



CLUG DEMONSTRATION OF READINESS FOR RAIL - CLUG 2.0

D5.3 PERFORMANCE ANALYSIS REPORT

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Leader of this Deliverable: Grégory Durand, Siemens Mobility (SMO)

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REPORT CONTRIBUTORS

NAME	COMPANY	DETAILS OF CONTRIBUTION
Anas Darwich	SNCF	Chapters 4.8, 4.9, 4.11, 5.3.1
Andrin Schneider	SMO	Chapters 3.3, 4.13, 5.4
Franziska Goettl	ADS	Chapters 4.2, 5.1, 5.2, 5.6
Gabriele Ligorio	ADS	Chapters 3.1, 5.8.2
Grégory Durand	SMO	Chapters 2.1, 4.1, 4.3, 4.5, 4.6, 4.12, 5.7, 6
Niko Harnge	SMO	Chapters 2.2, 5.8.1
Roman Ehrler	SBB	Chapters 4.4, 4.7, 4.10, 5.3.2, 5.5, 5.8.3
Stephane Potiron	SYN	Chapter 3.2
Arnault Sfeir	ADS	Technical Reviewer
Mariya Kayalova	RINA-C	Quality check
Jose Bertolin	UNIFE	Final check and submission to reviewers and EUSPA



EXECUTIVE SUMMARY

This document constitutes the deliverable D5.3 “Performance Analysis Report” of the “Work package WP5 – Integration & Testing (including Site Demonstrator)” of the CLUG 2.0 project which stands for Certifiable Localisation Unit using Global Navigation Satellite System (GNSS) in the railway environment.

This document presents the analysis that was conducted on the data output by the LOC-OB algorithm in post-processing using real sensor data collected in the field by the test train Domino from the SBB. The basis for the analysis is the CLUG 2.0 system requirements defined in D2.4 LOC-OB System Requirements [R1].

The conducted analysis shows that the LOC-OB performs adequately for its intended purpose, and is in line with today’s railway localisation needs, with most of the key requirements either fulfilled or nearing fulfillment, even in challenging GNSS environments.

LIST OF ACRONYMS

ACRONYM	CONCEPTS
ADS	Airbus Defence & Space
CAF	Construcciones y Auxiliar de Ferrocarriles
CI	Confidence Interval
CLUG	Certi fiable Localization Unit with GNSS in the railway environment
Clug2SFA	CLUG2.0 Sensor Fusion Analysis
CMC	Code-Minus-Carrier
CNO	Carrier to noise
CPH	Carrier phase
CSL	Cycle slip detector
CSV	Comma Separated Values
DFMC	Dual Frequency Multiconstellation
DFMC+PR+PV	Dual Frequency Multiconstellation with Pseudo-Range and Pseudo-Velocity integrity
DOP	Doppler measurements
DRS	Doppler Radar Sensor
EGNOS	European Geostationary Navigation Overlay Service
EKF	Extended Kalman Filter
ELV	Elevation
ETCS	European Train Control System
EU	European Union
FDE	Fault Detection and Exclusion
GAL	Galileo
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GT	Ground Truth
Has	HaslerRail optical pulse generator (also called “wheel tachometer”)
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
KPI	Key Performance Indicator

ACRONYM	CONCEPTS
LOC-OB	Localisation On-Board
MCI	(specified) Maximum Confidence Interval
MHD	Mahalanobis distance
OPG	Odometer (or Optical) Pulse Generator
PFA	Probability of false alarm
PPP	Precise Point Positioning
PRN	Pseudo-Random Noise
PSR	Pseudorange
PVT	Position, Velocity, and Time
R2DATO	Rail to Digital automated up to autonomous train operation
RBC	Radio Block Center
RINEX	Receiver Independent Exchange Format
RLG	Ring Laser Gyroscopes
RTK	Real-time kinematic
SBAS	Satellite-Based Augmentation System
SBB	Swiss Federal Railways (Schweizerische Bundesbahnen)
SIL	Safety Integrity Level
SMO	Siemens Mobility
SNCF	Société Nationale des Chemins de Fer français
SYN	Syntony
SW	Software
Tacho	Wheel Tachometer (also called "OPG")
TFFR	Tolerable functional failure rate
THR	Tolerable Hazard Rate
TS	Track Selectivity
TSI	Technical Specification for Interoperability
TTA	Time To Alert
WP	Work package

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1 DESCRIPTION OF THE ANALYSIS TOOLCHAIN

1.1 Sensor Fusion Analysis

The “CLUG2.0 Sensor Fusion Analysis” (Clug2SFA) focuses on analysing the output data computed by the LOC-OB system which is needed by the European Train Control Systems (ETCS):

- Distance
- Confidence interval for distance
- Speed
- Confidence interval for speed

In addition, it analyses:

- 3D position;
- Detailed information on collected GNSS satellites and signals;
- GNSS and system fault detection and exclusion (FDE) algorithm statuses.

It shall be noted that the CLUG2.0 Sensor Fusion Analysis discards from the analysis the first 60 s of each trip, starting when the train is moving in order to ensure that the LOC-OB algorithm is converged.

In addition, it discards from the analysis the datapoints for which no valid Ground Truth has been made and assessed available.

The results of the CLUG2.0 Sensor Fusion Analysis are output in the following files:

- A spreadsheet <vehicle>-5501-Clug2-Clug2SFA.xlsx containing the “numbers” (also called “performance indicators”) and event lists.
- Plot-files, stored as picture-files (.png) and whenever useful as .fig-files (to be opened with Matlab).

