on or too close to the tracks** is more likely in these areas. Furthermore, these areas are constrained in space and this feature may enhance the performance of specific technological detection solutions with also the potential adoption of track-side detection system.

An additional requirement of the obstacle detection function concerns the presence of **road vehicles** (e.g., cars, trucks ...) on or too close to tracks at level crossings. Specific requirements have been inserted for the detection of these types of obstacles since the detection of road vehicles can be eased by innovative technological solutions based on the Intelligent Transport System framework in which all transport vehicles are part of a connected and smart management system.

The use case “*Management of emergency situations*” highlights the need of finding **the best location for a stopping area**. This requirement does not aim to identify which characteristics this location should have or any related decision making aspects. This requirement takes into account the need of the ATO function to be able to perceive the surrounding environment and to identify enough environment features that can allow the ATO function to perform the decision.

The last ATO function that we consider is “*Trackside signals detection*”. It has been envisaged for the cases in which the train does not rely on external protection systems during specific driving operations, such as it can happen for unprotected level crossing, ERTMS equipped train start up, running at sight and shunting. This function requires, as the name suggests, to be able to **recognize traffic lights and other signals**.

ID	Requirements of ATO functions	Notes
F4	F4 – Precise train localization	
F4-1	Localization of train for precise stopping in stations, yards or other special area	Need to determine position with centimetre-level accuracy

ID	Requirements of ATO functions	Notes
F4-2	<i>Train localization at the start up</i>	Required in particular to be able to discriminate the track
F5	Calibration of the odometry	
F5-1	<i>Localization methods to calibrate the odometry</i>	Correct error introduced by odometry or improve odometry performance
F6	Detection of unexpected obstacles on track	
F6-1	<i>Detection of fixed obstacles on tracks</i>	This requirement refers to the detection of generic fixed obstacle present on tracks
F6-2	<i>Detection of moving obstacles (i.e. people or animals) along the line</i>	Detection not constrained to a specific area but all along the tracks and devoted to moving obstacles
F6-3	<i>Detection of moving obstacles at stations, level crossing, yards or other special area during shunting and other specific operations</i>	Devoted to a specific area and to moving obstacles
F6-4	<i>Detection of cars and other vehicles at level crossing</i>	Specific requirement due to peculiarity of obstacles and area
F8	Detect the next safe location to stop	
F8-1	<i>Detection of safe location stopping area</i>	Not possible to define a priori all possible safe location stopping areas
F10	Trackside signals detection	
F10-1	<i>Signals recognition</i>	Recognition of traffic lights and of other signals to manage particular situations not covered by ETCS

Table 3.4 – Requirements of ATO functions.

3.4 Technologies resume for automated driving systems

The ASTRail deliverable D3.1 “*State of the Art of Automated Driving technologies*” [RD.1] aimed to identify **which technologies and related sensors are currently employed or they are being developed to be employed** in automated driving systems. The deliverable D3.1 surveyed the automotive sector and other application fields, such as the maritime, the avionics, the agriculture and the industrial environment, to find which technological solutions are exploited in these sectors.

The survey focused on the technological solutions for the “*Navigation*” functionality, which concerns the provision of vehicle motion information (e.g., speed, heading, acceleration ...) and of information related to the driving environment (e.g., other vehicles, people, potential obstacles ...). Control algorithms have not been considered in the survey since all control aspects are strictly related to the vehicle’s characteristics. Consequently, it is unlikely to leverage knowledge regarding control practices from other application sectors.

In the remaining of this section a brief resume of the technological solutions identified in D3.1 is introduced. The identified technologies and related sensors **implement the localization and perception functionalities** required by automated driving systems. This set of technologies has then been evaluated for possible reuse in the railway sector.

3.4.1 Localization technologies

The technologies concerning the vehicle’s localization can be classified in two main categories: **absolute localization** and **relative localization**. In the first one the position of the vehicle is provided within a global reference frame, while in the latter the vehicle’s position is provided in an incremental way considering the

measured motion of the vehicle. The vehicle's localization is typically based on several localization technologies, both absolute and relative ones.

The set of localization technologies identified in ASTRail D3.1 are resumed in Table 3.5.

Localization method	Type of method	Type of localization	Note
GNSS	Beacons-based	<i>Absolute</i>	Most common localization method. Several GNSS systems are available (e.g., GPS, Galileo, GLONASS ...). Advanced systems, such as Differential GPS (DGPS) or Real-Time Kinematic GPS (RTK-GPS), can be characterized by higher accuracy.
Mobile Positioning Systems	Beacons-based	<i>Absolute</i>	Exploit wireless communication technologies. Determine location using ranging techniques based on time propagation (e.g., Time of Arrival or Time of Flight).
Artificial landmarks	Landmarks-based	<i>Absolute (Relative)</i>	Artificial landmarks installed specifically for the positioning of the vehicle. Vehicle requires to be able to recognize landmarks (typically using RADARs, LiDARs or visual cameras) and to know their absolute position. This method can be also classified as relative if landmarks are used to define a relative position such as the case of lane detection in the automotive sector where road markings are exploited for vehicle relative localization.
Natural landmarks	Landmarks-based	<i>Absolute</i>	Similar concept to artificial landmarks. Natural landmarks are likely more difficult to be identified since already present in the environment and not expressly designed for easing the recognition.
Maps	Map-based	<i>Absolute</i>	Vehicle senses the surrounding environment using visual cameras, LiDARs or RADARs and compare the gathered information with a global map. Enough accurate map of the navigation environment is required.
Wheel Odometry	Dead Reckoning	<i>Relative</i>	Estimate the movement of a wheeled vehicle counting the number of revolutions of the wheels. Not accurate on long time periods and periodic absolute position correction is required.
Inertial navigation	Dead Reckoning	<i>Relative</i>	Inertial forces, such as acceleration and angular velocity, can be exploited to determine speed, direction and movement of the vehicle. Not affected by characteristics of the driving surface.
Doppler RADAR	Dead Reckoning	<i>Relative</i>	Estimate the movement of the vehicle using the Doppler Effect that consists in a shift in the frequency when radiated energy reflects on a surface that is moving with respect to the emitter.
Visual odometry	Visual-based	<i>Relative</i>	Motion of the vehicle is estimated using image processing techniques. Estimation performed analysing consecutive video frames to identify matches and determine relative movements.
Simultaneous Localization And Mapping	Map-based	<i>Relative</i>	Vehicle builds a map of the environment while navigating and it uses the built map for positioning. No map or landmarks are known to the vehicle.

Localization method	Type of method	Type of localization	Note
Wireless cooperative positioning	Wireless communication-based	<i>Absolute</i>	Similar to Mobile Positioning Systems, but not based on fixed infrastructure. Exploit position knowledge of other vehicles and ranging techniques.

Table 3.5 – Localization technologies identified in ASTRail deliverable D3.1 [RD.1].

3.4.2 Perception technologies for obstacle detection

The perception technologies are used to sense the environment in the surrounding of the vehicle. The main task is to **identify all objects that can be an obstacle for the vehicle**. Several algorithms for obstacles detection have been proposed in the literature and they are strictly correlated to the features of sensors that are employed for gathering information from the environment. In this work the evaluation will focus on the technologies, on which sensors are based, and on the related characteristics.

Two main categories of sensors can be identified: **passive** and **active** sensors. Passive sensors exploit the energy (i.e., mainly light) already present in the environment to gather the information, while active sensors illuminate the environment and detect the reflected energy to acquire information. Several different types of passive sensors and of active sensors are available.

Other possible method to identify obstacles is to rely on the communications among vehicles and between vehicle and the road-side infrastructure. Each vehicle can broadcast information about the position, speed and future trajectory to inform other vehicles and prevents possible collisions. Furthermore, identified dangers can be broadcasted as well to alert all road actors.

A list of the sensors identified in the survey of D3.1 is presented in Table 3.6. Main characteristics of each sensor are briefly introduced. A more detailed analysis of the different sensors is available in D3.1. Each type of sensor is indeed characterized by specific performance. In particular, weather and light conditions have a significant impact on the achievable performance.

