OPERATIONAL SCENARIOS

D2.2

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D2.2 – OPERATIONAL SCENARIOS

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VERSIONS OF THE DOCUMENTS

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0.1	24/01/2020	Initial structure of document
0.2	17/02/2020	Initial input from DB
0.3	03/03/2020	Input from DB
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1.0	26/10/2020	Stable Version DB
1.1	29/10/2020	Consistent numbering and naming; cosmetic changes
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2.0	13/11/2020	Final version
2.1	25/11/2020	Integrated reviews by ADS
2.2	27/11/2020	Integrated review comment by ADS
2.3	14/01/2021	DRS review integrated
2.4	22/01/2021	Feedback from DRS review meeting integrated

EXECUTIVE SUMMARY

This document is the deliverable "D2.2 – Operational Scenarios" of the European project "CERTIFIABLE LOCALISATION UNIT WITH GNSS IN THE RAILWAY ENVIRONMENT" (hereinafter also referred to as "CLUG").

The purpose of the Operational Scenario definition is to specify operations, scenarios and environmental conditions for a train run under which the system under consideration has to function according to the specification.

The definition of scenarios includes standard situations, but also challenging environments and situations which might define design parameters and impact the key performance of the localisation system. The operational scenarios might be influenced, for example, by conditions and parameters such as a maximum length of GNSS shading, GNSS multipath or non-line of sight (NLOS) effects or challenging manoeuvres for inertial measurement units (IMUs) including shock and vibration.

This deliverable is to be used by the project in particular by WP4 for data acquisition and testing.

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APPLICABLE DOCUMENTS

The following documents define the contractual requirements that all project partners are required to comply with:

- Grant Agreement N°870276 (which includes DOW, Grant Preparation Forms and annexes): This is the contract with the European Commission which defines what has to be done, how and the relevant efforts.
- Consortium Agreement: This defines our obligations towards each other.

Each of the above documents was established at the start of the project, and copies were supplied to each partner. Each document could potentially be updated independently of the others during the course of the project following a prescribed process. In the event of any such update, the latest formal issued version shall apply.
In the event of a conflict between this document and any of the contractual documents referenced above, the contractual document(s) shall take precedence.

REFERENCES

[1] High Level Principles, Railways Localisation System High Level Users' Requirements, ERTMS Users Group (EUG) LWG, Version 2, Released: 10/12/2019, https://ertms.be/workgroups/localisation_working_group.

[2] Mission Profiles, Localization Performance Requirements form use cases, ERTMS Users Group (EUG) LWG, Version 3, Released: 10/12/2019, https://ertms.be/workgroups/localisation_working_group.

[3] CLUG Mission Requirements from WP 2 (Deliverable 2.1)

[4] CLUG System Requirements from WP 2 (Deliverable 2.3)

[5] DIN EN 50121-3-2:2016/A1:2019 (VDE 0115-121) Railway applications – Electromagnetic Compatibility – Rolling stock apparatus

[6] DIN EN 50125:2014 (VDE 0115-108) Railway applications – Environmental conditions for equipment

[7] DIN EN 50155:2017 (VDE 0115-200) Railway applications – Rolling stock – Electronic equipment

[8] DIN EN 61373:2010 (VDE 0115-106) Railway Applications – Rolling stock equipment – Shock and vibration tests

[9] German railway regulations „EBO Eisenbahn-Bau- und Betriebsordnung“ (BGBl. 1967 II S. 1563, last changed on 5. April 2019 (BGBl. I S. 479))

[10] DIN EN 45545:2020 Railway applications - Fire protection on railway vehicles

[11] UIC 758:2005 Use of mobile radio on the railways - antennas

[12] UIC 533:2011 Vehicles protection by earthing of metal parts

[13] TSI (EU) 132/2014 Locomotives and passenger rolling stock (LOC&PAS), Released: 18/11/2014

ACRONYMS

1 INTRODUCTION

1.1 Identification, Purpose and Usage

The definition of operational scenarios is essential not only to identify use cases, but also the environmental and situational conditions under which a train localization system must fulfil the functional and non-functional requirements.

The definition of scenarios includes standard situations, but also challenging environments and situations which might define design parameters and the key performance of the localisation system. The operational scenarios might be influenced, for example, by parameters such as a maximum length of GNSS shading, GNSS multipath or non-line of sight (NLOS) effects or challenging manoeuvres for inertial measurement units (IMUs) including shock and vibration. These scenarios are then provided to WP4 to derive dedicated test cases and to record real world data with test trains.

Users	Outputs
WP4	Derive test cases and record real world data
Requirements Team	Read the operational scenarios and formulate the requirements to be best suiting for the operations

Table 1 Usage of document

The description of the D2.2 operational scenarios consists of this document and the accompanying table "**D2.2_Operational_Scenario_Table**" containing the operations, conditions, affected sensors and the derived scenarios.

1.2 Context

The ETCS (European Train Control System) is part of the ERTMS (European Railway Train Management System) and focuses on interoperability between the European countries. This means it is designed to replace the more than 20 different national train control systems in Europe and allows for a trans-European railway operation.

Today ETCS baselines define several modes to operate a train (such as full supervision, limited supervision, staff responsible, reversing, shunting etc.). These modes have different prerequisites on available information to the ETCS system. Even though they are defined for the different ETCS levels not all modes have to be implemented. The CLUG TLOBU is designed to be used as a future ETCS onboard localization system, the actual ERTMS integration is not in the scope of the project. For this reason, the defined ETCS modes will not be discussed here. However, the underlying operational scenarios will be defined.

1.3 Prior Assumptions

The following assumptions are considered:

Serial Number	Assumption	Examples
1	Once the train unit is powered up, the TLOBU is assumed to be ready for initialisation irrespective of the operational state of the train.	Start up or power off state of the train unit is not in the scope of the project, therefore the TLOBU unit is assumed to be switched on and ready for initialisation.
2	Rail-road vehicles and similar track maintenance trains and actions do not require the TLOBU localisation unit.	During track maintenance the section of the track is occupied and blocked (engineering possession). A TLOBU is not required inside the section. (This does not apply to maintenance train where during the train run from and to the maintenance site, the localisation is required.)
3	The TLOBU does not rely on axle counters for a track selective localization.	According to [4] D2.3 SFUNC-10, the system has to provide a track selective positioning. Axle counters are not part of the system and therefore the system has to provide the positioning within a sufficient across track error at any time.
4	The TLOBU does not require Euro-balises for a relocation or along track error limitation.	According to [4] D2.3 SFUNC-10, the system has to provide a track selective positioning. Balises are an optional part of the system and therefore the system has to provide the positioning within a sufficient along track error, if no balises are present. In some environmental conditions where GNSS is not available and IMU drift is too high, balises are optional for track selective localization purposes.
5	Track Selectivity is required during operations for supervision of the location and movement authority.	According to [4] D2.3 SFUNC-10, the system has to provide a track selective positioning. The track selectivity shall be independent of any environmental condition or operation scenario. Therefore, the system has to provide the positioning within a sufficient across track error at any time.
6	Restricted or degraded measurements of any sensor are in scope and considered nominal conditions, only defects of sensors are out of scope regarding the operational scenarios.	Only defects of sensors are out of scope, restricted or degraded measurements, due to any environmental conditions, are considered in scope and need to be handled or mitigated by the system. Any environmental conditions defined in the operational scenarios are considered nominal conditions, under which the system is expected to operate according to specifications.
7	The system is operating within the limits of the specification and the system requirements prior to conducting an operational scenario.	The precondition of each operational scenario is a nominal and non-degraded behaviour of the TLOBU within the limits of the specification and the system requirements, e.g. it is assumed, that the train unit has not run several kilometres inside a tunnel

		leading to degraded accuracy of the position before conducting an emergency brake.
8	Erroneous or outdated maps are out of scope regarding the operational scenarios.	In any scenario, it is assumed that the map data is available, correct and up to date. Availability of map data is assumed to be present in any condition.
9	GNSS augmentation data unavailability and system events causing an outage of GNSS are out of scope regarding the operational scenarios.	In any scenario, it is assumed that GNSS augmentation data is available, correct and up to date. Availability of augmentation is assumed to be present in any condition. A nominal operation of the GNSS system is present, including no presences of GNSS system events or relevant ionospheric or tropospheric effects. Availability of GNSS augmentation data is assumed to be present in any condition in any condition, or at least with a better availability than GNSS signal reception availability, but in this case assumption 6 and 11 apply and it is therefore out of scope.
10	GNSS spoofing and GNSS jamming are out of scope regarding the operational scenarios.	GNSS spoofing and jamming are external events leading to outage of the system or a maliciously incorrect position independent of operational conditions or scenarios. The detection and avoidance or mitigation of those events shall be part of the safety case.
11	The system is assumed to be fully functioning in any environmental condition according to required railway certifications (e.g. temperature conditions or electromagnetic conditions).	Environmental conditions and electromagnetic interference effects, according to DIN/EN railway approval and standards (e.g. [5] EN50121, [6] EN50125, [7] EN50155, [8] EN61373, [10] EN45545, [11] UIC758 and [12] UIC533 etc.), are assumed to nominal operating conditions and therefore the system operation shall be independent of these in any operational scenario or conditions. Any environmental conditions defined in the operational scenarios are considered nominal conditions, under which the system is expected to operate according to specifications.
12	Irregularities and special circumstances (e.g. as defined in Section 3.4 Irregularities) are out of scope of the operational scenarios for the CLUG system.	This includes, among other, track closures due to engineering passion of the line or other irregularities and special circumstances, such as insertion of rail-road vehicles onto a track section, moving of rail-road vehicles within a track section, uncoupled pushing of trains using bank engines, irregularities requiring reversing/pushing of a train with localization at train tail etc.