The «Test and analysis list» [R2] provides through the column “Name in Excel/Directory” traceability from D2.4 LOC-OB System Requirements [R1] to:

- The names of the corresponding parameters used in the spreadsheet file <vehicle>-5501-Clug2-Clug2SFA.xlsx (column “Type” of the «Test and analysis list» [R2] = “number”).
- The names of the plot-files or directories where the corresponding plot-files are stored (column “Type” of the «Test and analysis list» [R2] = “plot”).

The CLUG2.0 Sensor Fusion Analysis creates the following plots:

Table 1: List of plots

Content	File name
Speed	YYMMDD_HHMMSS_CLUG2-SFA(1Delta)-Clug2(5501).png
Distance	YYMMDD_HHMMSS_CLUG2-SFADistance1D(1Delta)-Clug2(5501).png
Track Edge	YYMMDD_HHMMSS_CLUG2-SFATrackEdge(1Delta)-Clug2(5501).png
3D position	YYMMDD_HHMMSS_CLUG2-SFA3DPosErrors(1Delta)-Clug2(5501).png
Satellite carrier phase	YYMMDD_HHMMSS_CLUG2-SFASatInfocph(1Delta)-Clug2(5501).png
Satellite doppler	YYMMDD_HHMMSS_CLUG2-SFASatInfodop(1Delta)-Clug2(5501).png
Satellite pseudoranges	YYMMDD_HHMMSS_CLUG2-SFASatInfopsr(1Delta)-Clug2(5501).png

Each plot contains outputs from the LOC-OB (e.g. speed, distance, track edge ID) as well as a comparison between the LOC-OB outputs and the computed ground truth (e.g. Delta Speed and Delta distance) showing the speed and distance errors, targeting the ground truth is fault free, as well as the confidence intervals computed by the LOC-OB. In addition, the plots show various validity flags, which are either directly output by the LOC-OB or computed by the Clug2SFA based on the comparison of the LOC-OB output with the ground truth.

The plots in the MATLAB *.fig format allow zooming in and out and enabling or disabling of specific curves.

For each event (e.g. apparent deviation to the requirement), a separate “zoom”-plot is created, showing the data only for the time frame of the deviation to the Ground Truth. In case there are too many events during a trip, instead of creating many “zoom”-plots, only one plot is created for the entire duration of the trip, containing only a subset of the data impacted by the deviations.

The following sections provide a detailed description of the plots and spreadsheet file.

1.1.1 Speed plot

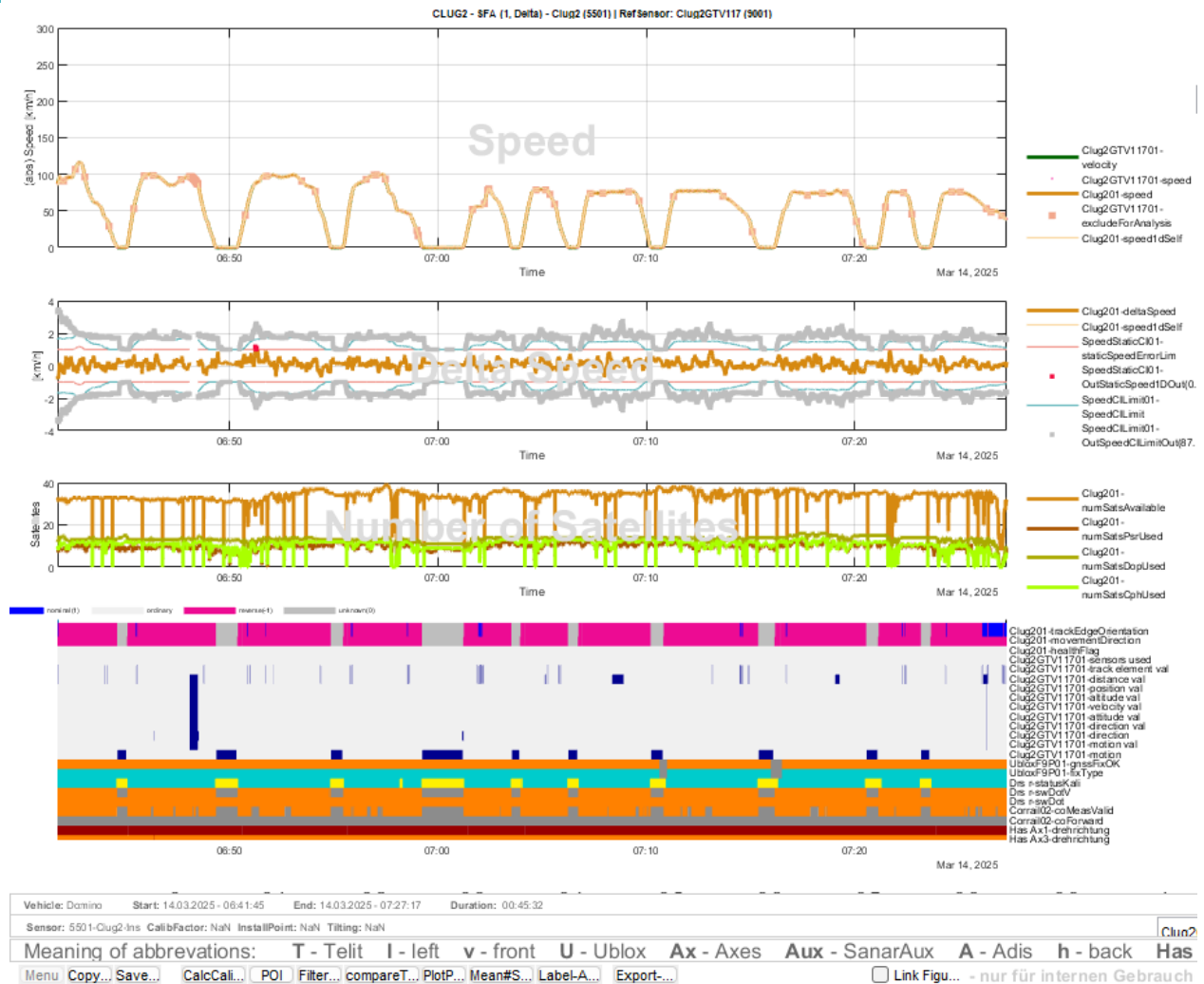


Figure 1-1: Speed plot

The speed plot contains 4 subplots:

- Speed
- Delta speed
- Number of collected satellites
- Status bits

The speed subplot shows the following data (the name shown in parentheses corresponds to the label used in the plot legend):

- the speed computed by the LOC-OB (Clug201-speed);
- the speed confidence interval computed by the LOC-OB with respect to the speed computed by the Ground Truth (Clug201-speed1dSelf);
- the speed computed by the ground truth, either as datapoints (Clug2GTVxxxxx-speed, "xxxxx" being here the current version of the Ground Truth) or as a curve (Clug2GTVxxxxx-velocity);

- whether the speed computed by the ground truth is invalid and thus excluded for the analysis (Clug2GTVxxxx-excludeForAnalysis).

The delta speed subplot provides the following data (the name shown in parentheses corresponds to the label used in the plot legend):

- the difference between the LOC-OB speed and the computed Ground Truth speed (Clug201-deltaSpeed);
- the speed confidence interval computed by the LOC-OB (Clug201-speed1dSelf);
- the maximal speed error defined in D2.4 LOC-OB System Requirements [R1] (SpeedStaticCI01-staticSpeedErrorLim);
- the maximal confidence interval for the speed defined in D2.4 LOC-OB System Requirements [R1] (SpeedCILimit01-SpeedCILimit);
- the datapoints for which the confidence interval computed by the LOC-OB is outside the limits defined in D2.4 LOC-OB System Requirements [R1] (SpeedCILimit01-OutSpeedCILimitOut).

The satellite subplot provides the following information:

- Number of collected satellites available for the LOC-OB computation (Clug201-numStatsAvailable);
- Number of FDE filtered satellite pseudoranges used for the LOC-OB computation (Clug201-numStatsPsrUsed);
- Number of FDE filtered satellite Doppler measurements used for the LOC-OB computation (Clug201-numStatsDopUsed);
- Number of FDE filtered satellite carrier phases used for the LOC-OB computation (Clug201-numStatsCphUsed).

The status bits plot shows status of information provided by the LOC-OB (Clug201-xxx), by the Ground Truth (Clug2GTVxxx) and from some speed sensors and GNSS receivers.