Perception sensor	Type of sensor	Note
RADAR	<i>Active</i>	Based on emission of radio waves and exploiting the Doppler Effect. Not significantly affected by weather conditions and light. Performance can be affected by the presence of objects characterized by low reflectiveness to radio waves.
LiDAR	<i>Active</i>	Exploiting light emission. Bad weather conditions and sunlight may impact on the performance. It can achieve an accurate three-dimensional representation of the environment that can be better than those achieved by RADARs.
SONAR	<i>Active</i>	Based on sound propagation, typically on the emission of ultrasonic waves. Used for short range applications such as parking manoeuvres.
Infrared-equipped visual camera	<i>Active</i>	Visual camera equipped with an infrared dots projector that can improve the distance estimation of traditional passive cameras.
Monocular camera	<i>Passive</i>	Typically the less expensive cameras, but they gather only two-dimensional data. Three-dimensional representation of the environment can be reconstructed but requiring high computational power.

Perception sensor	Type of sensor	Note
Stereo camera	<i>Passive</i>	More expensive but three-dimensional representation is easier to be reproduced since these cameras are based on the same principle of human vision.
Omnidirectional camera	<i>Passive</i>	Characterized by a 360-degree field of view in the horizontal plane. Provide a very accurate three-dimensional environment representation.
Infrared camera	<i>Passive</i>	Detect infrared radiations. Used for the effectiveness of recognizing people and animal during night or low lighting conditions.
Wireless communication	<i>Cooperative</i>	Vehicle-to-vehicle and vehicle-to-infrastructure can be exploited to share information about potential obstacles and dangers. Vehicles can broadcast their position and expected trajectory to inform nearby vehicles and prevent collisions.

Table 3.6 – Technological solutions for perception identified in ASTRail deliverable D3.1.

3.4.3 Multi-sensors data fusion

The approach of multi-sensors data fusion is typically exploited in automated driving systems for both localization and perception functions. This approach consists in not relying on only one specific technology for a specific functionality, such as the vehicle's localization, but to gather information from several different sensors and then fuse together the gathered information to improve accuracy, availability and reliability of the given function. For example, always referring to road vehicle's localization function, the position of the vehicle is obtained exploiting positioning information from GNSS systems (GPS, Galileo, GLONASS ...), from dead reckoning methods (odometry, inertial navigation sensors ...) and from visual-based methods (maps, artificial landmarks for lane recognition, visual odometry ...).

The need to use a multi-sensors data fusion approach is that each technology, and thus each sensor, presents advantages and drawbacks. The data fusion allows to enhance the overall performance mitigating the weaknesses of sensors and exploiting their strengths. The concepts on which multi-sensors data fusion is based on are indeed the *redundancy* (several sensors are better than few), *complementary* (each sensor collects information in a different way and with different characteristics) and *cooperativeness* (different sensors can complement the performance of each other).

In Section 4 the set of suitable technologies for satisfying a specific requirement of ATO function will be identified. This set will be analysed also from a data fusion perspective. The aim is to provide a high-level overview of the strengths and weaknesses of a potential system based on the identified suitable technologies.

4 Reusability assessment of the selected technologies

The evaluation of an automated driving technology for reuse in the railway sector needs to take into account several different features related to performances, requirements and operational aspects. **A straightforward evaluation is not easy since all the aspects to consider are not strictly related to each other and they may have a different relevance in the final evaluation.**

A possible approach to a fair and complete evaluation is to use a Multi-Criteria Decision Making (MCDM) method [9]. Several of these methods have been introduced in the literature so far. Other overviews of these methods can be found also in [10] and in [11].

The common characteristic of these methods is that the decision is based on a set of criteria, which may also be conflicting, that are defined considering the specific application area. In particular, these criteria can be evaluated considering only a qualitative approach and they do not require precise quantitative information. Each MCDM method differs instead on the procedures to be followed to achieve the final decision.

The MCDM methods have been judged to be the more appropriate for the evaluation of autonomous driving technologies. In the current work the Weighted Sum Model (WSM) method has been selected for the evaluation of the most suited automated driving technologies to be reused in the railways. In Section 4.1 a brief overview of this method is provided.

4.1 Weighted Sum Model method

The WSM method will be used for the **evaluation of the autonomous driving technologies with respect to the specific requirements of ATO functions** that have been introduced in Section 3.3. This method is appropriate for the decision-making process when several factors have to be considered. These factors can be objective or numerically defined as well as subjective or qualitative.

In details, the WSM method can be applied to all cases in which, being defined m alternatives and n criteria, it is possible to assign a weight to each of the n criteria and to score each alternative considering the n criteria. The overall WDM score of alternative k can be computed as follows [12]:

$$WSM - score_k = \sum_{h=1}^n w_h \cdot s_{kh}$$

where w_h is the value of the weight of the h criterion and s_{kh} is the score of the alternative k with respect to criterion h . The best alternative among the m available will be the one that maximizes the *WSM-score*.

This model is based on the additive utility assumption [9], [12]. This assumption implies that the overall score of a given alternative is equal to the sum of the products of the score of each criterion times the weight of that criterion. This is valid if all criteria have the same units or if they are dimensionless quantities. In case that more dimensions are used for the criteria, the WSM method needs to take this into account.

The WSM method, as other MCDM methods, consists in main three principal phases:

- *Identification of the alternatives and of the criteria*, in this specific case, the alternatives are the autonomous driving technologies to be evaluated that are those identified in ASTRail deliverable D3.1 and resumed in Section 3.4, criteria are introduced in Section 4.2;
- *Criteria weighting*; this step consists in assigning the weights to all the criteria, the way adopted to meaningfully assign the weights in this work is explained in Section 4.2;
- *Rating of the alternatives*; this concerns the assignment of the score to an alternative for each of the n criteria, the score assignment for the autonomous driving technologies is introduced in Section 4.4.

In this work, the evaluation of the autonomous driving technologies will be performed for each of the requirements of the ATO functions that have been introduced in Section 3.3.

4.2 Criteria to be used for the evaluation

The criteria that have been selected are generic criteria that have been used for the assessment of any of the technology under evaluation for each of the considered requirement of ATO functions. However, for each requirement of ATO functions, each criterion has to consider different aspects, features, technical characteristics and parameters.

As anticipated in Sect. 3, a qualitative assessment is the target of the evaluation of each technology. For each criterion, technical characteristics and parameters of sensors, which have been developed for other application fields, have been taken into consideration for the evaluation.

In the following of this Section, the criteria are introduced and for each of them the relevant technical characteristics and parameters, which have been considered, are specified. Eventually, the rationale for the selection of these criteria for the evaluation is also explained.

Some of the parameters are related to the potential of the technology to be compliant with Railway RAM requirements. RAM (Reliability, Availability, Maintainability) addresses the specifications and standards that manufacturers and operators have to meet to comply with operational railway objectives.

Currently, the RAM targets are referred to operational availability and average allowed service delay. In this sense, ATO must not worsen the overall performance of the system:

- The ERTMS/ETCS quantifiable contribution to operational availability, due to hardware failures and transmission errors, shall be not less than 0.99984;
- The probability of having delay caused by ERTMS/ETCS failures shall be not greater than 0.0027;
- The allowed average delay per train due to ERTMS/ETCS failures, at the end of an average trip of duration of 90 min., shall be not greater than 10 min;
- The downtime requirements are defined in terms of the allowed mean downtimes ($DT = (1 - A_o) \times 8760$) shall not be greater than 1.40 hours/year.

4.2.1 Maturity

This criterion assesses the level of technology maturity and readiness of the considered technological solution within the other application fields that have been considered. It reflects if a given technology has been introduced since long time into the market of a given application field and if its development permitted to achieve a mature state or if it is a new technology that is still in a developing phase and not fully achieving its potential performance.

Parameters that have been into account to qualitatively evaluate the maturity of each technology have been the number of years since the introduction in the market of sensors based on a given technology, the number of application fields that this technology has been employed and the widespread of use of this technology in the application fields in which it has been employed.

The maturity is a highly important property for the application on field; however, for the present analysis, it is not fundamental due to the low TRL level of present research activity. The technology readiness for the ATO application can evolve in parallel with the evolution of the selected technology.