Table 2 Assumptions

2 APPROACH

The **Concept of Operations** defines how the business operates and is independent of the concrete system or the technology (partly reflected in the [4] D2.3 High mission requirements).

The **Operational Concept** contains besides economic considerations for the customer also the system capabilities and **Tactical Railway Operations:**

- [T1] Prepare train unit for mission
- **[T2] Perform mission movement**
- [T3] Perform freight exchange
- [T4] Perform passenger exchange
- [T5] End of mission

For the definition of the relevant operational scenarios for CLUG, we focus on T2 (Perform mission movement).

Figure 1 CLUG Scope

In order to systematically define all scenarios, operations and environmental conditions, these are defined separately. Operational scenarios are then derived by combination of those and decomposition into specific scenarios. All environmental conditions identified are based on expert and domain knowledge as completely as possible. This allows a further formal and methodological approach to derive a complete list of scenarios within the extend of identified conditions.

First, the categorization of scenarios by operation, track section and movement type are conducted in **Section 3** Categorization of scenarios (e.g. shunting unit acceleration in a station track section).

Second, the environmental conditions are defined in **Section 4 Sensor impact by Environmental conditions**. Environmental conditions met in railway operation are listed. Afterwards the environmental conditions affecting a sensor and leading to specific sensor errors are identified. This is done by deriving effect-cause diagrams with applicable environmental conditions with regard the relevant sensor error for each sensor (e.g. GNSS denied environment is caused by tunnels, station roofs etc.).

Third, for each scenario, the applicable environmental conditions are identified in a table overview in **Section 5 Operational Scenarios Methodology.** Here the affected sensor by the specific environmental condition in this scenario is determined (e.g. initialisation within a tunnel is affected by GNSS outage).

Last, by decomposition of each scenario into each applicable environmental condition, a specific operational scenario is derived in **Section 6 Scenario Decomposition** (e.g. acceleration in a tunnel). This decomposition of all scenarios into each applicable environmental condition will result in a methodologically derived list of operational scenarios.

However, for the purpose of deriving test cases, individual operational scenarios and multiple environmental conditions and operations can be considered together.

Test cases are therefore to be derived by combination of operational scenarios in specific sequences (e.g. standstill, acceleration, constant speed and deceleration in a tunnel). The sum of all test cases shall then cover all individual operational scenarios, as far as possible.

3 CATEGORIZATION OF SCENARIOS

The categorization of scenarios by operation, track section and movement type are conducted is this section.

3.1 Operations

Conducted typical operations in the railway environment are as follows:

- **#1** Initialising
- **#2** Start rolling from standstill
- **#3** Acceleration
- **#4** Normal running (Drive with constant speed)
- **#5** Deceleration and target stop to standstill
- **#6** Standstill
- **#7** Coupling drive*

3.2 Track sections

These operations can be conducted in different track section:

- **A** Station
- **B** Open Track

3.3 Movement types

Further three train movement types can be separated:

- Shunting movements
- Train movements
- Train movements in closed track sections ("Sperrfahrten" e.g. track closure due to engineering possession of the line or irregularities)

These movement types can be conducted in any track section defined above. Train movements in closed track sections are considered as train movements as well and therefore are not further differentiated in operational scenarios.

3.4 Irregularities

Irregularities and special circumstances are out of scope of the operational scenarios for the CLUG system as defined in assumption 12. Specific irregularities are defined as following, but not necessarily complete, as no claim to completeness can be made:

- **C** Conversion/Insertion of rail-road vehicles onto a track section
- **D** Moving of rail-road vehicles within a track section
- **E** Uncoupled pushing of trains using bank engines
- **F** Irregularities requiring reversing/pushing of a train with localization at train tail
- **G** Level crossing protection
- **H** Train tail localization to ensuring the evaluability e.g. in an emergency brake override area

3.5 Categories

This results in the following categories defined:

Section and Movement	#	Operation/Description
A **Shunting Movements within station area**	1	Initialization
	2	Start rolling from standstill
	3	Acceleration
	4	Normal running (Drive with constant speed)
	5	Deceleration (Target stop to standstill)
	6	Standstill
	7	Coupling drive
B **Train movements within station area and track sections**	1	Initialization
	2	Start rolling from standstill
	3	Acceleration
	4	Normal running (Drive with constant speed)
	5	Deceleration (Target stop to standstill)
	6	Standstill
C*	Conversion/Insertion of rail-road vehicles onto a track section	
D*	Moving of rail-road vehicles within a track section (Localization of road rail vehicle)	
E*	Banked/Pushed train (Uncoupled pushing of trains using bank engines)	
F*	Irregularities requiring reversing/pushing of a train with localization at train tail	
G*	Level crossing protection	
H*	Ensuring the evacuability (Localisation of entry and exit of emergency brake override area (NBÜ) e.g. tunnels, bridges, outside stations)	

Table 3 Categories defined by operations, areas and movement type

*** #7 coupling drive and C, D, E, F, G and H** are listed here for completeness but considered out of scope for the system as defined in assumption 2. Operation of these is handled currently by generally accepted codes of practice and operating regulations. Within the scope of the project it is assumed, that these will remain for the time being and hence a TLOBU system is currently not yet required.

4 SENSOR IMPACT BY ENVIRONMENTAL CONDITIONS

Several local environmental conditions can have an adverse impact on the performance of the Train Front Localization system. In this chapter, the major environmental conditions that affect the following sensors are considered:

4.1 SENSORS

- GNSS
- IMU
- Wheel encoder
- Optional: Doppler Radar
- Optional: Optical Encoder

Balises are optional for track selective localization purposes, as defined in assumption 4, in case of some environmental conditions where GNSS is not available and a significant IMU drift is present for a prolonged duration, which leads to an error above the required lateral across track accuracy to determine track selectivity. Based on the required track spacing of 4.0 meters (down to 3.5 meters in existing legacy tracks and 3.8 meters for track uniquely used by s-trains) according to reference [9] §14 EBO, this results in a maximal lateral across track error of 2.0 meters (1.75 meters) to determine track selectivity. Balises and the reading modules are assumed to be working independent of environmental conditions, therefore balises are not further considered in the operational scenario or regarding environmental conditions.

The map is assumed to be available, up-to-date, correct and not impacted by operational scenarios, as defined in assumption 8.

4.2 CONDITIONS

In general, for any sensor the following conditions have been identified to impact the system performance and grouped into 8 categories. Where applicable, a parameterization has been defined as proposal for the derivation of test case. Proposed parameters are generic assumptions estimated by expert and domain knowledge and not based on official regulations, which shall be applicable to all European railways and networks. Specifically, the German railway network has been considered by the authors and parameters have been reviewed and agreed by the contributors, with regard to the France and Swiss networks.

Parameters for conditions stated as “n/a” cannot be defined quantitatively. There is no fixed, unique threshold or measurement for this particular parameter, it is situational dependent always an occurrence more or less to a certain degree.

4.2.1 Driving behaviour

Standstill	Maximal < 3 km/h or slower, depending on technical solution and capability (reference LOC&PAS [13] 4.2.5.5.2 (5))
Acceleration: weak	≈0,02m/s² to ≈0,1 m/s²
Acceleration: strong	≈0,1m/s² to ≈0,7m/s² (≈1,2m/s²)

Speed: slow	>0km/h (different to standstill) to ≤25km/h
Speed: normal	>25km/h to ≤160km/h
Speed: fast	>160km/h to max. speed (500km/h)
Deceleration: service braking	≥3,5 Bar brake pipe pressure or ≈< -0,8m/s^2
Deceleration: full braking	≈3,5 Bar brake pipe pressure or ≈> -0,8m/s2 to ≈< -1,2m/s^2
Deceleration: emergency braking	≈0 Bar brake pipe pressure or ≈> -1,2m/s^2

4.2.2 Operational conditions

Traction power applied	up to ≈550kN for freight trains with screw couplers or respective maximal starting tractive effort for other trains
Tilting Trains	Tilt up to 8,6°
Train weight: light train or locomotive only	n/a, see 4.4 Wheel encoder: Slip and Slide and 4.5 IMU: Shock and Vibration
Train weight: heavy train	
Power distribution: loco hauled	
Power distribution: multiple unit	
Brake distribution: unbraked vehicles	
Brake distribution: all braked vehicles	

4.2.3 Track parameters

Track type: slab track	n/a, see 4.5 IMU: Shock and Vibration and 4.7 Doppler Radar: restricted measurements
Track type: ballasted track	n/a
Electrification: overhead line	n/a
Electrification: conductor rail	n/a
Electrification: no electrification	n/a

4.2.4 Topology/Track elements

Straight section	n/a
Curves and curve transitions	depending on track,

	speed and superelevation: ≥300m curve radius main lines (≥180m curve radius for branches/secondary lines) at ≤40km/h till ≈4000m curve radius with ≈300km/h at 160mm superelevation (reference [9] §40 EBO)
Switches (moveable and non-moveable frog point)	n/a, see 4.5 IMU: Shock and Vibration and 4.7 Doppler Radar: restricted measurements
Railway crossings	n/a, see 4.7 Doppler Radar: restricted measurements
Rail joints	n/a, see 4.5 IMU: Shock and Vibration