1.1.2 Distance plot

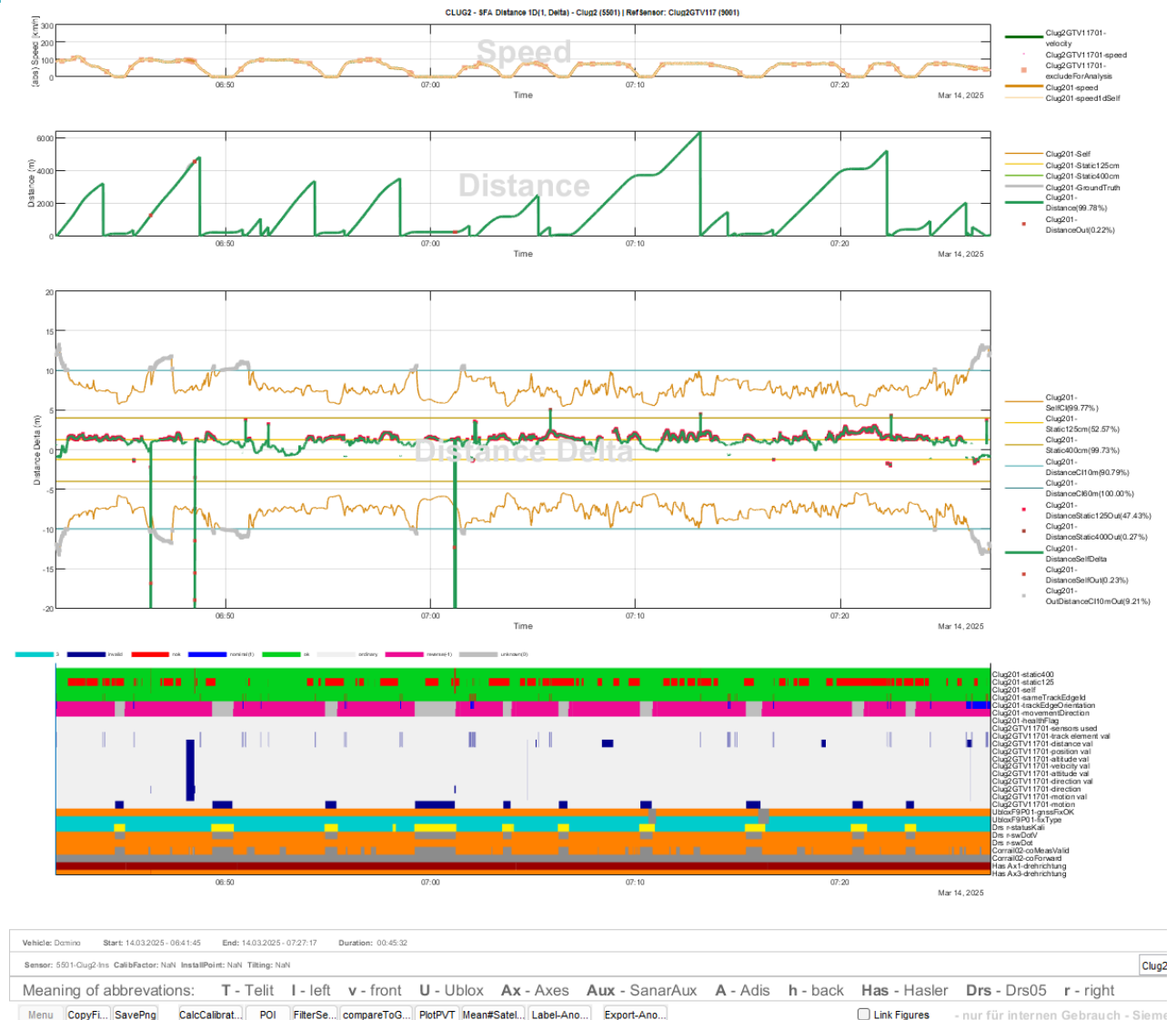


Figure 1-2: Distance plot

The distance plot contains 4 subplots:

- Speed
- Distance
- Distance Delta
- Status bits

The data presented in the speed subplot is identical to that shown in the speed plot (refer to chapter 1.1.1).

The distance plot provides the following data (the name shown in parentheses corresponds to the label used in the plot legend):

- the overestimated and underestimated distance computed by the LOC-OB (Clug201-Self);
- the maximal distance errors defined in D2.4 LOC-OB System Requirements [R1] which have been added to the Ground Truth computed distance (SpeedStaticCI01-Static125cm, SpeedStaticCI01-Static400cm);
- the distance to the start node computed by the Ground Truth (Clug201-GroundTruth);
- the distance to the start node computed by the LOC-OB (Clug201-Distance);
- the datapoints for which the distance error (difference of the distance computed by the LOC-OB to the distance computed by the Ground Truth) is outside of the confidence interval computed by the LOC-OB (Clug201-DistanceOut).

The distance delta subplot provides the following data (the name shown in parentheses corresponds to the label used in the plot legend):

- the difference between the overestimated and underestimated distance computed by the LOC-OB to the Ground Truth estimated distance (Clug201-SelfCI);
- the maximal distance errors defined in D2.4 LOC-OB System Requirements [R1], (Clug201-Static125cm, Clug201-Static400cm);
- the confidence intervals for the distance defined in D2.4 LOC-OB System Requirements [R1], (Clug201-DistanceCI10m and Clug201-DistanceCI60m);
- the datapoints for which the distance error is outside the limits defined in D2.4 LOC-OB System Requirements [R1] (Clug201-DistanceStatic125Out, Clug201-DistanceStatic400Out);
- the difference between the distance computed by the LOC-OB and by the Ground Truth (Clug201-DistanceSelfDelta);
- the datapoints for which the distance error is outside the confidence interval computed by the LOC-OB (Clug201-DistanceSelfOut);
- the datapoints for which the confidence interval computed by the LOC-OB is outside the limits defined in D2.4 LOC-OB System Requirements [R1] (Clug201-OutDistanceCI10mOut, Clug201-OutDistanceCI60mOut).

The status bits plot shows status of information provided by the LOC-OB (Clug201-xxx), by the Ground Truth (Clug2GTVxxxxx) and from some speed sensors and GNSS receivers.