4.2.2 Accuracy

The accuracy reflects the qualitative evaluation of the effectiveness of a given technology to satisfy the function requirement. For each of the considered ATO functions, specific parameters have been identified. In details, the localization accuracy has been considered for ATO functions F4 "*Precise train localization*" and F5 "*Calibration of the odometry*". The accuracy for ATO function F6 "*Detection of unexpected obstacles on track*" refers both to the correct identification of the obstacles and on their positioning. Similarly, for ATO functions F8 "*Detect the next safe location to stop*" and F10 "*Trackside signals detection*" the accuracy refers both to the correct identification of safe location area or of trackside signals and to their precise localization. These parameters have been qualitatively evaluated considering the technical performances of sensors employed in other application fields.

It is considered highly important criterion since it characterizes how a given technology can be effective to satisfy a specific requirement (e.g. precise positioning, precise detection) of each scenario.

4.2.3 Reliability

This criterion evaluates the probability that a given technology can effectively sustain the required function over time, in particular it is an evaluation of the strength of the technological solution to operate in degraded operation conditions and to resist to accidental or deliberated interferences. For example, considering ATO function F6 “*Detection of unexpected obstacles on track*”, the evaluation considers if a given detection technology can well perform even in adverse weather conditions.

The reliability of the selected technologies has been evaluated considering the technical characteristics and the performances of their sensors when employed in other application fields.

This criterion is highly important due to strict Railway requirements.

4.2.4 Availability

The availability criterion refers to the probability that a given technological solution can properly operate considering overall operation conditions and specific function requirements. For example, considering “*Precise train localization*”, this criterion evaluates if a technology is always available or if there are some locations, such as tunnels, where a given positioning technology is not available.

The availability of the selected technologies has been evaluated considering the technical characteristics and the performances of their sensors when employed in other application fields.

This criterion is highly important due to strict Railway requirements.

4.2.5 Maintainability

This criterion assesses the effort required to maintain operative a given technological solution considering both deploying and maintenance aspects. It considers both accidental and voluntary damages that may occur to the implemented solutions considering the peculiarity of the railways environment.

The maintainability of the selected technologies has been evaluated considering the technical characteristics of their sensors when employed in other application fields.

This criterion is highly important due to strict Railway requirements.

4.2.6 Cost

The cost evaluates the expensiveness of a given technology with respect to other considered technologies when implemented in other application fields.

The cost represents an important aspect of the deployment phase of the solution, however, at this stage, it is more important to find technologies that can satisfy the function requirements, in particular considering those aspects that are evaluated by precision, reliability and availability criteria.

4.2.7 Energy consumption

This criterion represents a qualitative assessment of the consumed energy by a given technology.

The energy consumption of the selected technologies has been evaluated considering the technical characteristics and the performances of their sensors when employed in other application fields.

As for the cost criterion, at this stage it is more important to find technologies that can satisfy the function requirements.

4.2.8 Suitability to specific function requirement

This criterion reflects a qualitative estimation of the suitability of a technology to effectively satisfy peculiarities of the requirements of the ATO functions. Indeed, each requirement may present some specific characteristics

that can represent an issue for some technologies, while other technologies can well deal with these characteristics without representing an issue for them.

The technological characteristics and the performance of sensors based on the selected technologies have been exploited for qualitatively evaluate the suitability of a given technological solution to address a given requirement.

4.3 Scores assignment

The values of the weights of the criteria and the scores to the requirements of the ATO functions for all the criteria were attributed using a collaborative approach inspired by [13] that is known as **experts judgment**. This method implies that a group of experts individually assigns the values of the scores and weights. The experts judgment method is widely applied to different sectors and it can be used either for quantitative or qualitative and comparative evaluations [14].

The group of experts was formed by the involved ASTRail partners (i.e. ISMB, SIRTl, ARD) that are railway or automotive technologies experts. The experts performed independently the evaluation and the results have been averaged to achieve a meaningful, objective and fair evaluation. The experts involved had different technical expertise due to different education and work activities and for this reason it was considered correct not to attribute different priorities when making the average contributions.

It is foreseen the possibility to update the weights and scores assignment with the contribution of experts participating in the complementary S2R projects and in the ASTRail Advisory Board.

The values of the weights can be either 1, 2 or 3, where 1 is low relevance/importance, 2 is medium relevance/importance while 3 is a high relevance/importance.

The scores to the technologies are based on a scale of 3. In the specific, a score of 1 means low rate, a score of 2 is an average rate and 3 is a high rate. Following guidelines have considered by the experts during the assessment:

- A score of 1 for a given technology means that sensors based on this technology can provide a scarce performance for a specific criterion for the considered ATO function's requirement and, thus, it is not suggested their employment. Only a significant improvement of the performance of this sensors' technology may lead to provide adequate performance for the employment of this technology in the railways;
- A score of 2 means that it is likely that sensors of a given technology can provide adequate performance, in relation to the considered criterion and the function requirement, in case that a proper development of these sensors, taking into account the peculiarities of the railway domain, is performed;
- A score of 3 indicates that the sensors based on this technology presents technical characteristics that make them very suitable to well satisfy the considered criterion; this means that a development of sensors based in this technology for the railway domain can bring to have a category of sensors that may optimally address the examined requirement for the considered criterion.

A specific technology can be not applicable to a given function requirement due to technical limitations that impairs the capability of this technology to satisfy the requirement. In this case, this technology is not evaluated for the considered requirement (i.e., score is 0 for all criteria). Indeed, not all technologies can be used to satisfy each requirement, but just a subset of them may be employed. For example, SONAR based sensors can be scarcely applicable in the railways due to their limited range of few meters. The selection of not applicable technologies for each requirements has been agreed among the experts before the independent technologies evaluation.

This choice has been done since, as explained in the introduction of Section 3, a qualitative evaluation of the technologies is feasible, while a quantitative evaluation is hardly to be done since not enough quantitative information about sensors is available for the railway sector. However, the qualitative evaluation is performed considering the technical characteristics, parameters and performance of the sensors, based on the selected

technologies, when they are developed for other application fields, such as the automotive, the maritime or the avionics sectors.

The final score of a given technology for a specific ATO function requirement corresponds to the overall WSM score that can be computed as explained in Section 4.1.

A **normalized score** is also provided where the normalization is performed considering the maximum score achievable by a given technology (i.e. the technology has a score of 3 for all the criteria). The normalized score has been introduced in order to give an order of suitability to the technologies to satisfy the ATO function requirement. Indeed, **we are not interested in finding which the best technology is for a specific ATO function requirement, but in identifying a set of enough suitable technologies that can be further developed for implementing jointly in a multi-sensors data fusion system for the railway sector.**

4.3.1 Weights of the criteria

Table 4.1 introduces the weights values of the criteria that have been used identified using the experts judgment method.

Criteria	Weight (1 -3)
<i>Maturity</i>	1.5
<i>Accuracy</i>	2.7
<i>Reliability</i>	2.8
<i>Availability</i>	2.7
<i>Maintainability</i>	2.2
<i>Cost</i>	1.8
<i>Energy consumption</i>	1.2
<i>Suitability to specific function requirement</i>	2.8

Table 4.1 – Generic criteria for technology assessment

4.4 Autonomous driving technologies evaluation and ranking

In the following of this Section, for each specific requirement of the ATO functions a Table illustrates the ranking of the technologies and their evaluation. Columns indicate the criteria, while rows are the technologies. Last column reports the normalized score that has been computed as described in Sect. 4.3. The ranking of the technologies is done considering the normalized score. Scores have been discretized using three colours to highlight performance aspects of the technologies for all the criteria: red for low marks (i.e. below and equal 1.8), yellow for intermediate marks (i.e. between 1.8 and 2.5) and green for good marks (i.e. above or equal than 2.5). After the independent technologies scoring, all the involved experts exchanged their consideration about the technologies evaluation performing an expert elicitation whose outcomes are introduced as comments to the tables in the following of this Section.

4.4.1 Precise train localization

Two specific requirements have been identified for the ATO function “*Precise train localization*” (F4):

- *Localization of train for precise stopping in stations, yards or other special area (F4-1);*
- *Train localization at the start up (F4-2).*

The evaluation of positioning technologies for these two requirements is presented in the following of this section.