4.2.5 Topography/Wayside elements

Flat section	n/a
Inclination: upwards slope	max. 12,5 ‰ main lines (40 ‰ for secondary lines) - step routes up to ≈60-70 ‰ (in DE)
Inclination: downwards slope	max. 12,5 ‰ main lines (40 ‰ for secondary lines) - step routes up to ≈60-70 ‰ (in DE)
Tunnels	≈10km (in DE) to max. 57km (in CH), underground railway lines and underground stations (e.g. Berlin North to South) up to ≈6 - 10km
Bridges	max. ≈6,5km (in DE), viaducts possibly longer (e.g. Berlin Stadtbahn ≈11km)
Super elevation	up to 180mm (in DE), transition up to 1:400
Overcrossings and undercrossings	n/a, height and width at least limited by clearance gauge
Noise barriers	possibly higher than 4m (up to ≈6m), distance to rail centreline min. 3,60m to 3,80m
Railroad cuts	n/a, width at least limited by clearance gauge
Railroad embankments	n/a
Platforms and roofs	up to 432m length (Berlin Spandau), especially terminus stations up to ≈400m
Vegetation between rails/encrustation	n/a

4.2.6 Geographical and surrounding conditions

Open sky	n/a, see 4.3.1 GNSS Open Sky
Forests and vegetation	n/a see 4.3.2 GNSS Multipath
Mountains	
Canyons	
Urban area and large structures	
Metal structures and masses	

4.2.7 Environmental and weather conditions

Snow and closed snow cover	n/a see 4.4 Wheel encoder: Slip and Slide, 4.7 Doppler Radar: restricted measurements, and 4.8 Optical Encoder: restricted measurements
Ice and icing	
Leaves and plants	
Rain	
Fog and Humidity	
Dust and dirt	

4.2.8 Traffic conditions

Parked trains	up to 740m (835m)
Oncoming trains	up to 740m every ≈90s to ≈120s on every rail
Passing trains	up to 740m every ≈90s to ≈120s on every rail

In the following, relevant conditions have been identified which cause effects resulting in sensor error. Effect cause diagrams (also known as *fishbone diagrams*) have been used as a tool, as shown in the generic, complete example diagram below.

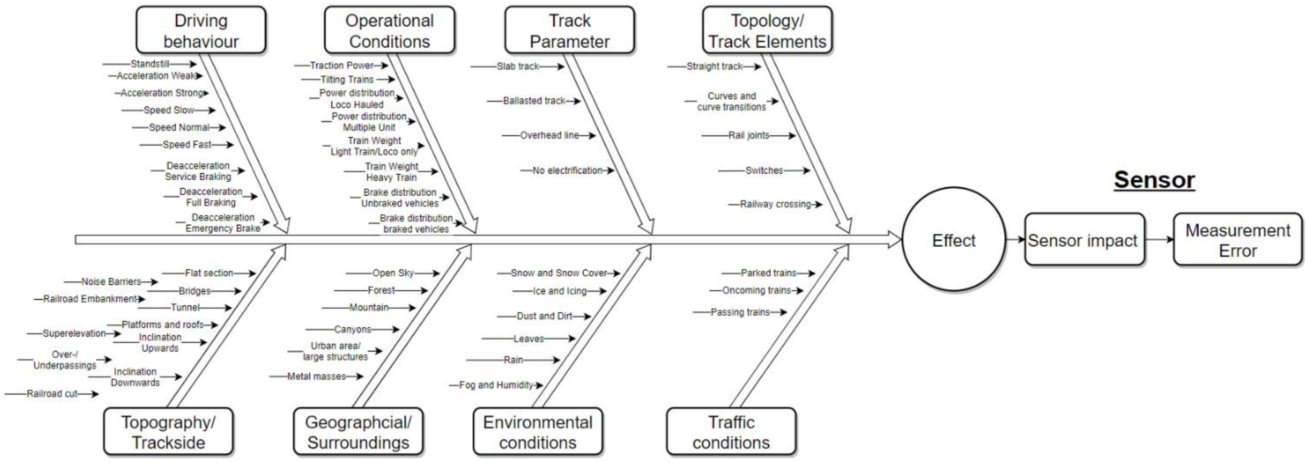


Figure 2 Generic effect cause diagram with all conditions

4.3 GNSS: Multipath and Shadowing

4.3.1 GNSS Open Sky

Open sky represents the best environmental condition for the uncompromised performance of a GNSS receiver. An open sky environment is typically characterized by a good satellite visibility and good satellite geometry.

GNSS is additionally impacted by general circumstances, which are independent of the operation scenario:

- Latitude and Longitude position of system
- Availability of GNSS corrections

However, effects might compromise GNSS performance. These effects are listed and described in the following:

4.3.2 GNSS Multipath

Multipath and interference represents one of the most challenging environments for GNSS receivers. Multipath and interference typically occur in urban environments where operational scenarios such as shunting, coupling, station approach are likely to happen. Coupled together with the high-performance requirements required for such operations and the high likelihood of positioning errors due to decreased GNSS performance, this makes multipath effects one of the most challenging environments for the Train Front Localization system in general. Multipath effects can significantly be amplified by reflecting environments, e.g. snow or rain on trees in forests or by metal structures.

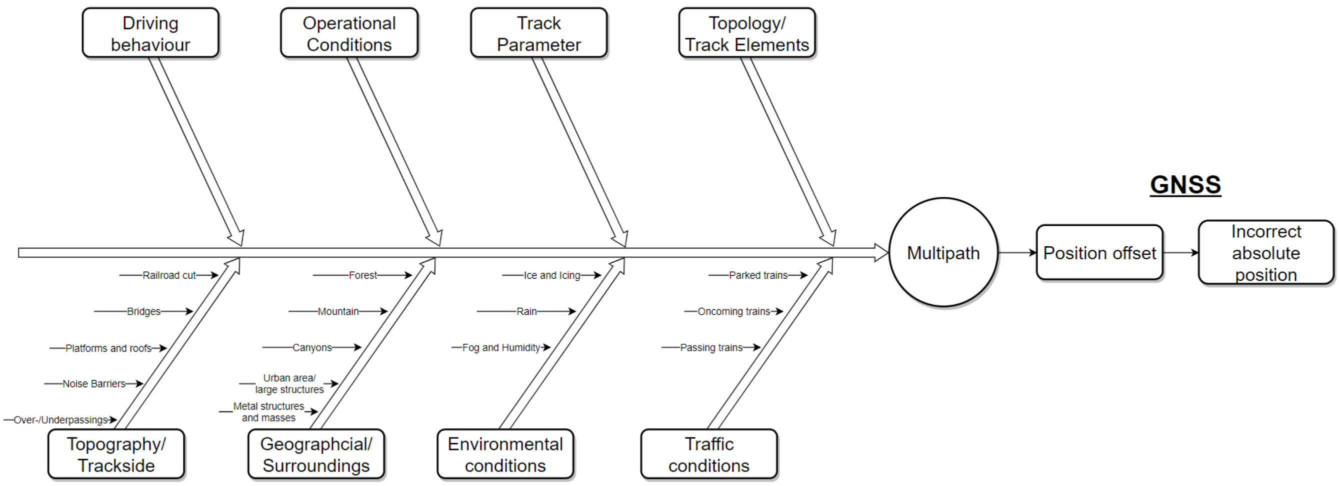


Figure 3 GNSS multipath effect cause diagram

4.3.3 GNSS Denied – shadowing and outage

GNSS denied environments in which no satellite signals are available at all, like tunnels, underground train stations, roofs other closed environments represent a challenge for the design of the Train Front Localization system whose primary positioning sensor is GNSS.

Other environments, like large structures, mountains, canyons, trains etc. are shadowing GNSS reception and therefore reduce the number of available satellites significantly. Once the number of satellites is reduced below a minimal required number, e.g. less than 4 satellites, the GNSS becomes unavailable. Additionally, poor satellite geometry affects GNSS performance significantly due to a high DOP. However, satellite geometry is independent of the operational scenario, but dependant on global external circumstances and therefore not considered additionally here. GNSS denied environments or shadowing may also restrict the availability of GNSS correction data, if correction data, e.g. SBAS, is transmitted via satellites.