1.1.3 Track Edge ID plot

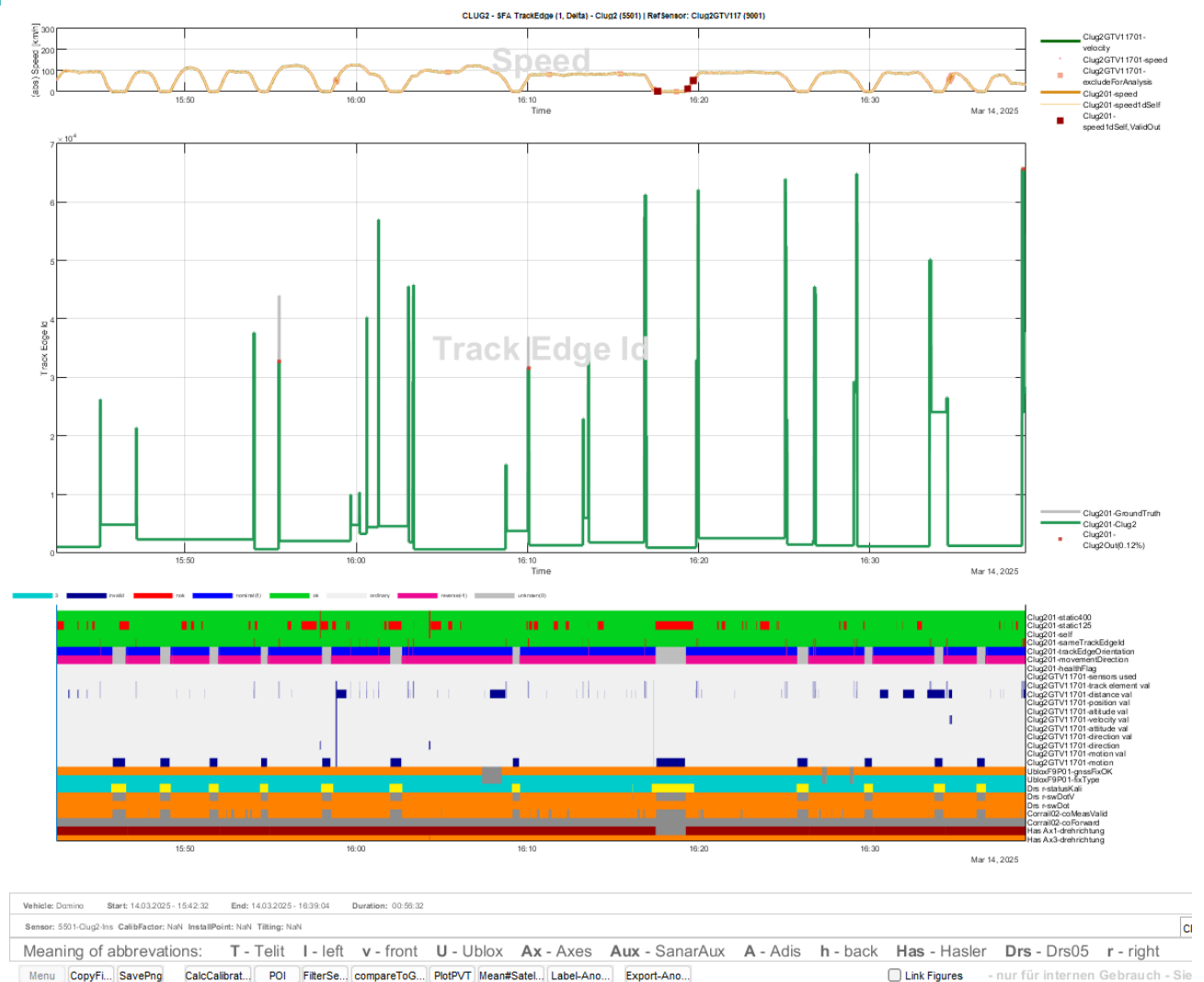


Figure 1-3: Track Edge ID plot

The track edge ID plot contains 3 subplots:

- Speed
- Track Edge Id
- Status bits

The data presented in the speed subplot is identical to that shown in the speed plot (refer to chapter 1.1.1).

The track edge id plot provides the following data (the name shown in parentheses corresponds to the label used in the plot legend):

- The identifier of the track edge computed by the Ground Truth (Clug201-GroundTruth).
- The identifier of the track edge computed by the LOC-OB (Clug201-Clug2).

- The datapoints for which the track edge identifier computed by the Ground Truth differs from the one computed by the LOC-OB (Clug201-Clug2Out).

The status bits plot shows status of information provided by the LOC-OB (Clug201-xxx), by the Ground Truth (Clug2GTVxxxxx) and from some speed sensors and GNSS receivers.

1.1.4 3D Position Error plot



Figure 1-4: 3D position error

The 3D position error plot contains 5 subplots:

- Speed
- Along Track error
- Across Track error
- Horizontal error
- Altitude error

The data presented in the speed subplot is identical to that shown in the speed plot (refer to chapter 1.1.1). In addition, it shows speed values measured by additional sensors (“Has” stands for wheel tachometer, “DRS” for Doppler radar sensor).

The along-track subplot shows the difference between the 3D position computed by the LOC-OB and the one computed in the Ground Truth projected along the track.



The across-track subplot shows the difference between the 3D position computed by the LOC-OB to the one computed in the Ground Truth projected in the direction orthogonal to the track.

The horizontal error subplot shows the difference between the 3D position computed by the LOC-OB to the one computed in the Ground Truth projected on the horizontal plane.

The altitude error subplot shows the difference between the 3D position computed by the LOC-OB with the one computed in the Ground Truth projected on the vertical axis z.

In addition, the subplots provide the standard deviations computed by the LOC-OB and projected to the respective directions.

1.1.5 Satellite Information plot



Figure 1-5: Satellite information plot

The CLUG2.0 Sensor Fusion Analysis generates 3 satellite plots providing detailed information on the GNSS data:

- “Dop” for Doppler measurements
- “Cph” for carrier phases
- “Psr” for pseudoranges

Each satellite information error plot contains 4 subplots:

- Speed
- Distance delta
- Satellites <dop> or <psr> or <cph>
- Satellites FDE <dop> or <psr> or <cph>

The data presented in the speed subplot is identical to that shown in the speed plot (refer to chapter 1.1.1). In addition, it shows speed values measured by additional sensors (“Has” stands for wheel tachometer, “DRS” for Doppler radar sensor).

The data presented in the distance delta subplot is identical to that shown in the distance plot (refer to chapter 1.1.2).

The *satellites <dop> or <psr> or <cph>* subplots show the number of GNSS signals per constellation (GPS, Galileo) and frequencies (GPS L1, GPS L5, GAL E1, GAL E5a) for which all FDE checks have set the data to “valid”.

The *satellites FDE <dop> or <psr> or <cph>* subplots show the number of GNSS signals that have been flagged by a specific FDE check. More detailed information on the GNSS FDE flags can be found in [R3].

1.1.6 Clug2SFA spreadsheet

Besides the plots described in previous sections, the “CLUG2.0 Sensor Fusion Analysis” creates a spreadsheet <vehicle>-5501-Clug2-Clug2SFA.xlsx containing, among other detailed statistics, the key performance indicators according to D2.4 LOC-OB System Requirements [R1].

Table 2: Performance indicators

Performance indicator	Requirement ID in [R1]	Explanation
Distance Along Track Error < 1.25 m:	SpecSysReq[005]	Percentage of datapoints for which the distance error is inside the specified limit of 1.25 m. Note: The requirement is applicable to constrained areas (operational surroundings ± 500 m around a stop), however the performance indicator does not distinguish the constraint and the non-constraint areas.
Distance Along Track Error < 4 m:	SpecSysReq[006]	Percentage of datapoints for which the distance error is inside the specified limit of 4 m. Note: The requirement is applicable to the non-constrained areas, however the performance indicator does not distinguish the constraint and the non-constraint areas.
Distance Error < Distance CI:	SpecSysReq[007]	Percentage of datapoints for which the distance error is inside the computed confidence interval applied to the ground truth distance.
Distance CI < 10 m:	SpecSysReq[003]	Percentage of datapoints for which the computed confidence interval for the distance is inside the specified limits of ± 10 m.