4.4.1.1 Localization of train for precise stopping in stations, yards or other special area

	Maturity	Accuracy	Reliability	Availability	Maintainability	Cost	Energy consumption	Suitability to specific function	Normalized score
Artificial landmarks	2.3	2.8	2.5	2.8	2.5	2.7	2.5	2.8	0.89
GNSS	2.7	2.3	2.2	2.3	2.5	2.3	2.2	2.7	0.80
Doppler RADAR	2.3	2.2	2.5	2.5	2.5	2.0	2.0	2.2	0.77
Inertial navigation	2.8	1.8	2.5	2.7	2.5	1.8	2.0	2.0	0.76
Mobile Positioning Systems	2.5	2.2	2.3	2.2	2.2	1.7	1.8	2.3	0.72
Maps	2.5	2.5	2.0	2.2	2.2	2.0	2.0	2.0	0.72
Wheel Odometry	3.0	1.5	1.7	2.2	2.2	2.2	2.3	1.7	0.66
Natural landmarks	2.0	1.8	1.5	2.0	2.2	2.3	2.3	2.0	0.66
Visual odometry	2.0	1.8	1.8	2.0	2.3	2.0	2.0	1.7	0.65
Wireless cooperative positioning	1.7	2.0	2.0	2.2	1.8	2.0	2.0	1.7	0.64
Simultaneous Localization And Mapping (SLAM)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

Table 4.2 – Ranking of positioning technologies for train localization for precise stopping.

Table 4.2 introduces the ranking of the positioning technologies for precise train positioning (F4-1).

The “Simultaneous Localization And Mapping (SLAM)” has not been considered suitable for the selected positioning requirements since this positioning solution is exploited mainly to navigate in unknown environments using a relative positioning approach. These features make this solution scarcely accurate preventing its utilization for precise train localization

The most suitable localization solution for precise train localization has been judged to be “Artificial landmarks”. The installation of physical landmarks for train localization can guarantee high accuracy since these landmarks can provide precise references of the stopping position. Visual sensors may be the most suited sensors for the recognition of these landmarks, alternatively RADAR or LIDAR may be employed. In this particular case, it is possible to envision the use of this technology to determine a relative positioning similar to the solutions for lane detection in the automotive sector. A precision in the positioning in the order of tens of centimetres can be ensured satisfying the precise stopping requirement which is mainly related to the precision along the longitudinal direction.

The maturity of this solution is not high since it has not yet widely deployed for precise localization function. Furthermore, the landmarks recognition algorithms employed to detect the landmarks are still being developed. The main weakness of this solution is the need to install the landmarks and to ensure that these are always visible and not damaged. This aspect impacts on the reliability and maintainability of this solution.

The other positioning technologies, which have been evaluated, can be considered not so suitable for precise train positioning and none of them can be considered as only-standing solution. Nevertheless, these other technologies can be adopted in a multi-sensors data fusion positioning system. Positioning technologies, such as GNSS system, Mobile Positioning System and Maps, can provide the absolute train position within a general framework reference. Relative positioning methods can contribute to improve the accuracy of the positioning in the multi-sensor positioning system.

GNSS can indeed provide quite accurate positioning, in particular if Real-Time Kinematic (RTK) GNSS technique is employed. Indeed, RTK-GNSS can provide a positioning accuracy in the order of few tens of centimetres or even less in favourable conditions [15]. However, the performance are strictly related to the environment. Buildings and other obstacles can significantly impair the performance, making this technological solution not specifically suitable for the specific requirements of positioning in railway stations or other special areas where buildings are likely to be present.

Mobile positioning systems can typically provide an absolute position with a precision of few tens of meters [16]. This solution can be included, but it is not possible to use it alone for achieving the required positioning accuracy of the considered requirement. Similar motivation concerns a “Map” based solution. Indeed, considering a future potential deployment of this solution in the railway sector, it is strongly suggested to consider as many as possible of the absolute and relative positioning technologies in the multi-sensors data fusion. In the literature of the automotive sector, field experience shows that accuracy is increased with the number of sensors employed [2].

The main consideration is that a single positioning technology, even if employing a very expensive and theoretically accurate sensor, may perform worse than two or more technologies exploiting average quality sensors. This is due to the peculiarity of each sensor since a given sensor can provide accurate positioning information just in some specific contexts. The challenge of data fusion is then to understand which set of technologies may perform the best together and which technology can provide reliable information in some specific conditions.

4.4.1.2 Train localization at the start up

	Maturity	Accuracy	Reliability	Availability	Maintainability	Cost	Energy consumption	Suitability to specific function	Normalized score
Artificial landmarks	2.5	3.0	2.5	2.8	2.5	2.7	2.5	3.0	0.91
GNSS	2.7	2.0	2.3	2.2	2.5	2.3	2.2	2.3	0.77
Mobile Positioning Systems	2.5	2.2	2.3	2.2	2.2	1.7	1.8	2.0	0.71
Maps	2.3	2.2	2.0	2.2	2.2	2.0	2.0	1.8	0.69
Natural landmarks	2.0	1.7	1.5	2.0	2.2	2.3	2.3	1.8	0.64

	Maturity	Accuracy	Reliability	Availability	Maintainability	Cost	Energy consumption	Suitability to specific function	Normalized score
<i>Wireless cooperative positioning</i>	2.2	1.7	2.2	2.2	1.8	2.0	2.0	1.5	0.64
<i>Wheel Odometry</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
<i>Inertial navigation</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
<i>Doppler RADAR</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
<i>Visual odometry</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
<i>Simultaneous Localization And Mapping (SLAM)</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

Table 4.3 – Ranking of positioning technologies for train localization at the start up.

The evaluation of positioning technologies for train localization at the start up is reported in Table 4.3.

The relative positioning technologies (i.e. Wheel Odometry, Inertial navigation, Doppler RADAR, Visual odometry, SLAM) are not applicable in this specific requirement of the ATO since they cannot provide an absolute position and neither can they help in improving the accuracy of the train localization. Indeed, train is not expected to be travelling and these technologies are instead based on the perception of the motion of the vehicle to provide incremental position information.

The “*Artificial landmarks*” positioning technology has been considered the only suitable one for ensuring good performance for train localization at the start up. In this specific case, this technology would be used to provide an absolute train localization, adopting a different approach with respect to the previous case of precise train stopping.

The absolute train position can be achieved using trilateration or triangulation techniques measuring ranges or angles with respect to artificial landmarks installed in known positions. Otherwise, artificial landmarks can directly provide information to the train. The artificial landmarks can codify information about the train position such as the track on which the train is. This information can be provided using a similar approach of barcodes or QR-codes. This may be the most suited approach for ensuring the best performance, in particular for what concerns track discrimination.

The main issue is to envision a practicable and reliable method to implement the landmark that requires to be easily identifiable and understandable by the recognition system and, in the meanwhile, it has to be robust to external interference such intentional landmark modifications or vandalism.

The “GNSS”, “*Mobile Positioning System*” and “*Wireless Cooperative Positioning*” can provide an absolute positioning that is quite accurate, but not enough accurate for track discrimination. Indeed, an uncertainty of few meters in the cross-track direction makes impossible to exactly determine the track on which the train is. Furthermore, GNSS-based system may suffer from low sky visibility situations that may be likely situations for several railway stations.

The “*Natural landmarks*” solution, even if based on a similar approach to the “*Artificial landmarks*”, is not suited to the purpose of satisfying this requirement since it cannot ensure adequate accuracy. In “*Natural landmarks*”, the landmarks are not expressly installed for the localization, but they are elements already installed in the environment. They cannot thus provide direct information to the train and they can only be used for trilateration or triangulation techniques.

In addition to that, the “*Natural landmarks*” solution, as well as “*Maps*”, can suffer from aliasing that is the situation in which an environment cannot be distinguished by another one. Indeed, it seems likely that railway stations may present common and recurring elements, while it is difficult to have always peculiar elements that can uniquely identify the position of the train in a given station and on a specific track. The “*Maps*” solution can in addition be penalized by the dynamic environment of a station that may affect the possibility to precisely locate the train on the track.