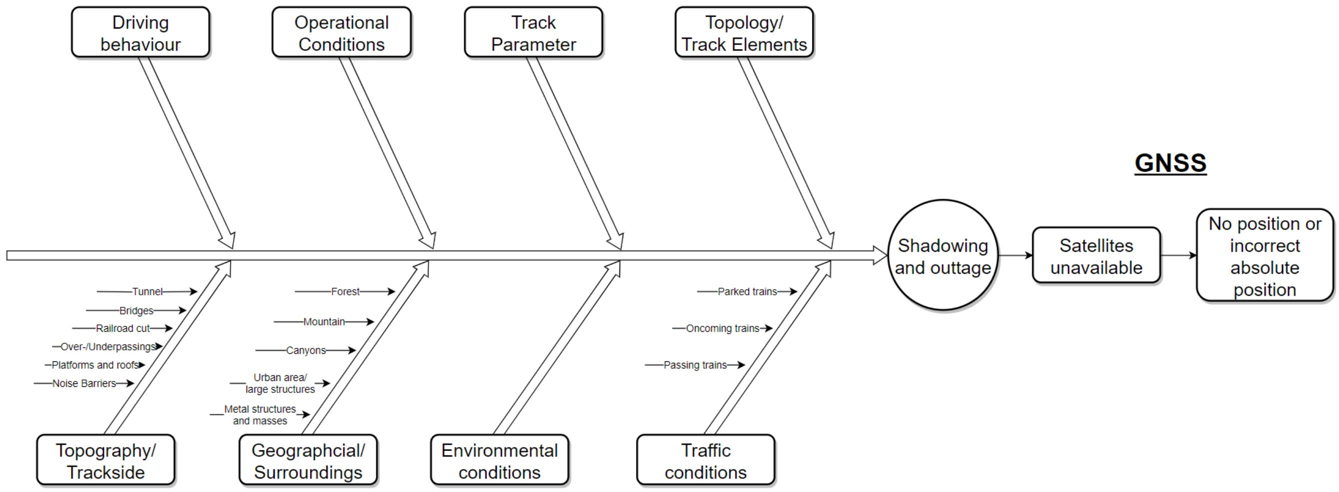


Figure 4 GNSS denied effect cause diagram

4.3.4 GNSS Ionospheric and Tropospheric Effects

Most GNSS receivers and corrections services i.e. Precise Point Positioning, Space-based augmentation Systems have good models for typical ionospheric and tropospheric activity. However, excessive ionospheric scintillation and extreme local tropospheric activity represent local environmental conditions that are typically harder to model and mitigate. According to assumption 9, these effects are out of scope, as the occurrence of these phenomena are independent of a specific railway environment.

4.3.5 GNSS System Events

Typical GNSS system wide events e.g. satellite manoeuvres, invalid satellite ephemeris, unhealthy ephemeris is usually broadcast in advance to all GNSS receivers. However, it is possible that there are system wide events that adversely impact the performance of GNSS receivers are not broadcast in advance thereby leading to performance issues. Typical system wide events include:

- Unknown satellite manoeuvres
- Invalid satellite ephemeris being broadcast as valid ephemeris
- IODE anomaly
- Year roll over (known system wide event that frequently leads to issues)
- System outage (e.g. Galileo incident in 2019)
- Corrupted satellite clock

This also includes malicious system wide events, such as:

- GNSS spoofing
- GNSS jamming

According to assumption 9, these effects are out of scope, as the occurrence of these phenomena are independent of a specific railway environment.

4.4 WHEEL ENCODER: SLIP AND SLIDE

In general, systematic or random errors can largely impacting the performance of the wheel encoder independent of the environmental conditions. An accurate measurement by the wheel encoder is requiring a mounting on passive axles, as motorized or braked axle are showing significantly larger slip and slide. Additionally, the wheel encoder requires the correct diameter or circumference of the wheel to accurately measures the travelled distance. The diameter is impacted however by continuous wear or defects and needs to be correctly recalibrated after any changes due to maintenance. Systems may include an estimator for the continuous wear.

- **Type of mounting:**
    - Passive axle
    - Motorized/braked axle

- **Maintenance/Wear:**
    - Diameter/Circumference of wheels
    - Maintenance
    - Wear
    - Hot Box / Axle
    - Flat spots on the wheel

Environmental conditions that induce additional slip and slide in wheel encoders e.g. braking manoeuvres, acceleration etc. represent the typical conditions that shall be considered for the validation of the wheel encoder performance. Slip and slide is also resulting from varying friction coefficients between the wheel and rail due to environmental circumstances. These are considered nominal conditions. It is assumed, that wet leaves or wet dirt and dust may lead to even lower friction than ice or snow.

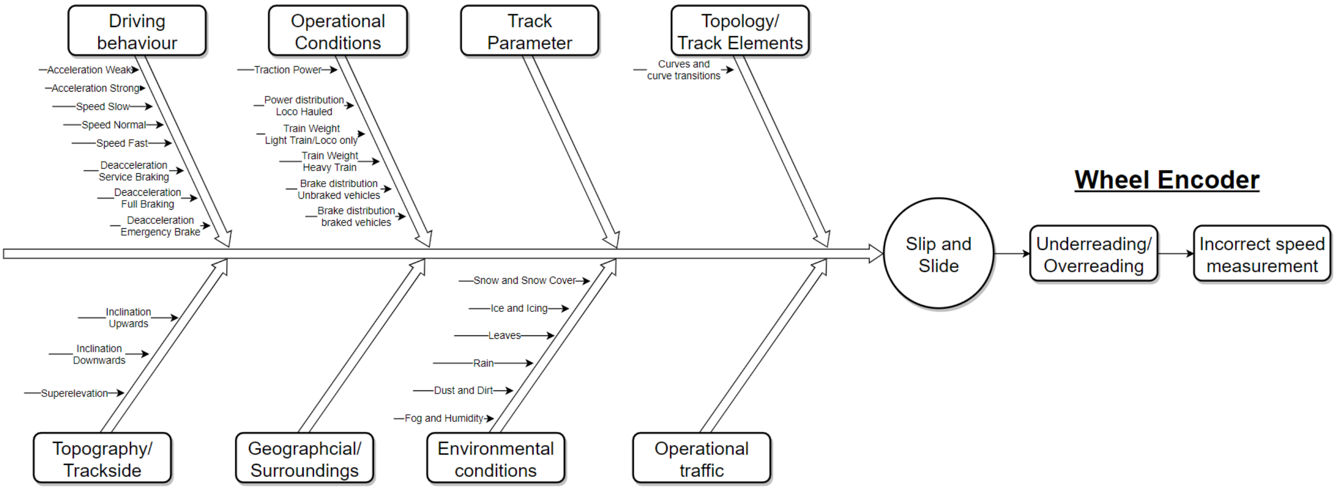


Figure 5 Wheel encoder slip and slide effect cause diagram

4.5 IMU: Shock and Vibration

It is expected that the IMU sensors are mounted in a way that minimizes shock and vibration during normal railway operation. The hunting oscillation is a fundamental phenomenon in trains which needs to be filtered and compensated. However, movements on sensors induced by shock and vibrations are considered nominal conditions.

Also, the mounting position of the IMU is highly relevant for the resulting measurement, as there is an offset and a different of movement of the boogies and the railway car body. This offset between the track centre and the IMU has to be considered during measurements.

Regarding environmental conditions, certain driving behaviour, such as strong acceleration or deceleration (e.g. emergency brake) will significantly induce additional shock and vibration in the IMU sensors. The occurring accelerations and deceleration forces depend on the train weight, brake and traction power distribution and capabilities. Very smooth tracks, such as slab track, may significantly reduce the measurable vibrations while defects in rail joint may increase vibrations. Track topography i.e. curve radius, inclinations and superelevation etc. also play a role in the accelerations measured by IMU sensor. Therefore, it is important to consider local topology and topography, e.g. curves, switches and slopes.

Occurring vibrations or shocks, as caused by oncoming or passing trains may add additional errors.

All these effects are considered nominal conditions.

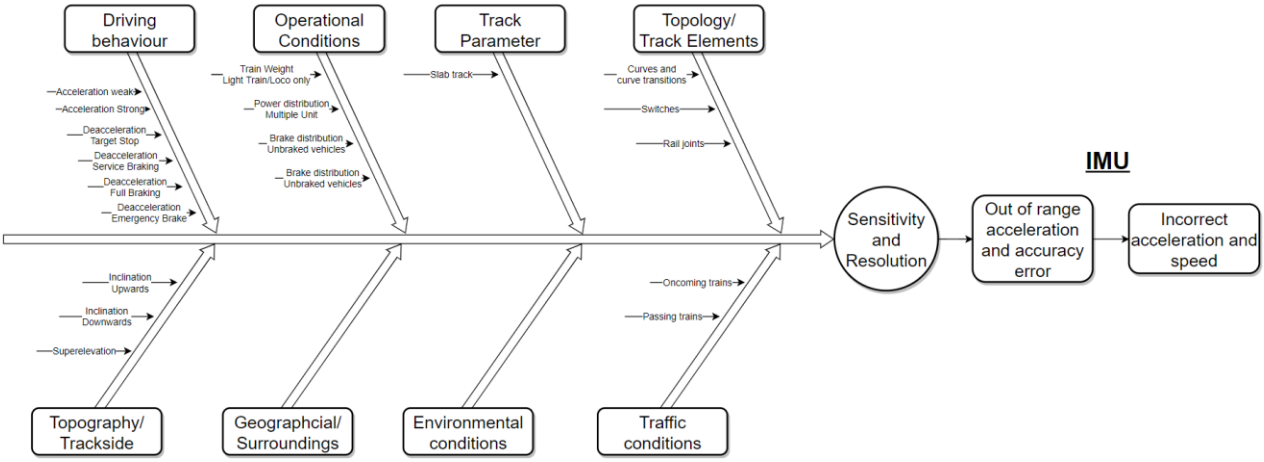


Figure 6 IMU sensitivity and resolution effect cause diagram

4.6 IMU: Drift

A major problem for the determination of position and speed by IMU measurements is the general issue of accumulated error by integrating acceleration from a relative sensor.

Even in standstill, the IMU will measure small accelerations over time and this is accumulated to a position error over time in a INS. This is known as drift. If no other absolute sensor is available, this effect cannot be corrected, and the error can grow indefinitely. Drift can be compensated by additional sensors, which detect the presence of movements, e.g. wheel encoders or optical encoder.

Occurring vibrations or shocks, as caused by oncoming or passing trains may add additional errors.

All these effects are considered nominal conditions.