Performance indicator	Requirement ID in [R1]	Explanation
		Note: The requirement is applicable to constrained areas (operational surroundings ± 500 m around a stop), however the performance indicator does not distinguish the constraint and the non-constraint areas.
Distance CI < 60 m:	SpecSysReq[004]	Percentage of datapoints for which the computed confidence interval for the distance is inside the specified limits of +/- 60 m. Note: The requirement is applicable to the non-constrained areas, however the performance indicator does not distinguish the constraint and the non-constraint areas.
Speed Error < (± 1 km/h v < 100 km/h, $\pm 1\%$ v > 100 km/h):	SpecSysReq[010]	Percentage of datapoints for which the 1D speed error is inside the specified limit of: ± 1 km/h for speeds from 0 km/h to 100 km/h $\pm 1\% * v$ for speeds from 100 km/h to 500 km/h
Speed Error < Speed CI:	SpecSysReq[011]	Percentage of datapoints for which the 1D speed error is inside of the computed confidence interval applied to the ground truth speed.
<p>CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:</p> <p>TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:</p>	SpecSysReq[009], SUBSET-041 §5.3.1.2	<p>Percentage of datapoints for which the computed confidence interval for the 1D speed is inside the specified limits:</p> <p><u>SpecSysReq[009]:</u></p> <p>(Underestimation of the estimated train speed - Overestimation of the estimated train speed) < 2 km/h for speeds lower than 30 km/h, and increasing linearly up to 12 km/h for speeds between 30 km/h and 500 km/h.</p> <p><u>TSI (SUBSET-041 §5.3.1.2, [R5]):</u></p> <p>In addition to the CLUG2-requirement SpecSysReq[009], the requirement 5.3.1.2 from SUBSET-041 [R5], which is part of the mandatory specifications from the TSI CCS is also considered for the speed CI:</p>

Performance indicator	Requirement ID in [R1]	Explanation
		<p>(Overestimation of the estimated train speed - estimated train speed) < 2 km/h for speeds lower than 30 km/h, and increasing linearly up to 12 km/h for speeds between 30 km/h and 500 km/h; and</p> <p>(estimated train speed - underestimation of the estimated train speed) < 2 km/h for speeds lower than 30 km/h, and increasing linearly up to 12 km/h for speeds between 30 km/h and 500 km/h.</p> <p>The TSI requirement is also applicable in R2DATO (REQ: FP2-ASTP-SRS-080 from [R14]). The requirement is assumed passed when the value is greater than 98.3 % (1 min unavailability over 1 hour on the basis of REQ: FP2-ASTP-SRS-050 from [R14])</p>

The spreadsheet contains tabs listing all the events. For each event a hyperlink on the time stamp in column A allows to open the respective “zoom”-plot for this event.

In addition, it provides general information about the trip such as the duration of the trip, the distance travelled and the mean and maximum speed.

2 GROUND TRUTH

In the safety-critical railway domain, precise localization of vehicles and infrastructure components is essential to ensure safety, efficiency, and automation. The computed Ground Truth (GT) serves as a reference for validating localization algorithms and safety-relevant functions. The requirements for such Ground Truth can be specified particularly with respect to the following parameters: position, distance, speed, acceleration, and orientation.

Position must be captured with high spatial accuracy, as even small deviations can lead to misinterpretations of track occupancy or signal states. In modern systems, sub-meter accuracy is targeted, especially when validating satellite-based or inertial localization systems [R13].

Distance between vehicles, to infrastructure points, or within track segments must be reliably and continuously available. This is critical for maintaining safety margins and correctly interpreting movement authorities. Ground Truth data must document both absolute and relative distances with high precision.

Speed and acceleration are key dynamic parameters needed for evaluating braking distances, collision avoidance, and driving dynamics. GT must provide these values with high temporal resolution and synchronization with position data to enable a consistent motion description [R11].

Orientation (spatial alignment) is particularly relevant during curve negotiation, switch transitions, and when interacting with digital track models. GT must capture both horizontal and vertical alignment of the vehicle, ideally in terms of roll, pitch, and yaw angles.

Capturing such Ground Truth data requires the use of high-precision sensors (e.g., RTK-GNSS, IMUs, Lidar) as well as robust data fusion and synchronization. The validity of GT depends not only on sensor quality but also on calibration, environmental modeling, and the traceability of data processing [R13].

2.1.1 Ground Truth Requirements for Validating Train Localization Systems

In safety-critical applications such as railway localization, the Ground Truth (GT) used as a reference dataset must be significantly more accurate, one order of magnitude, than the system under test. Only then can validation be considered reliable. For example, the CLUG 2.0 project defines a positional accuracy requirement of ± 1.25 m (95%) in constrained areas. To reliably verify this requirement, the Ground Truth should achieve an accuracy of at least ± 0.25 m or better.

According to the international standard DIN EN ISO/IEC 17025:2018-03 [R12], which defines general requirements for the competence of testing and calibration laboratories, measurement uncertainty must be estimated and considered when making conformity assessments (Sections 7.6 and 7.8 of the DIN EN ISO/IEC 17025:2018-03). This means that the uncertainty of the Ground Truth must be small enough to avoid influencing the decision about whether the system meets its specification. In practical terms, this implies that the Ground Truth should be significantly more accurate than the system under test—typically by a factor of 3 to 10, depending on the acceptable risk of false acceptance or rejection.