4.4.2 Calibration of the odometry

The ATO function “*Calibration of the odometry*” (F5) has the only requirement of “*Localization methods to calibrate the odometry*” (F5-1). In Section 4.4.2.1, absolute positioning methods are evaluated for determining their effectiveness in the correction of the error introduced by the odometry, while relative positioning methods are evaluated for a possible joint implementation with the odometry to improve the overall system performance (i.e. odometry corresponds to “*Wheel odometry*” technology that is not evaluated in this case since it cannot correct its error or improve its own performance).

4.4.2.1 Localization methods to calibrate the odometry

	Maturity	Accuracy	Reliability	Availability	Maintainability	Cost	Energy consumption	Suitability to specific function	Normalized score
<i>Artificial landmarks</i>	2.5	3.0	2.5	2.8	2.5	2.7	2.5	2.8	0.90
<i>Doppler RADAR</i>	2.7	2.7	2.5	2.5	2.5	2.0	2.0	2.7	0.83
<i>Inertial navigation</i>	2.8	1.8	2.5	2.7	2.5	1.8	2.0	2.8	0.80
<i>Maps</i>	2.7	1.8	2.0	2.2	2.2	2.0	2.0	2.0	0.69
<i>Visual odometry</i>	2.0	1.8	1.8	2.0	2.3	2.0	2.0	2.0	0.66
<i>Natural landmarks</i>	1.8	1.5	1.5	2.0	2.2	2.3	2.3	1.8	0.63
GNSS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
<i>Mobile Positioning Systems</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
<i>Wheel Odometry</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

	Maturity	Accuracy	Reliability	Availability	Maintainability	Cost	Energy consumption	Suitability to specific function	Normalized score
<i>Simultaneous Localization And Mapping (SLAM)</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
<i>Wireless cooperative positioning</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

Table 4.4 – Ranking of positioning technologies for calibrating the odometry.

The most suited absolute positioning technology to correct the error introduced by the odometry is “Artificial landmarks” as it is possible to notice in Table 4.4. Same considerations introduced in the analysis of previous requirements hold also for this case.

The other absolute positioning systems (i.e. GNSS, Mobile Positioning Systems and Wireless cooperative positioning) have not been evaluated since their accuracy has not been judged sufficient to correct the odometry error. GNSS technology cannot ensure adequate accuracy in all conditions since its performance can be impaired by the presences of buildings that reduce the sky visibility. Instead, Mobile Positioning Systems cannot ensure sufficient precision as it is typically in the order of few tens of meters.

“Maps” may be used to correct the error, but with expected lower accuracy. Furthermore, it may suffer from aliasing and dynamic environments.

The relative positioning technologies seem to be applicable for improving the odometry performance. However, none of them has been reputed to be determinant. Wheel Odometry and SLAM method have not been judged to achieve a sufficient precision for being useful for this requirement.

As for the precise train stopping requirement, the most likely solution is the development of a multi-sensors data fusion positioning system that exploits results from several absolute and relative positioning technologies. At the end this solution may be the only viable way to guarantee a certain improvement of the performance with respect to an odometry-only based system.

4.4.3 Detection of unexpected obstacles on track

The ATO function “*Detection of unexpected obstacles on track*” (F6) has been analysed and the following specific requirements have been identified:

- *Detection of fixed obstacles on tracks (F6-1)*
- *Detection of moving obstacles (i.e. people or animals) along the line (F6-2)*
- *Detection of moving obstacles at stations, level crossing, yards or other special area during shunting and other specific operations (F6-3)*
- *Detection of cars and other vehicles at level crossing (F6-4)*

The technologies for obstacles detection, which have been summarized in Section 3.4.2, are evaluated for each of these requirements in the following of this section.

The “SONAR” based technological solution has not been considered suitable for any requirement due to its low operative range. However, it may be effectively employed for all the cases in which the detection of objects/obstacles is expected to be performed in the range of few meters. An example, in which SONAR-based technology can be employed, is to detect a buffer stop.

4.4.3.1 Detection of fixed obstacles on tracks

	Maturity	Accuracy	Reliability	Availability	Maintainability	Cost	Energy consumption	Suitability to specific function	Normalized score
<i>RADAR</i>	3.0	2.2	2.2	2.5	2.3	2.2	1.5	3.0	0.80
<i>Stereo camera</i>	2.5	1.8	2.0	2.0	2.7	2.0	2.2	2.0	0.70
<i>Omnidirectional camera</i>	2.3	2.3	2.0	2.0	2.5	1.8	2.0	1.7	0.69
<i>LiDAR</i>	2.2	2.5	2.0	2.0	2.2	1.3	1.8	2.2	0.69
<i>Monocular camera</i>	2.8	1.7	1.7	1.7	2.5	2.0	2.2	1.5	0.64
<i>SONAR</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
<i>Infrared-equipped visual camera</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
<i>Infrared camera</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
<i>Wireless communication</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

Table 4.5 – Ranking of perception technologies for fixed obstacles detection on tracks.

Table 4.5 illustrates the ranking of obstacles detection technologies for the specific requirement of fixed obstacles detection on tracks.

Some detection technologies have not been considered since they have been judged to not be suitable for this requirement. A SONAR-based solution is not practicable due to the limited range of SONAR sensors. A similar motivation concerns infrared-equipped visual camera. Infrared cameras are instead not suited since in this requirement it is not expected that obstacles emit thermal radiations. Eventually, wireless communication for obstacles detection are applicable only if the “obstacle” can communicate wirelessly its position.

The RADAR-based technology is the most suited obstacles detection technology according to experts' evaluation. This technology is highly mature since it is employed since several years in other transportation sectors such as in the avionic and in the maritime sectors. It can ensure good availability and reliability with respect to the other considered technologies since it can operate during night time and its performance is not affected by rain, fog and other bad weather conditions.

The RADAR working range is likely to satisfy the requirement concerning the distance at which an obstacle should be detected in order to allow the train to brake with a proper deceleration as detailed in Section 3.3. Indeed, maritime RADARs can achieve a range of few kilometres [21]. It is necessary to develop RADARs suitable for the railway environment that can achieve similar ranges.

The accuracy of this solution is mainly constrained by the scarce achievable level of detail in the scene reconstruction (i.e. it is possible to detect objects but with low details). A further aspect that impacts on the accuracy and reliability is the low effectiveness in detecting non-metallic and small-surface objects, since radiated waves only partially reflect back.

The main weaknesses of the RADAR are the cost and the energy consumption that characterize all active sensors. Furthermore, RADAR based on mechanically rotating parts may present some issues for the maintainability.

Visual camera may represent a good technological solution for this requirement, but main issues are related to its low reliability in case of bad weather conditions and during night time. For the latter aspect, in this requirement the “*Infrared camera*” solution has not been considered since the targets are fixed obstacles that do not emit heat (e.g., rocks, trees and other inanimate debris). Other aspects that are against the use of visual cameras are their limited range and low suitability for high speed.

Visual based solutions can however be possible if rugged cameras, which have been enhanced for special environmental conditions and long range cases, are employed [17]-[18]. These cameras have been developed to operate also at night and in case of fog. Furthermore, they can achieve operating ranges in the order of few kilometres. These cameras are typically designed for harsh environments. It is necessary to understand if it is possible to develop similar visual cameras achieving similar performance at trains’ speed and in the railway environment.

Please remember that this requirement is specific for the case when the train is moving along the line, potentially at high speed and being characterized by significantly high braking distances. This peculiarity makes not applicable the employment of “*Infrared-equipped visual camera*” since the Infrared illuminator typically operates at the range of few tens of meters in the best cases. Some experimental devices are however currently in study for achieving longer ranges. Thus, the “*Infrared-equipped visual camera*” can work as a traditional camera without the infrared illuminator and this does not add anything in the analysis with respect to other cameras.

Among the considered visual cameras, the “*Stereo camera*” and the “*Omnidirectional camera*” have a better rate with respect to “*Monocular camera*” since the first ones can provide more accurate distance information. Indeed, the monocular camera can only provide distance information through complex image processing algorithms.