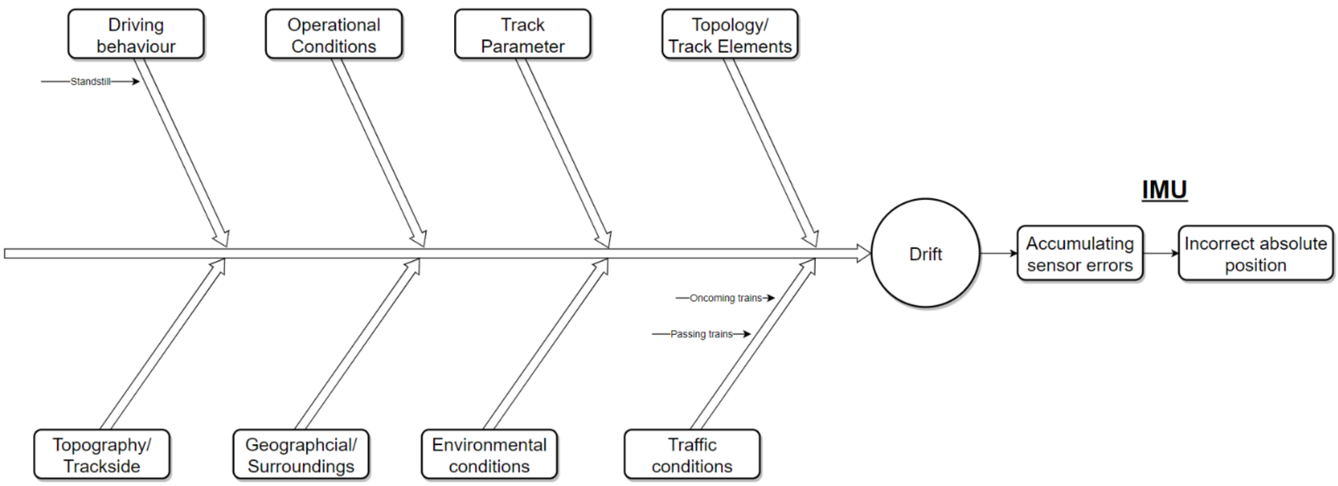


Figure 7 IMU drift effect cause diagram

4.7 Doppler Radar: Restricted Measurements

Doppler radars measure speed based on radar reflections on the ground below the train. The Doppler radar is usually mounted between rails below the train. The measurement is therefore depending on the speed of the train and the ground surface structure and texture. The Doppler radar is impacted by smooth surfaces which degrade or restrict reflections and therefore the measurements, e.g. slab track, railway crossing and especially even plane surfaces covering the rails, e.g. snow covers or water surfaces.

All these effects are considered nominal conditions.

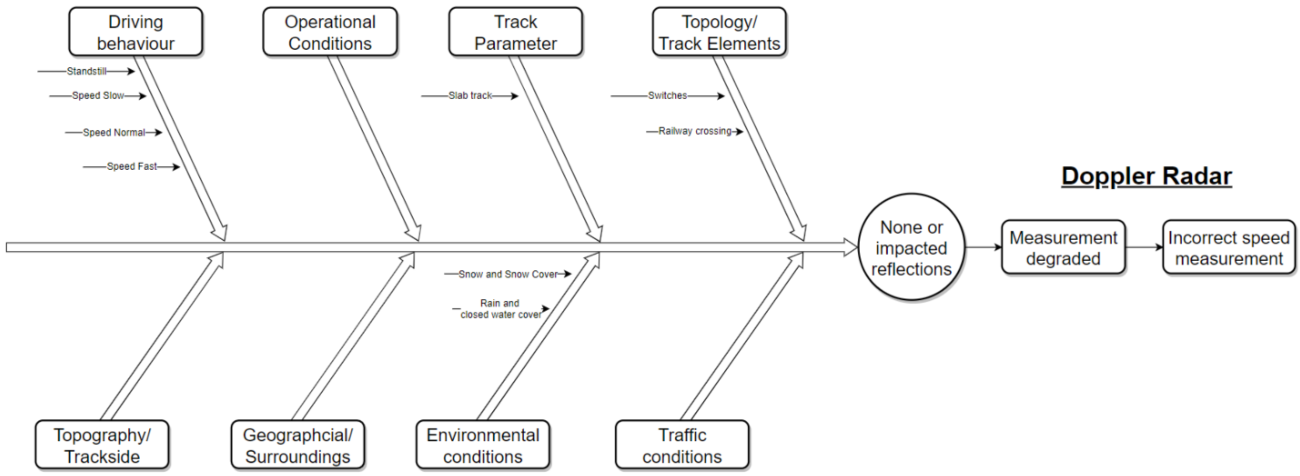


Figure 8 Doppler radar effect cause diagram

4.8 Optical Encoder: Restricted Measurements

The optical encoder (also known as *"CORRail"* sensor) uses optical reflection on the railhead surface captured by a high-frequency camera and shifts of surface structures between frames to deliver track bed independent direct speed measurement, much like an optical laser mouse. The sensor is therefore speed dependent.

The optical encoder is mainly affected by dirt or covering of the camera, e.g. snow or dirt filled and blocked sensor. Additionally, the surface and structure of the railhead and/or therefore unreadable railhead surface may impact the sensor. All these effects are considered nominal conditions.

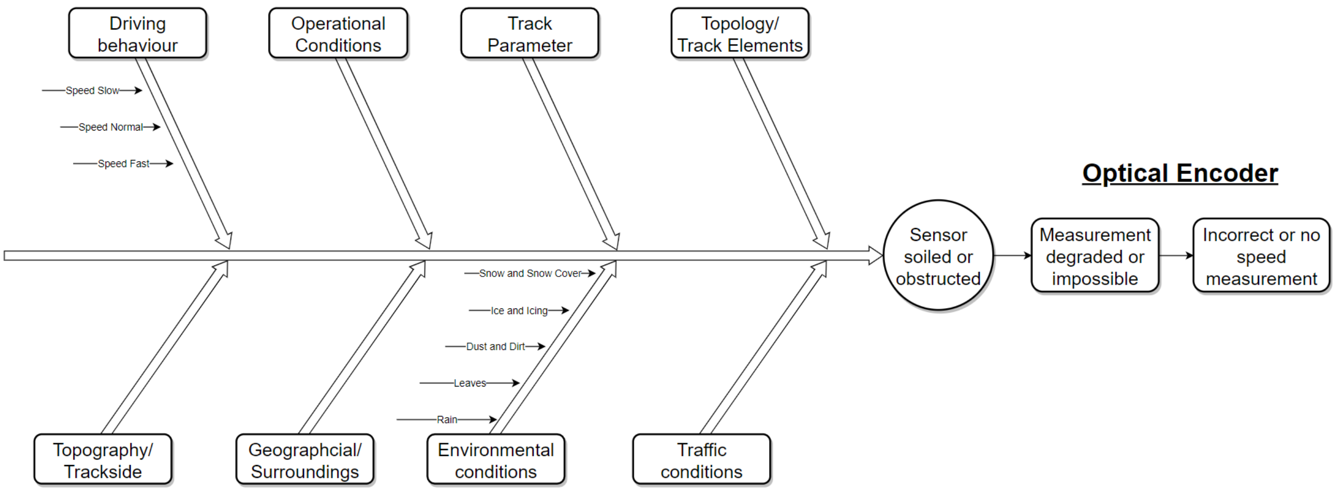


Figure 9 Optical encoder restricted measurements effect cause diagram

4.9 Operating conditions and electromagnetic interferences

Operating conditions and electromagnetic interference effects, according to DIN/EN railway approval and standards (e.g. [5] EN50121, [6] EN50125, [7] EN50155 and [8] EN61373, [10] EN45545, [11] UIC758 and [12] UIC533 etc.), are assumed to be general environmental effects and there independent of the operational scenario or conditions. These include, depending on the environmental classes, among others:

- High temperature
- Low temperature
- Humidity
- Shock
- Vibration
- Electromagnetic compatibility (EMC)

All these effects are considered nominal conditions. They shall be defined as general system requirements.

5 OPERATIONAL SCENARIOS METHODOLOGY

This section describes the accompanying table "**D2.2_Operational_Scenario_Table**" containing the operations, conditions, affected sensors and the derived scenarios.