This requirement applies not only to position but also to speed, acceleration, and orientation parameters. Ground Truth must therefore be precise, consistent, synchronized, and thoroughly documented to serve as a valid benchmark in safety-relevant testing.

The following table summarizes the accuracy requirements defined for the LOC-OB system in CLUG 2.0 and provides recommended Ground Truth accuracy levels based on ISO/IEC 17025 [R12] principles. These recommendations ensure that measurement uncertainty does not compromise the validity of conformity assessments.

Table 3: Recommended Ground Truth Accuracy for Validating LOC-OB Requirements

Parameter	System Requirement (CLUG 2.0)	Recommended GT Accuracy	Rationale
Distance (1D)	±1.25 m (95%) in constrained areas (nearby stations, switches or stop location)	≤ ±0.25 m	Based on ISO/IEC 17025: GT uncertainty must not affect conformity decision
Distance (1D)	±4.00 m (95%) in other areas	≤ ±0.8. m	Ensures reliable validation margin
Position (3D)	±1.25 m (95%) in constrained areas (nearby stations, switches or stop location)	≤ ±0.25 m	GNSS/IMU calibration, environmental modeling
Position (3D)	±4.00 m (95%) in other areas	≤ ±1.00 m	Ensures reliable validation margin
Speed (1D)	±1 km/h (0–100 km/h), ±1% * v (100–500 km/h)	≤ ±0.2 km/h	Based on ISO/IEC 17025: GT must be significantly more accurate
Speed (3D)	±2 km/h per axis	≤ ±0.5 km/h	Validates motion direction and dynamics
Acceleration (1D)	±0.05 m/s ² (95%)	≤ ±0.01 m/s ²	Evaluates energy efficiency and driving behavior
Acceleration (3D)	±0.05 m/s ² per axis	≤ ±0.01 m/s ²	Validates dynamic train behavior
Orientation (Attitude)	Yaw: ±0.1°, Pitch/Roll: ±0.5° (95%)	Yaw: ≤ ±0.02°, Pitch/Roll: ≤ ±0.1°	Relevant for perception and curve negotiation
Timestamp	Data age ≤ 200 ms	≤ 50 ms	Synchronization with real-time data

Parameter	System Requirement (CLUG 2.0)	Recommended GT Accuracy	Rationale
Data Frequency	≥10 Hz	≥20 Hz	Captures rapid motion changes

2.1.2 Ground Truth Generation for CLUG2.0

In order to analyse the performance of the positioning solutions under development, Ground Truth data are required as the reference. Such ground truth data will have to be generated for each trip, from which data shall be analysed, and it will depend on available track data, position references and odometry sensors.

As part of the project, two different Ground Truth (GT) systems were used, each offering specific strengths and methodological approaches for high-precision position and motion analysis: the iMAR-GT, based on the iMAR iNAT-RQT-4003 platform, and the SMO-GT, a further development from the research projects STARS and CLUG.

2.1.2.1 iMAR-GT

The iMAR-GT is based on the iNAT-RQT-4003 from iMAR Navigation, a high-precision GNSS/INS platform designed for demanding navigation and surveying applications. The system combines ring laser gyroscopes (RLG), high-precision servo accelerometers, and a powerful real-time strapdown processor. It supports all major GNSS constellations (GPS, GLONASS, GALILEO, BeiDou) and offers RTK and PPP capabilities.

Technical specifications (excerpt):

- Attitude accuracy: up to 0.001° in roll, pitch, and yaw
- Gyroscope drift: 0.010 °/h
- Accelerometer bias: 0.100 mg
- Data output rate: up to 400 Hz (configured to 10 Hz in the project)
- Interfaces: Ethernet (TCP/UDP), RS422/232, CAN, ARINC429/825, NMEA 183
- Storage: 32 GB internal, expandable to 128 GB

(Source: [iMAR Navigation – iNAT-RQT-4003 Datasheet](#) [R8])

The system was configured and supported in collaboration with iMAR and SBB. The reference point of the navigation solution was aligned with the SMO-GT reference point in the Eurobalise antenna, enabling direct comparability of both systems without additional transformations.

Data is exported via CSV by extracting information from various iMAR-specific telegrams and converting it into the format defined in D5.2 Raw Data [R3]. The system provides continuous output at 10 Hz, including:

- Timestamp
- 3D position
- 1D and 3D velocity
- 3D attitude (roll, pitch, yaw)
- 3D acceleration

Due to the lack of track information of the real-time device in the current version, no track-related information is available. Consequently, no relative distances to defined reference points can be derived.

2.1.2.2 SMO-GT

The SMO-GT was developed as a continuation of the Ground Truth approaches from the STARS and CLUG projects. In contrast to the iMAR-GT, the position solution is computed entirely in post-processing.

Input data:

- Track data provided and regularly updated by SBB;
- Eurobalise data recorded via AirGap recorders on RE450 and Domino trains;
- Speed information calculated offline from two odometer pulse generator (OPG) sensors and an optical speed sensor.

Speed is determined through a multi-step process:

1. Calibration of sensors using an independent reference
2. Slip and slide detection via triple sensor comparison
3. Calculation of a consistent speed profile

The position is calculated in several steps:

1. Eurobalise passages are used to determine absolute positions based on the timestamp of passage. Each Eurobalise transmits a unique ID in its telegram, which is matched against the Eurobalise entries stored in the track data. This allows the system to retrieve the exact geographical position of the Eurobalise from the map and use it as a reference point.
2. Pathfinding between Eurobalises is performed using the track topology and the distance travelled, derived from the speed profile. A new feature is the ability to support this process using an SBB route file.
3. Intermediate positions are interpolated using odometry data and mapped to the geographical track layout. Differences between path length and sensor data are corrected in favour of the track data.