The “*LiDAR*” technology is the one with the higher accuracy score since it can reconstruct with high accuracy the surrounding environment providing also precise distance information. However it is not well rated in the overall since it is not yet a mature technology and LiDAR sensors are currently highly expensive. Furthermore, LiDAR sensors are typically equipped with rotating parts making them demanding from maintenance aspects. Other issue concerns the operating range. However, for the latter aspects long range LiDAR have been developed with operating range up to 1 kilometre [19].

Further development of the LiDAR technology may lead to an improvement of these devices for what concerns price and maintainability aspects. The LiDAR should in any case jointly used with other perception sensors since its performance may suffer from light conditions as it is based on the reflection of light beams.

The last sentence introduces, also for the obstacles detection, the need of integrating more perception technologies in a multi-sensors data fusion perception system. As for the positioning, the best obstacles detection system can hardly be based on only one technology. Considering the specific requirement of fixed obstacles detection, it is likely that a future potential detection system is based on RADAR for long range detection in any environmental condition, LiDAR for intermediate and more accurate scene reconstruction while visual cameras, in particular stereo or omnidirectional camera, can provide visual information that can help in identifying the types of obstacles.

4.4.3.2 Detection of moving obstacles along the line

	Maturity	Accuracy	Reliability	Availability	Maintainability	Cost	Energy consumption	Suitability to specific function	Normalized score
<i>RADAR</i>	2.7	2.3	2.2	2.5	2.3	2.2	1.5	2.3	0.76
<i>Infrared camera</i>	2.8	2.3	2.2	2.3	2.5	1.8	2.2	2.2	0.76
<i>Stereo camera</i>	2.3	1.8	2.0	2.0	2.7	2.0	2.2	2.0	0.70
<i>Omnidirectional camera</i>	2.3	2.3	2.0	2.0	2.5	1.8	2.0	1.7	0.69
<i>LiDAR</i>	2.2	2.3	2.0	2.0	2.2	1.3	1.8	2.0	0.67
<i>Monocular camera</i>	2.8	1.7	1.7	1.8	2.5	2.0	2.2	1.7	0.65
<i>SONAR</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
<i>Infrared-equipped visual camera</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
<i>Wireless communication</i>	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

Table 4.6 – Ranking of perception technologies for moving obstacles detection along the line.

The two technologies which experts have identified to be the most suited for moving obstacles detection along the lines are “*Infrared camera*” and “*RADAR*” based solutions as it is possible to notice in Table 4.6. Moving obstacles are considered to be people or animals. The Infrared camera can well identify warm bodies, even during night time, and it is strongly suggested to be used for satisfying the specific requirement of identifying moving obstacles. However, it may present some limitations for what concerns the operative range and the reliability in case of bad weather conditions. This requirement is indeed referring to the situation in which the train is travelling at a potential high speed. These sensors are thus required to be installed on-board of the train. However, some long range thermal cameras have been developed for applications in vehicle and mobile system ensuring a detection range of few hundred meters [20].

The RADAR can well complement the Infrared camera since it can operate in any weather condition. RADAR has been however considered less suitable to this requirement with respect to the requirement of fixed obstacles detection since people are typically characterized by small not-metallic surfaces and these characteristics make them less easy to be identified by RADAR.

Visual based solutions can also be applicable for moving obstacles detection. In particular, visual cameras permit to identify people (or animals) using image processing algorithms. It can be foreseen to reuse pedestrian recognition systems that are currently being developed for the automotive sector. These solutions still suffer from ranges and reliability issues in night time and bad weather conditions.

LiDAR sensors can as well provide a satisfying accuracy, but main weaknesses, which have been illustrated in the previous section, are still present. Furthermore, both LiDAR and RADAR can provide information about the presence of an obstacle, but they can hardly identify this obstacle as a human person, animal or as a fixed obstacle. This possibility can be only ensured by visual cameras as previously stated.

SONAR and Infrared-equipped visual camera have not evaluated since not suited for satisfying this requirement due to the limited working range. Wireless communication may be relevant if moving obstacles are equipped with some wireless transmitters (i.e. mobile phone), but we judged that this case may be applicable just for railway workers along the line and for this reason we do not consider in the evaluation.

4.4.3.3 Detection of moving obstacles at stations, level crossing, yards or other special area during shunting and other specific operations

	Maturity	Accuracy	Reliability	Availability	Maintainability	Cost	Energy consumption	Suitability to specific function	Normalized score
Infrared camera	2.8	2.3	2.2	2.3	2.5	1.8	2.2	2.3	0.77
RADAR	2.7	2.3	2.2	2.5	2.3	2.2	1.5	2.2	0.75
Infrared-equipped visual camera	2.5	2.5	2.3	2.3	2.2	1.7	2.0	1.8	0.73
Omnidirectional camera	2.3	2.5	2.2	2.2	2.3	1.5	2.0	2.0	0.71
Stereo camera	2.3	1.8	2.2	2.3	2.3	1.7	2.0	2.3	0.71
LiDAR	2.3	2.2	2.0	2.0	2.2	1.3	1.8	2.2	0.67
Monocular camera	2.8	1.8	1.7	2.0	2.3	2.0	2.2	1.8	0.67
SONAR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
Wireless communication	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

Table 4.7 – Ranking of perception technologies for moving obstacles detection at stations and in other specific areas.

The requirement of detecting moving obstacles at stations or in other well-defined and specific areas has been introduced since the detection of people is spatially constrained and this may allow the deployment of fixed detection systems that cover the desired limited areas. The fixed detection system can identify people on tracks or in dangerous positions and it can inform in advance the train in order that it takes proper actions.

The peculiarity of this requirement may impact on the judgement of some of the considered technologies, in particular those that are limited in the range. Table 4.7 reports the ranking of the perception technologies for this requirement and it is possible to notice that visual based solutions have slightly higher scores. However, maintainability scores are decreased since fixed detection systems are typically more expensive to be managed.

Due to the limited area of operations, “Infrared-equipped visual camera” has been also evaluated and it has been considered as a relevant technology since it joins, in the same sensor, the distance accuracy provided by the Infrared illuminator together with the richness of information provided by the visual camera. The Infrared illuminator allows to precisely reconstruct the environment, while the visual information makes possible to distinguish and correctly identify people. This sensors has not previously considered due to the limited operating range of few tens of meters.

Same comments, which have been introduced in the evaluation of previous requirement, are still valid for the other technologies.

4.4.3.4 Detection of cars and other vehicles at level crossing

	Maturity	Accuracy	Reliability	Availability	Maintainability	Cost	Energy consumption	Suitability to specific function	Normalized score
RADAR	3.0	2.7	2.2	2.5	2.3	2.2	1.5	2.5	0.80
Infrared camera	2.8	2.0	2.2	2.3	2.5	1.8	2.2	1.8	0.73
Infrared-equipped visual camera	2.7	2.2	2.3	2.3	2.2	1.7	2.0	2.0	0.72
Omnidirectional camera	2.3	2.5	2.2	2.3	2.3	1.5	2.0	2.0	0.72
Wireless communication	2.0	2.3	2.2	2.2	2.0	1.7	2.3	2.5	0.72
Stereo camera	2.3	1.8	2.2	2.3	2.3	1.8	2.0	2.3	0.72
LiDAR	2.3	2.3	2.0	2.0	2.2	1.3	1.8	2.2	0.68
Monocular camera	2.8	1.7	1.7	2.2	2.2	2.0	2.2	1.7	0.66
SONAR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

Table 4.8 – Ranking of perception technologies for detection of cars and other vehicles at level crossing.

The requirement of detection of cars and other vehicles at level crossing has been analysed since cars, and more in general all vehicles, present some particular characteristics that may influence the technologies evaluation.

Most suited technology, as it can be noticed in Table 4.8, is the RADAR. Indeed, cars present typically large metallic surface making them easily identifiable by RADAR-based sensors. Other technologies present similar evaluation of previous requirement (i.e. detection of moving obstacles, such as people, at stations or other specific areas) apart from “Infrared camera” that may not perform as well in this case since cars and other vehicles can have the same temperature of the surrounding environment (e.g., in the case of very hot temperatures or in the case that cars have been stopped since long time).