5.1 TABULAR CATEGORIZATION BY SCENARIOS, OPERATIONS AND AREAS

Based on the previous definitions in:

- **Section 3.1 Operations**
- **Section 3.2 Track sections**
- **Section 3.3 Movement types**

the following categories, as derived and defined in **section ▯**

Categories, are listed with cross-reference to the specific operations. The relevant excerpt is shown below:

➔ Table "**D2.2_Operational_Scenario_Table**" sheet "**Operations_overview**" - **Columns A:M and rows 9:27**

ID	Track section	Operation	Short description	Examples	Operations							
					Initialising	Start rolling	Acceleration	Normal running	Deceleration	Target stop	Stop/standstill	Coupling drive
#1 (A)	Station	Shunting movements	Start up of vehicle, Initialization of vehicle, Announcement to train dispatcher	Initial localization of the vehicle at standstill	X	-	-	-	-	-	-	-
#2 (A)	Station	Shunting movements - brake pipe/air hoses connected - brake pipe/air hoses unconnected - hauled/pulled - banked/pushed - loco mid-train	Start rolling from standstill		-	X	-	-	-	-	-	-
#3 (A)	Station	Shunting movements	Acceleration		-	-	X	-	-	-	-	-
#4 (A)	Station	Shunting movements	Normal running	Absolute localization at maximum speed of 25km/h (40 km/h if free track is	-	-		X	-	-	-	-

				supervised/announced - Modul 408.4814)								
#5 (A)	Station	Shunting movements	Deceleration Target stop to standstill	Supervision of braking distances Target stop till standstill	-	-	-	-	X	X	-	-
#6 (A)	Station	Shunting movements	Standstill supervision		-	-	-	-	-	-	X	-
#7 (A)	Station	Shunting movements	Automated coupling drive with automatic coupler (e.g. Scharfenberg coupler)		-	-	-	-	-	-	-	X
#1 (B)	Station	Initialization for train movements	Start up of vehicle, Initialization of vehicle, Self-test (if required for daily preparation), Train Data Entry for Start of Mission	Train data entry in ETCS for Start of Mission Faultless operation of localization system Initial localization of vehicles	X	-	-	-	-	-	-	-
#2 (B)	Open track Station	Train Movements Train Movement in closed sections (*Sperrfahrt*)	Start rolling from standstill		-	X	-	-	-	-	-	-
#3 (B)	Open track Station	Train Movements Train Movement in closed sections (*Sperrfahrt*)	Acceleration		-	-	X	-	-	-	-	-
#4 (B)	Open track Station	Train Movements Train Movement in closed sections (*Sperrfahrt*)	Normal running	- Normal running at slow speed - Normal running at station top speed - Normal running at line top speed - *Sperrfahrt* hauled/pulled: up to top speed 50km/h - *Sperrfahrt* banked/pushed: up to top speed 20km/h	-	-	-	X	-	-	-	-

#5 (B)	Open track Station	Train Movements Train Movement in closed sections (*Sperrfahrt*)	Deceleration Target stop to standstill	Supervision of braking distances - Service braking - Full braking - Fast braking /emergency braking - Target stop till standstill/stopping point	-	-	-	-	X	X	-	-
#6 (B)	Open track Station	Train Movements Train Movement in closed sections (*Sperrfahrt*)	Standstill	- Standstill supervision - Roll-away detection	-	-	-	-	-	-	X	-
#C	Open track Station	*Sperrfahrt* Conversion/Insertion of rail-road vehicles onto a track section	Detection / localization of inserted road-rail vehicles on a track section.	Rail-road vehicles are converted and inserted in alignment with the train dispatcher on the specified track	*	-	-	-	-	-	-	-
#D	Open track	*Sperrfahrten* Moving of rail-road vehicles within a track section	Localization of moving road-rail vehicles on a track section.	Rail-road vehicles are moved in alignment with the train dispatcher on the specified track withing the worksite (engineering possession of the line	-	*	*	*	*	*	*	-
#E	Open track	Banked/Pushed Train	Uncoupled banking of trains	A train is pushed by a push/banking locomotive that is not coupled to the train	*	X	X	X	X	X	X	*
#F	Open track	Irregularities - Reversing/Pushing of a train - Localization at train tail	Returning a train to the previous station as a train movement with max. 10km/h	- Reversing a train with staff occupied train front end - Reversing a train without staff occupied train front end	-	X	X	X	X	-	X	-
#G	Open track	Train Movements	Level crossing protection	-Localization at specified point (contact point) - Target stop	-	-	-	-	-	-	-	-
#H	Open track	Train Movements	Ensuring the evacuability	Localisation of entry and exit of emergency brake override area e.g. tunnels, bridges, outside stations	-	-	-	-	-	-	-	-

Table 4 Operations_overview (excerpt from column A to M)

*** C, D, E, F, G and H** are listed here and in **section 3.4 Irregularities** for completeness but considered out of scope for the system as defined in assumption 2. Operation of these is handled currently by generally accepted codes of practice and operating regulations. Within the scope of the project it is assumed, that these will remain for the time being and hence a TLOBU system is currently not yet required.

5.2 Sensors affected by environmental conditions

Based on the previous definition in:

- **Section 4 Sensor impact by Environmental conditions**

The impacted sensors as listed in **section 4.1 Sensors**, the conditions as listed in **section 4.2 Conditions** and the resulting sensor impact as listed in **section 4.3 GNSS: Multipath and shadowing** till **section 4.8 Optical Encoder: restricted measurements** for each sensor are reflected here:

➔ Table "**D2.2_Operational_Scenario_Table**" sheet "**Operations_overview**" - **Columns N:BN and rows 3:7**

For every condition, an indication which sensors are impacted by the specific condition is given. These are congruent with the previously defined effect-cause diagrams for each sensor and effect.

Shown below is an extract from the table for any sensor affected by **Topography/Wayside elements**:

		Topography/Wayside Elements											
		Flat section	Inclination Upwards slope	Inclination Downwards slope	Tunnel	Bridges	Superel evation	Overcrossings and undercrossings	Noise Barriers	Railroad cut	Railroad embankment	Platforms and roofs	Vegetation between rails/encrustation
Affected Sensors	GNSS				X	X		X	X	X		X	
	IMU		X	X			X						
	Wheel encoder		X	X			X						
	Doppler radar												(X)
	Optical encoder												

Table 5 Operations_overview (excerpt from column N to BN)

Categorization X indicates sensors which are **significantly impacted.** Those effects are translated into individual operational scenarios later.

Categorization (X) indicates sensors which are **eventually impacted.** Those effects may not need to be translated into dedicated operational scenarios later.

5.3 SENSORS AFFECTED BY TRAIN TYPES CONDITIONS

Any scenario could possibly be conducted with different train types, e.g. loco-only, light multiple unit passenger trains or heavy loco hauled freight trains etc. A train here refers to a *train unit* as defined in CLUG terms and definitions.

The train type is therefore independent from the operational scenarios conducted and applicable environmental conditions present, however it will have a significant impact on the degree and significance of issues and degraded measurements for affected sensors. Due to the maximal available traction power, train weight and traction power distribution as well as brake distribution, the resulting accelerations and decelerations will vary significantly. Considerable impact on slip and slide is also expected.

This may vary also depending on the environment conditions, e.g. slopes or ice, snow, leaves, dirt etc. Overall, the train type will therefore influence the IMU and wheel encoder as shown below.

		Operational/train type conditions							
		Traction power applied	Tilting Trains	Train Weight Light train or Loco only	Train Weight Heavy Train	Traction Power distribution Locomotive hauled train	Traction Power distribution Multiple Unit	Brake distribution unbraked	Brake distribution braked vehicles
Affected Sensors	GNSS		(X)						
	IMU	(X)	(X)	X	(X)	X	X	X	X
	Wheel encoder	X		X	X	X	X	X	X
	Doppler radar								
	Optical encoder								

Table 6 Operations_overview (excerpt showing train categories)

However, given the actual test trains which can be used within the project, the train parameters are predetermined based on the partner undertaking the specific tests. It is expected, that the TLOBU will function and operate mostly **unaffected by of the specific train unit**.

Therefore, for reasons of simplification, the **different train types are not further considered** for the individual defined operation scenarios during decomposition.

5.4 SENSORS AFFECTED BY OPERATION SPECIFIC CONDITIONS

Each environmental condition is now combined with the respective operation, which causes the expected effect to the sensor. The degree of impact on the mentioned sensor in a specific operation is color-coded as following:

Green categori-zations	no sensor impacted or slight impact by condition	**Yellow categori-zations**	sensors affected to a significant degree	**Red categori-izations**	sensors affected critically or unavailable

Table 7 Categorization of sensor effects

Categorization in RED indicates sensors which are **critically impacted by this specific condition during the respective operation or unavailable.** Each red indicator is later decomposed and reflected into **one individual operational scenario.**

Categorization YELLOW indicates sensors which are **significantly impacted or where impacts are amplified in combination with other conditions (e.g. iced trees in a forest).** Yellow indicators are later decomposed and reflected into **combined operational scenario.**

Categorization GREEN indicates combinations where sensors are **not significantly impacted.** Green indicators are not reflected in operational scenarios.

Proposed categorizations are generic and are defined by expert and domain knowledge and not based on official regulations, however they shall be applicable to all European railways and networks. Specifically, the German railway network has been considered by the authors and categorization have been reviewed and agreed by the contributors, with regard to France and Swiss networks. The specific impact, degree of impact and possibly additional effects have to be determined and confirmed by performed test cases in WP4. Shown below is an extract from the table for any operation and the affected sensor by the conditions **"Topography/Wayside elements"**:

ID	Track section	Short description	Topography/Wayside Elements											
			Flat section	Inclination Upwards slope	Inclination Downwards slope	Tunnel	Bridges	Superelevation	Over-/Undercrossing	Noise Barriers	Railroad cut	Railroad ·	Platforms and roofs	Vegetation between rails/encrustation
Affected Sensors	GNSS					X	X		X	X	X		X	
	IMU			X	X			X						
	Wheel encoder			X	X			X						
	Doppler Radar													(X)
	Optical Encoder													
#1(B)	Station	Initialization				GN SS	GN SS		GN SS	GN SS	GN SS		GN SS	
#2(B)	Open track Station	Start rolling from standstill		Wheel Encoder IMU										Doppler Rader
#3(B)	Open track Station	Acceleration		Wheel Encoder IMU		GN SS	GN SS	IMU Wheel Encoder	GN SS	GN SS	GN SS		GN SS	Doppler Rader
#4(B)	Open track Station	Normal running				GN SS	GN SS	IMU Wheel Encoder	GN SS	GN SS	GN SS		GN SS	
#5(B)	Open track Station	Deceleration Target stop to standstill			Wheel Encoder IMU	GN SS	GN SS	IMU Wheel Encoder	GN SS	GN SS	GN SS		GN SS	Doppler Rader
#6(B)	Open track Station	Standstill		Wheel Encoder IMU	Wheel Encoder IMU									

Table 8 Operations_overview (excerpt showing sensor effects)

6 SCENARIO DECOMPOSITION

In this section, the complete list of scenarios is derived by decomposition of all previously identified sensor effects in any operation or condition into individual operational scenarios.