In this specific requirement, the sharing of the cars’ position information exploiting wireless communication has been considered feasible. This case may be considered as potential future solution considering the future framework of “Intelligent Transport System” [22]. This framework foresees that all transportation vehicles would be wireless connected in a same system. It is indeed likely that in the next future cars and other vehicles would be required to be connected and to broadcast messages announcing their position and expected trajectory [23]. This may be exploited also by trains for verifying that no vehicles are stopped in dangerous positions at level crossing. This technological solution would complement the other selected technologies.

4.4.4 Detect the next safe location to stop

The evaluation of the technologies for the requirement “Detection of safe location stopping area” (F8-1) is presented in this section. The evaluation has been performed to just identify which technologies can be

exploited for sensing the surrounding environment and detecting a possible safe location stopping area. For the evaluation no characteristics of the safe location stopping area have been assumed. The analysis refers only to the capability and suitability of the technologies to perceive the environment and related characteristics.

4.4.4.1 Detection of safe location stopping area

	Maturity	Accuracy	Reliability	Availability	Maintainability	Cost	Energy consumption	Suitability to specific function	Normalized score
Omnidirectional camera	2.7	2.8	2.0	2.0	2.5	1.8	2.0	2.8	0.79
Stereo camera	2.7	2.7	2.0	2.0	2.7	2.0	2.2	2.7	0.79
RADAR	3.0	2.0	2.2	2.5	2.3	2.2	1.5	1.8	0.73
Infrared-equipped visual camera	2.5	2.2	2.3	2.3	2.2	1.7	2.0	1.8	0.71
Monocular camera	2.8	1.7	2.0	2.2	2.2	2.0	2.2	2.0	0.69
LiDAR	2.2	2.3	2.0	2.0	2.2	1.3	1.8	2.3	0.69
SONAR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
Infrared camera	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
Wireless communication	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

Table 4.9 – Ranking of perception technologies for detection of safe location stopping area.

It is possible to see from Table 4.9 that “Omnidirectional” and “Stereo” cameras have been judged as the most suited from the experts. Indeed, these types of cameras can ensure well accurate distance information and, in the meanwhile, they can provide high level of detail about the scene for allowing the recognition of features that may identify a safe location stopping area. “Monocular camera” has received a lower score mainly due to the lower accuracy of the distance information that it can provide. “Infrared-equipped visual camera” has not been estimated as suited mainly due to the limited operative range in comparison with the other cameras. “Infrared camera” has not been considered to be applicable to this requirement since it is not expected to have objects emitting heat to be detected.

In this specific requirement, visual cameras are not impaired by the limited operating range since in this case no strict requirement about distances are required (operation upon limited speed), while it is more important the capability to extract features from the environment to recognize a safe stopping area.

RADAR and LiDAR are also possible technologies to be considered for this requirement, in particular for their inclusion in a multi-sensors data fusion system. These technologies, even if they cannot provide visive information of the environment, can provide an overall reconstruction of the environment thanks to their accuracy in distance measurements. A further advantage, in particular for the RADAR, is the possibility to work also in night time and bad weather conditions.

SONAR is not applicable due to limited operating range, while wireless communication may be applicable just in case safe stopping areas are equipped with wireless transmitters informing about the presence of a safe stopping area. This last case has been not considered relevant to the scenario under examination.

4.4.5 Trackside signals detection

The signals recognition requirement (*F10-1*) has been identified for all the cases in which the train has to identify and read traffic lights and other track-side signals for driving in very specific conditions and operations (e.g., unprotected level crossing, ERTMS equipped train start up, running at sight and shunting).

4.4.5.1 Signals recognition

	Maturity	Accuracy	Reliability	Availability	Maintainability	Cost	Energy consumption	Suitability to specific function	Normalized score
Stereo camera	2.7	2.7	2.0	2.0	2.7	2.0	2.2	3.0	0.80
Omnidirectional camera	2.7	2.8	2.0	2.0	2.5	1.8	2.0	2.7	0.78
Monocular camera	2.8	2.5	2.0	2.0	2.2	2.0	2.2	2.8	0.77
Infrared-equipped visual camera	2.3	2.2	2.3	2.3	2.2	1.7	2.0	1.8	0.71
Wireless communication	2.2	2.2	2.2	2.0	1.8	2.2	2.3	1.7	0.68
RADAR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
LiDAR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
SONAR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00
Infrared camera	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.00

Table 4.10 – Ranking of perception technologies for detection and recognition of signals.

Table 4.10 provides the ranking of the perception technologies for the signals recognition requirement. Most suited technologies are based on visual cameras, either stereo, omnidirectional or monocular cameras. Indeed, visual sensors are the only ones that provide the possibility to analyse signals for understanding the indication that they provide. For the same reason, RADAR and LiDAR are not considered in the evaluation. “*Signals recognition*” can leverage on the signals recognition techniques that are currently being developed in the automotive sector for autonomous driving vehicles.

Other possible solution is based on wireless communication. Similarly to the automotive sector, it is possible to envisage that signals may be equipped with some networking equipment that communicate to the train the information expressed by the signal [23]. This solution is however has been evaluated with the lowest score since significant effort in the deployment of track-side infrastructure is required.

Active sensors (RADAR, LiDAR, SONAR) may achieve the detection of traffic signals, however they are not able to recognize them and to understand the information that they can provide. Infrared camera are not suited to the detection since these sensors are suited to detect objects that emit thermal radiations.

5 Recommendations on Automatic Driving in the Railway Sector

In this Section, the recommendations on Automatic Driving in the Railway Sector are made taking into account the analysis and the assessment performed within the research activities of the ASTRail WP3.

The ASTRail project recommendations on Automatic Driving in the Railway Sector are related to the following three items:

1. The autonomous driving technologies reusable in the railway domain;
2. The exploitation of a single technology to satisfy multiple requirements;
3. The exploitation of multi-sensors data fusion.

In the following of this Section, each recommendation is detailed.

5.1 Technologies for autonomous driving can be reused in the railways

The evaluation of the technologies for assessing which of them are the most suited to be re-used in the railway domain is presented in Sect. 4.4.

A set of reusable technologies has been defined for the identified requirements of ATO functions. These technologies can be reusable in the railway domain, but further effort must be taken into account for the development of sensors that take into account the peculiarities of the railway environment.

The recommendations about which technologies can be considered for re-usability are introduced in the following of this Section for each identified requirement of each ATO function. Detailed discussions about strengths and weaknesses of each technology are already presented in Sect. 4.4. Description of the selected technologies is summarized in Sect. 3.4 and detailed in the ASTRail deliverable D3.1 [RD.1].

5.1.1 Precise train localization

5.1.1.1 Localization of train for precise stopping in stations, yards or other special area

We recommend following technologies for the precise train localisation related to stopping in predefined areas:

- Artificial landmarks
- GNSS
- Doppler RADAR
- Inertial navigation
- Mobile Positioning Systems
- Maps
- Wheel Odometry
- Natural landmarks
- Visual odometry
- Wireless cooperative positioning

5.1.2 Train localization at the start up

We recommend following technologies for train localization at the start up:

- Artificial landmarks
- GNSS
- Mobile Positioning Systems
- Maps
- Natural landmarks
- Wireless cooperative positioning

5.1.3 Calibration of the odometry

5.1.3.1 Localization methods to calibrate the odometry

We recommend following technologies for the calibration of the odometry:

- Artificial landmarks
- Doppler RADAR

- Inertial navigation
- Maps
- Visual odometry
- Natural landmarks

5.1.4 Detection of unexpected obstacles on track

5.1.4.1 Detection of fixed obstacles on tracks

We recommend following technologies for the detection of fixed obstacles on tracks:

- RADAR
- Stereo camera
- Omnidirectional camera
- LiDAR
- Monocular camera

5.1.4.2 Detection of moving obstacles along the line

We recommend following technologies for the detections of moving obstacles (i.e. people or animals) along the railway tracks:

- RADAR
- Infrared camera
- Stereo camera
- Omnidirectional camera
- LiDAR
- Monocular camera

5.1.4.3 Detection of moving obstacles at stations, level crossing, yards or other special area during shunting and other specific operations

We recommend following technologies for the detection of moving obstacles in specific areas such as stations and level crossing:

- Infrared camera
- RADAR
- Infrared-equipped visual camera
- Omnidirectional camera
- Stereo camera
- LiDAR
- Monocular camera

5.1.4.4 Detection of cars and other vehicles at level crossing

We recommend following technologies for the detection of vehicles at the level crossing:

- RADAR
- Infrared camera
- Infrared-equipped visual camera
- Omnidirectional camera
- Wireless communication
- Stereo camera
- LiDAR
- Monocular camera

5.1.5 Detect the next safe location to stop

5.1.5.1 Detection of safe location stopping area

We recommend following technologies for the identification and localization of safe location stopping areas:

- Omnidirectional camera
- Stereo camera

- RADAR
- Infrared-equipped visual camera
- Monocular camera
- LiDAR

5.1.6 Trackside signals detection

5.1.6.1 Signals recognition

We recommend following technologies for the recognition of traffic signals:

- Stereo camera
- Omnidirectional camera
- Monocular camera
- Infrared-equipped visual camera
- Wireless communication

5.2 Exploitation of a single technology for multiple requirements

A single technology can be devoted to more than a single ATO function. For example, a visual camera can be employed for the obstacle detection, but it can be employed also for the identification of artificial landmarks for a precise train positioning.