As described above, the decomposition is done by defining

- **a single operational scenario for every sensor effect categorized in RED** and
- **additional scenarios combining the sensor effects categorized in YELLOW**, where applicable.

All effects on a sensor categorized in **RED** or **YELLOW** are covered therefore at least in one scenario, resulting in a complete list of decomposed scenarios.

Below, the resulting tabular decomposition is shown as an excerpt for the operation deceleration.

ID	Operation	Scenario	Sensors affected	Topography/Wayside Elements									
				Flat section	Inclination Upwards slope	Inclination Downwards slope	Tunnel	Bridges	Superelevation	Over-/Undercrossings	Noise Barriers	Cut	Platforms and roofs
#5.1	**Deceleration**	Best case	-										
#5.5	**Deceleration**	Downwards Slope	Wheel Encoder IMU			**Wheel Encoder IMU**							
#5.6	**Deceleration**	Super-elevation	IMU Wheel Encoder						**IMU Wheel Encoder**				
#5.7	**Deceleration**	Tunnel	GNSS				**GN SS**						
#5.8	**Deceleration**	Bridges	GNSS					**GN SS**					
#5.9	**Deceleration**	Over- and undercrossing	GNSS							**GN SS**			
#5.10	**Deceleration**	Noise Barriers	GNSS								**GN SS**		
#5.11	**Deceleration**	Railroad cut	GNSS									**GN SS**	
#5.12	**Deceleration**	Platforms and roofs	GNSS										**GNS S**

Table 9 Scenario decomposition (excerpt showing deceleration and topography conditions).

6.1 DECOMPOSED SCENARIOS LIST

The decomposition is done for all operations. The complete list of resulting scenarios is shown below.

ID	Operation	Scenario	Sensors affected
#1.1	**Initialization**	Best case	-
#1.2	**Initialization**	Tunnel	GNSS
#1.3	**Initialization**	Bridges	GNSS
#1.4	**Initialization**	Overcrossings and undercrossings	GNSS
#1.5	**Initialization**	Noise Barriers	GNSS
#1.6	**Initialization**	Railroad cut	GNSS
#1.7	**Initialization**	Platforms and roofs	GNSS
#1.8	**Initialization**	Forests and vegetations	GNSS
#1.9	**Initialization**	Mountains and canyons	GNSS
#1.10	**Initialization**	Urban areas and large structures	GNSS
ID	**Operation**	**Scenario**	**Sensors affected**
#2.1	**Start rolling from standstill**	Best case	-
#2.2	**Start rolling from standstill**	Curve	Wheel Encoder IMU
#2.3	**Start rolling from standstill**	Upwards inclination/slope	Wheel Encoder IMU
#2.4	**Start rolling from standstill**	Snow and Ice	Optical Encoder
#2.5	**Start rolling from standstill**	Wetness and Leaves (Rain/Fog)	Wheel Encoder
#2.6	**Start rolling from standstill**	Wetness and Dirt (Rain/Fog)	Wheel Encoder Optical Encoder
ID	**Operation**	**Scenario**	**Sensors affected**
#3.1	**Acceleration**	Ideal conditions	-
#3.2	**Acceleration**	Slab track or Railway crossing (flat, smooth surfaces)	IMU Doppler Radar
#3.3	**Acceleration**	Curves and Curve transitions	Wheel Encoder IMU
#3.4	**Acceleration**	Switches (Moveable, non-moveable frog point)	IMU
#3.5	**Acceleration**	Upwards Slope	Wheel Encoder IMU
#3.6	**Acceleration**	Superelevation	IMU Wheel Encoder
#3.7	**Acceleration**	Tunnel	GNSS
#3.8	**Acceleration**	Bridges	GNSS
#3.9	**Acceleration**	Overcrossing/Undercrossings	GNSS
#3.10	**Acceleration**	Noise Barriers	GNSS
#3.11	**Acceleration**	Railroad cut	GNSS
#3.12	**Acceleration**	Platforms and roofs	GNSS
#3.13	**Acceleration**	Forests and vegetations	GNSS
#3.14	**Acceleration**	Mountains and canyons	GNSS
#3.15	**Acceleration**	Urban areas and large structures	GNSS
#3.16	**Acceleration**	Closed Snow Cover, Closed water cover	Doppler Radar
#3.17	**Acceleration**	Snow and Ice	Optical Encoder
#3.18	**Acceleration**	Wetness and Leaves (Rain/Fog)	Wheel Encoder

#3.19	**Acceleration**	Wetness and Dirt (Rain/Fog)	Wheel Encoder Optical Encoder
#3.20	**Acceleration**	Oncoming trains	GNSS IMU
#3.21	**Acceleration**	Parked or passing trains	GNSS IMU
ID	**Operation**	**Scenario**	**Sensors affected**
#4.1	**Normal running** **Drive with constant speed**	Best case	
#4.2	**Normal running** **Drive with constant speed**	Slab track or Railway crossing (flat, smooth surfaces)	IMU Doppler Radar
#4.3	**Normal running** **Drive with constant speed**	Curves and Curve transitions	Wheel Encoder IMU
#4.4	**Normal running** **Drive with constant speed**	Switches (Moveable, non-moveable frog point)	IMU
#4.5	**Normal running** **Drive with constant speed**	Superelevation	IMU Wheel Encoder
#4.6	**Normal running** **Drive with constant speed**	Tunnel	GNSS
#4.7	**Normal running** **Drive with constant speed**	Bridges	GNSS
#4.8	**Normal running** **Drive with constant speed**	Overcrossings and undercrossings	GNSS
#4.9	**Normal running** **Drive with constant speed**	Noise Barriers	GNSS
#4.10	**Normal running** **Drive with constant speed**	Railroad cut	GNSS
#4.11	**Normal running** **Drive with constant speed**	Platforms and roofs	GNSS
#4.12	**Normal running** **Drive with constant speed**	Forests and vegetations	GNSS
#4.13	**Normal running** **Drive with constant speed**	Mountains and canyons	GNSS
#4.14	**Normal running** **Drive with constant speed**	Urban areas and large structures	GNSS
#4.15	**Normal running** **Drive with constant speed**	Closed Snow Cover, Closed water cover	Doppler Radar
#4.16	**Normal running** **Drive with constant speed**	Snow and Ice	Optical Encoder
#4.17	**Normal running** **Drive with constant speed**	Wetness and Leaves (Rain/Fog)	Wheel Encoder
#4.18	**Normal running** **Drive with constant speed**	Wetness and Dirt (Rain/Fog)	Wheel Encoder Optical Encoder
#4.19	**Normal running** **Drive with constant speed**	Oncoming trains	GNSS IMU
#4.20	**Normal running** **Drive with constant speed**	Parked or passing trains	GNSS IMU

ID	Operation	Scenario	Sensors affected
#5.1	**Deceleration**	Best case	-
#5.2	**Deceleration**	Slab track or Railway crossing (flat, smooth surfaces)	IMU Doppler Radar
#5.3	**Deceleration**	Curves and Curve transitions	Wheel Encoder IMU
#5.4	**Deceleration**	Switches (Moveable, non-moveable frog point)	IMU
#5.5	**Deceleration**	Downwards Slope	Wheel Encoder IMU
#5.6	**Deceleration**	Superelevation	IMU Wheel Encoder
#5.7	**Deceleration**	Tunnel	GNSS
#5.8	**Deceleration**	Bridges	GNSS
#5.9	**Deceleration**	Overcrossings and undercrossings	GNSS
#5.10	**Deceleration**	Noise Barriers	GNSS
#5.11	**Deceleration**	Railroad cut	GNSS
#5.12	**Deceleration**	Platforms and roofs	GNSS
#5.13	**Deceleration**	Forests and vegetations	GNSS
#5.14	**Deceleration**	Mountains and canyons	GNSS
#5.15	**Deceleration**	Urban areas and large structures	GNSS
#5.16	**Deceleration**	Closed Snow Cover, Closed water cover	Doppler Radar
#5.17	**Deceleration**	Snow and Ice	Optical Encoder
#5.18	**Deceleration**	Wetness and Leaves (Rain/Fog)	Wheel Encoder
#5.19	**Deceleration**	Wetness and Dirt (Rain/Fog)	Wheel Encoder Optical Encoder
#5.20	**Deceleration**	Oncoming trains	GNSS IMU
#5.21	**Deceleration**	Parked or passing trains	GNSS IMU
ID	**Operation**	**Scenario**	**Sensors affected**
#6.1	**Standstill**	Best case	-
#6.2	**Standstill**	Slab track	IMU Doppler Radar
#6.3	**Standstill**	Upwards Slope	Wheel Encoder IMU
#6.4	**Standstill**	Downwards Slope	Wheel Encoder IMU
#6.5	**Standstill**	Closed Snow Cover, Closed water cover	Doppler Radar
#6.6	**Standstill**	Snow and Ice	Optical Encoder

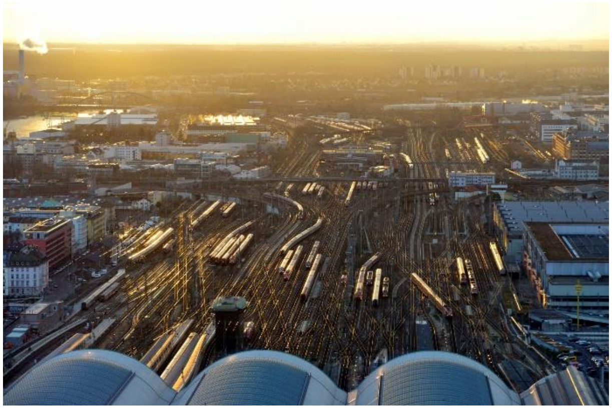
Table 10 Complete list of operational scenarios

For the derivation of test cases covering all operational scenarios, operations can be combined to a sequence, such as Initialising, Acceleration, Normal running, Deceleration, Standstill as one test case in various conditions and environments, e.g. Tunnel, Forest, Urban route in Snow, Rain or normal weather on varying topology and topography. This shall be done within WP4.

6.2 Exemplary Scenarios

With regard to the decomposed scenario list, an exemplary list of additional scenarios is specified below, derived from the these. This includes particularly detailed and exemplary scenarios, which are generically covered by the generic categorizations above, combinations of those or other which are further detailed situations, e.g. initialisation in a tunnel station, emergency brake or very slow coupling drive etc.

This list includes, but is not limited to these, examples and special cases.

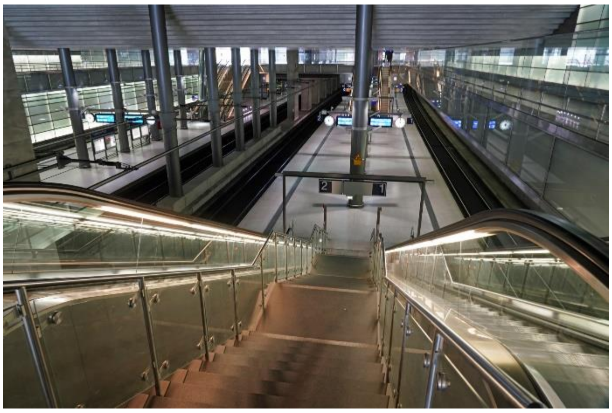
Ref. ID	Operation	Scenario	Sensors affected	Visualization
#1.10	**Initialization:** **Urban areas and large structures**	Initialisation within multiple, parallel tracks (e.g. shunting yard or station)	GNSS	 Figure 10 Complex railway station with multiple tracks © Deutsche Bahn AG / Volker Emersleben
#1.7	**Initialization:** **Platforms and roofs**	Initialization at terminus station (e.g. Frankfurt, Stuttgart, Munich)	GNSS	 Figure 11 Main station with metal roof © Deutsche Bahn AG / Wolfgang Klee

#1.2	**Initialization:** **Tunnel**	Initialisation at underground station (e.g. Berlin main station)	GNSS	 Figure 12 Highspeed train in underground station, © Deutsche Bahn AG / Oliver Lang
#1.10	**Initialization:** **Urban areas and large structures**	Initialisation within parallel tracks and complex track layout with many parked objects (e.g. shunting yards)	GNSS	 *Figure 13Trains in a shunting yard,* © Deutsche Bahn AG / Oliver Lang
Ref. ID	**Operation**	**Scenario**	**Sensors affected**	**Visualization**
#4.1	**Normal running Drive with constant speed:** **Best cases**	Keeping constant speed on downwards slope by using electric/dynamic brake	Wheel Encoder	 Figure 14 *Highspeed line with high slope* © Deutsche Bahn AG / Volker Emersleben

#4.11	**Normal running Drive with constant speed:** **Platforms and roofs**	Very low speed/crawling and coupling drive (e.g. "Kriechfahrt" or couple drive)	Doppler Radar IMU	 *Figure 15 Trains at a platform, © Deutsche Bahn AG / Oliver Lang*
#4.6	**Normal running Drive with constant speed:** **Tunnel**	Trains come up against each other and passing in opposite direction inside a single tube tunnel at high speed (e.g. VDE8)	IMU GNSS	 *Figure 16 Train leaving a tunnel, © Deutsche Bahn AG / Wolfgang Klee*
#4.7	**Normal running Drive with constant speed:** **Bridges**	Passing through large metal structures and bridges denying signal reception	GNSS	 *Figure 17 Train on a bridge with metal structure passing a river © Deutsche Bahn AG / Wolfgang Klee*

#4.12	**Normal running Drive with constant speed:** **Forest and vegetations**	Running through forests and canyons including reflections by wetness, snow or ice (e.g. tree canopy phenomena)	GNSS	 *Figure 18 Highspeed train passing forest and canyons, © Deutsche Bahn AG / Jochen Schmidt*
#4.8	**Normal running Drive with constant speed:** **Overpassings/ Underpassings**	Trains running at undercrossing and overcrossing passing at different levels of track and slopes	GNSS Wheel Encoder IMU	 *Figure 19 Train at undercrossing, © Deutsche Bahn AG / Uwe Miethe*
#4.14	**Normal running Drive with constant speed:** **Urban areas and large structures**	Train running on viaducts, bridges or large structures on an elevated railway tracks (e.g. 7 km length of S-Bahn Berlin in urban area)	GNSS	 Figure 20 Train on a viaduct, © Deutsche Bahn AG / Bartlomiej Banaszak

#4.7	**Normal running Drive with constant speed:** **Bridges**	Tunnels, Urban environment and Bridges in direct succession – entering and existing GNSS denied or restricted environments without sufficient relocalisation or position fix	GNSS	 *Figure 21 Highspeed train on bridge, © Deutsche Bahn AG / Claus Weber*
Ref. ID	**Operation**	**Scenario**	**Sensors affected**	**Visualization**
#5.7	**Deceleration:** **Tunnel**	Target stopping from top speed to standstill in GNSS denied environment (e.g. stopping in tunnels)	GNSS IMU Wheel Encoder	 *Figure 22 Tunnel, © Deutsche Bahn AG / Daniel Saarbourg*
#5.5	**Deceleration:** **Downwards slopes**	De-Acceleration on downwards slope with maximal brake force due to adhesion and slip	IMU Wheel Encoder	 *Figure 23 Regional train at open sky conditions, © Deutsche Bahn AG / Uwe Miethe*

#5.7	**Deceleration:** **Tunnel**	Emergency brake in GNSS restricted or denied environments (e.g. in a tunnel)	GNSS IMU Wheel Encoder	 *Figure 24 Emergency break, © Deutsche Bahn AG / Jet-Foto Kranert*
#5.12	**Deceleration:** **Platforms and roofs**	Precise target stopping at stopping point within a station or in a track occupied by another train (e.g. in a station with full roof/underground Hamburg Hbf)	GNSS	 *Figure 25 Main Station with roof, © Deutsche Bahn AG / Christian Bedeschinski*
#5.7	**Deceleration:** **Tunnel**	Precise target stopping in underground stations and underground rail lines within tunnels (e.g. Berlin Nord-Süd Tunnel)	GNSS	 *Figure 26 Underground station, © Deutsche Bahn AG / Volker Emersleben*

Ref. ID	Operation	Scenario	Sensors affected	Visualization
#6.1	**Standstill:** **Best case**	Acceleration or speed below measurement threshold in rollaway situation with regards to danger points	Doppler Radar IMU Optical Encoder Wheel Encoder	 *Figure 27 Locomotive of a cargo train, © Deutsche Bahn AG / Steve Wiktor*
#6.1	**Standstill:** **Best case**	Half-filled chemical wagons moving back and forth after target stop	IMU Wheel Encoder	 *Figure 28 Cargo wagons, © Deutsche Bahn AG / Uwe Miethe*

7 CONCLUSION

In this document, we presented a comprehensive overview of definitions for operational scenarios. The purpose is to specify operations, scenarios and environmental conditions for a train run under which the system under consideration has to function according to the specification. The definition of such scenarios includes standard situations, but also challenging environments and situations which impact design parameters and the key performance of the localisation system. The operational scenarios are influenced, for example, by conditions and parameters such as a maximum length of GNSS shading, GNSS multipath or non-line of sight (NLOS) effects or challenging manoeuvres for inertial measurement units (IMUs) including shock and vibration.

Operational scenarios are then derived by combination of operations and environmental conditions and decomposition into specific scenarios. All identified environmental conditions are based on expert and domain knowledge, as completely as possible, but do not claim for completeness. This allows a further formal and methodological approach to derive a complete list of scenarios within the extend of identified conditions.

First, the categorization of scenarios by operation, track section and movement type was conducted. Eight operations were identified. Second, environmental conditions are defined. Afterwards the environmental conditions affecting a sensor and leading to specific sensor errors were identified. This was done by deriving seven effect-cause diagrams with applicable environmental conditions with regard to the five relevant sensor error (GNSS denied environment is caused by tunnels, station roofs etc.). Third, by decomposing of each scenario into applicable environmental condition, a specific operational scenario is derived. Overall, 84 operational scenarios were derived.

Finally, for the purpose of deriving test cases, individual operational scenarios and multiple environmental conditions and operations can be considered together. Therefore, a list of 19 exemplary situational scenarios was derived. A methodical approach was defined and applied. It was shown that this approach is suitable to systematically assess environmental impacts, effects and causes with regard to sensor errors and to derive a list of resulting operational scenarios.

End of document.