The exploitation of a sensor for more functions can enhance the economical investment since the expenses can be amortised thanks to the multiple functionalities implemented by the sensor.

We recommend to consider each technology for all the functions that it may contribute to and not to take it into account just for a specific function.

5.3 Multi-sensors data fusion

The strict requirements of the Railway domain make difficult that a single technology can guarantee to satisfy them in all conditions and situations. Each technology presents strengths for specific conditions and utilization's cases, while it presents weaknesses for other aspects. Indeed, as presented in Sect. 4.4 and highlighted in Sect. 5.1, there are more than one technology that can be suitable to be re-used for the implementation of ATO functions requirements.

The multi-sensors data fusion system can exploit the strengths of all technologies, while mitigating their weaknesses. The development of a multi-sensors data fusion system can allow to satisfy requirements of ATO functions considering the safety and performance aspects that the railway environment requires. Both positioning and obstacle detection functions can be implemented following a sensors data fusion approach.

In the case of the positioning, it is possible to include one or more absolute positioning systems, such as GNSS based system, and to complement the absolute positioning system with one or more relative positioning systems such as odometry, inertial navigation. Visual-based positioning exploiting artificial landmarks can also provide accurate positioning in specific conditions such as at the arrival at a station.

The artificial landmarks positioning is the example of another characteristic of the multi-sensor data fusion. It is indeed not required that all the technologies are exploited in all conditions and at all times. A specific technology can contribute to satisfy a specific function only in particular conditions, while its contribution is neglected in the other cases.

Another example of the effectiveness of a multi-sensor data fusion system is related to areas where GNSS positioning cannot work, such as tunnels, or its performance is very degraded, such as in mountainous areas where the sky visibility is reduced. In these conditions, the GNSS positioning solution cannot be significantly reliable and the reliability of the multi-sensor positioning system can be ensured by the other positioning methods that are exploited in it.

The approach of multi-sensor data fusion system can be also effective for what concerning the obstacle detection function. Detection technologies based on visual cameras can identify and classify obstacles. However, their performances are influenced by light and weather conditions and the distance measurements, which can be performed with some types of cameras, may be limited in the accuracy and in the working range. Active sensors, such as RADAR and LIDAR, can be used for detecting obstacles at longer distances than visual cameras. These sensors can also achieve accurate obstacles distance measurements. Other type of detection sensors can be used in particular conditions. For example, infra-red cameras can instead be used for specifically identifying people during night time.

The recommendation is that a multi-sensors data fusion system, which is based on several technologies, can represent the most effective solution for achieving the required railway-specific performances.

6 Conclusions

The activities of the ASTRail WP3 “Automatic driving technologies for railways” end with this deliverable. **The scope of the WP3 is to identify which technologies employed in the automotive and in other application fields can be suitable for being reused also in the railway sector for implementing ATO.**

The first deliverable of WP3 is the D3.1 “State of the Art of Automated Driving technologies” [RD.1] that introduced the results of the survey on the automated driving technologies, considering both on-the-market and under development technologies. Focus of the survey is on positioning and on obstacle detections technologies for autonomous driving. These two categories of technologies have been then considered during the evaluation.

This deliverable, the D3.2, reports the consequent analysis of the identified technologies and the evaluation of their suitability for the railway field.

The first step of the autonomous driving technologies analysis has been to identify which are the basic implementation characteristics and the operation conditions for automated driving systems in the automotive and railway sectors. This activity has been carried on in task T3.2 “Analysis of Automatic Train Operations: operation conditions and implementation characteristics”. **A comparison between the characteristics and conditions for autonomous driving of these two sectors has been performed to identify similar needs. This comparison created a knowledge basis that has been then exploited to better assess the suitability of autonomous driving technologies in the railway sector.**

The evaluation of the autonomous driving technologies has been then performed assessing the suitability of the technologies to satisfy specific requirements of ATO functions. Available ERA documents concerning ATO have been analysed to identify the main ATO functions. Furthermore, potential functions, which can be foreseen to be deployed in the future, have been also taken into account. These potential ATO functions would complement existing systems maintaining backward compatibility with them.

The requirements of the selected ATO functions have then been specified considering their employment in particular railway use cases of interest. Some of the use cases are, for example, “Approaching a station”, “Plain line running” and “Level crossing”. Each use case requires a given ATO function to satisfy specific needs. These requirements have been identified and technologies have been evaluated versus each of these requirements.

The approach for the evaluation has been to perform a qualitative analysis since currently available sensors of the selected technologies have been designed to satisfy conditions and requirements different from the ones of the railway sector. Quantitative analysis would not be fair since performance of sensors is not compliant to railways’ needs. Sensors should be designed to address railways’ requirements for a meaningful evaluation. Furthermore, a Multi-Criteria Decision Making (MCDM) method has been exploited for the evaluation since several aspects concern the evaluation of a given technology and a straightforward evaluation is not possible. In the specific, the Weighted Sum Model method and the expert judgment method have been employed for achieving a fair and objective evaluation. Experts from the automotive and railway sectors have been asked to rate the technologies and final evaluation is an average of all scores.

The results and the analysis of the technologies highlighted that several technologies may be well suited to satisfy railway-specific requirements. However, it seems difficult that only one technology can guarantee an effective and reliable solution for all operation conditions and needs. **The development of multi-sensors data fusion system seems to be the only viable perspective to properly satisfy autonomous driving requirements.** Indeed, each sensor presents strengths and weaknesses and the multi-sensors data fusion system can take advantage on the specific strengths of a sensor to overcome weaknesses of other sensors.

This approach can be well explained considering as example the implementation of the obstacle detection function. The RADAR can operate effectively on long distance and in any light and weather conditions. However, it has a scarce capability to precisely reconstruct the surrounding environment and it is not effective in detecting small non-metallic surfaces such as people or animals. These can instead be effectively detected using infrared camera. Visual cameras can also be a good solution for identifying people. Indeed, thanks to

image processing, visual cameras allow to detect and also to classify the obstacle type. However, they may experience performance issues related to the operative range, to bad weather conditions and to night time periods. A multi-sensors data fusion system including the mentioned sensors may properly satisfy the detection of obstacles regardless the obstacle types and the environmental conditions.

Lastly, the following concluding remarks can summarize the main high-level outcomes of the WP3 activities:

- **Technologies for autonomous driving can be reused in the railways**, however a specific design of the sensors has to be performed to take into account the peculiar characteristics of the railway sector such as speed, braking distance, railway environment;
- **The automated driving system of a train needs to satisfy different requirements for the same ATO function**, e.g., the obstacle detection function has to take into account that an obstacle can be a rock or a person, or that it can have a very large or small surface;
- **It is difficult that a single technology can guarantee to satisfy a requirement in all conditions and cases**, a multi-sensors data fusion system, which exploits more than one technology, is expected to provide a more accurate, reliable and effective solution.

Acronyms

Acronym	Explanation
ATO	Automatic Train Operation
DTO	Driverless Train Operation
GNSS	Global Navigation Satellite System
GoA	Grade of Automation
LoA	Level of Automation
STO	Semi-automatic Train Operation
UTO	Unattended Train Operation

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