A key advantage of the SMO-GT is the ability to assign the train to a specific track: by combining Eurobalise positions recorded by the train with those stored in the track data, and applying pathfinding between Eurobalises, the actual track segment travelled can be identified. This enables the calculation of distances to define reference points, such as switches or Eurobalises, with high precision.

The SMO-GT provides continuous output with a freely configurable sample rate, as it is not limited by system constraints. The output includes:

- Timestamp
- Track information
- Distance (derived from speed)
- 3D position
- 1D speed

Attitude estimation is theoretically possible based on the trajectory of the track data but is highly dependent on the spatial resolution of the track model. As a result, the calculation of 3D velocities is only possible with limited accuracy.

2.1.2.3 Comparison of iMAR-GT and SMO-GT

The following table summarizes the key differences between the two Ground Truth systems used in the project. It highlights their respective strengths, technical characteristics, and also explicitly lists known limitations that are relevant for interpretation and integration of the data.

Table 4: Comparison of the iMAR-GT with SMO-GT

Parameter / Criterion	iMAR-GT	SMO-GT	Known Limitations
System type	Real-time GNSS/INS platform	Post-processing-based solution	SMO-GT: No real-time capability
Hardware basis	iMAR iNAT-RQT-4003	Custom solution using ETCS data, sensors, and track data	–
Data sources	GNSS, inertial sensors (RLG, accelerometers), odometer pulse generators real-time data	Balises, odometer pulse generators, optical speed sensor, track data incl. balise positions	BOTH: The odometer pulse generators used by the iMAR are also used as input for the speed information used for SMO-GT generation.
Output rate	Fixed at 10 Hz	Unlimited, freely configurable in post-processing	-
Timestamp	Yes	Yes	–

Parameter / Criterion	iMAR-GT	SMO-GT	Known Limitations
3D Position	Yes	Yes	SMO-GT: Accuracy depends on balise map quality
1D Velocity	Yes	Yes	–
3D Velocity	Yes	Indirectly possible via track geometry	SMO-GT: Not directly measured; resolution-dependent
3D Attitude (Roll, Pitch, Yaw)	Yes	Indirectly possible via track geometry	SMO-GT: Not directly measured; resolution-dependent
3D Acceleration	Yes	Indirectly possible via track geometry	SMO-GT: Not directly measured; resolution-dependent
Track information	Not available	Yes – via balise IDs, track data and path finding	iMAR-GT: No track reference
Distance to reference points	Not available	Possible – e.g., to switches or balises	iMAR-GT: No relative distance calculation possible
Balise integration	Not available	Balise ID matched with map data	SMO-GT: Accuracy depends on the correctness of balise positions in map
Processing type	Real-time	Offline	SMO-GT: Requires post-processing effort
Configurability	Fixed setup with reference point in balise antenna	Flexible via track data and SBB route files	iMAR-GT: The configuration for data that has already been recorded cannot be changed retrospectively.
GNSS shadowing sensitivity	Yes – position deviations observed in GNSS-obstructed areas	Not affected	iMAR-GT: GNSS signal loss impacts accuracy

Parameter / Criterion	iMAR-GT	SMO-GT	Known Limitations
Sensor latency sensitivity	Not critical	Yes – latency in sensor recording can affect accuracy	SMO-GT: Timing mismatches can distort position estimation
Speed data gaps	Not critical	Yes – gaps can prevent position estimation between balises	SMO-GT: No position possible without continuous speed data
Independence from LOC-OB	Limited – uses GNSS data from the same GNSS receiver and therefore also from the same GNSS antenna.	Limited – uses same map and OPG-based speed data	Both systems share components with LOC-OB, reducing independence

Planned Resolution in CLUG2 GT

To overcome the limitations listed above and ensure a robust, accurate, and available reference solution, the CLUG2 GT approach introduces a structured toolchain:

1. Independent generation of both GT solutions (iMAR-GT and SMO-GT) using their respective methods and data sources.
2. Systematic comparison and evaluation of both solutions to identify deviations, inconsistencies, and context-specific weaknesses (e.g., GNSS shadowing, sensor latency, map inaccuracies).
3. Fusion of both GTs into a central reference solution that combines the strengths of both systems while compensating for their individual weaknesses.

This fused GT will serve as a high-quality reference for evaluating the LOC-OB solution. It is designed to meet the key requirements of accuracy, availability, reliability, and independence. The fusion process will also explicitly address the lack of independence in both systems by transparently documenting shared data sources (e.g., map, OPG-based speed) and mitigating their influence through cross-validation and redundancy.

2.1.2.4 CLUG2-GT

The GT was generated by combining two complementary approaches: the real-time capable iMAR-GT and the track-referenced SMO-GT. The fusion of these systems resulted in a robust, consistent, and high-precision reference solution that performs reliably even under challenging environmental conditions.

Track Data Preparation: The foundation for the track-referenced GT was the extensive railway network data provided by SBB. These data were converted into the CLUG2-specific format, as defined



in deliverables D4.10 (Map Data) [R9] and D5.2 (Raw Data) [R3]. A closed node-edge model was constructed to represent the logical structure of the railway network. Faulty Eurobalise information and inconsistent track data were systematically identified and flagged to prevent errors in subsequent GT processing.

Sensor Data Acquisition and Reference Generation: In parallel with track data processing, comprehensive field data were collected. This included iMAR-GT data obtained via GNSS/INS systems equipped with ring laser gyroscopes and servo accelerometers, providing real-time 3D position, velocity, and attitude information. Additionally, a speed reference was generated using two independent wheel tachometers and an optical sensor. This setup enabled precise speed measurement and facilitated the detection of slip and slide events, which are critical for assessing data quality.

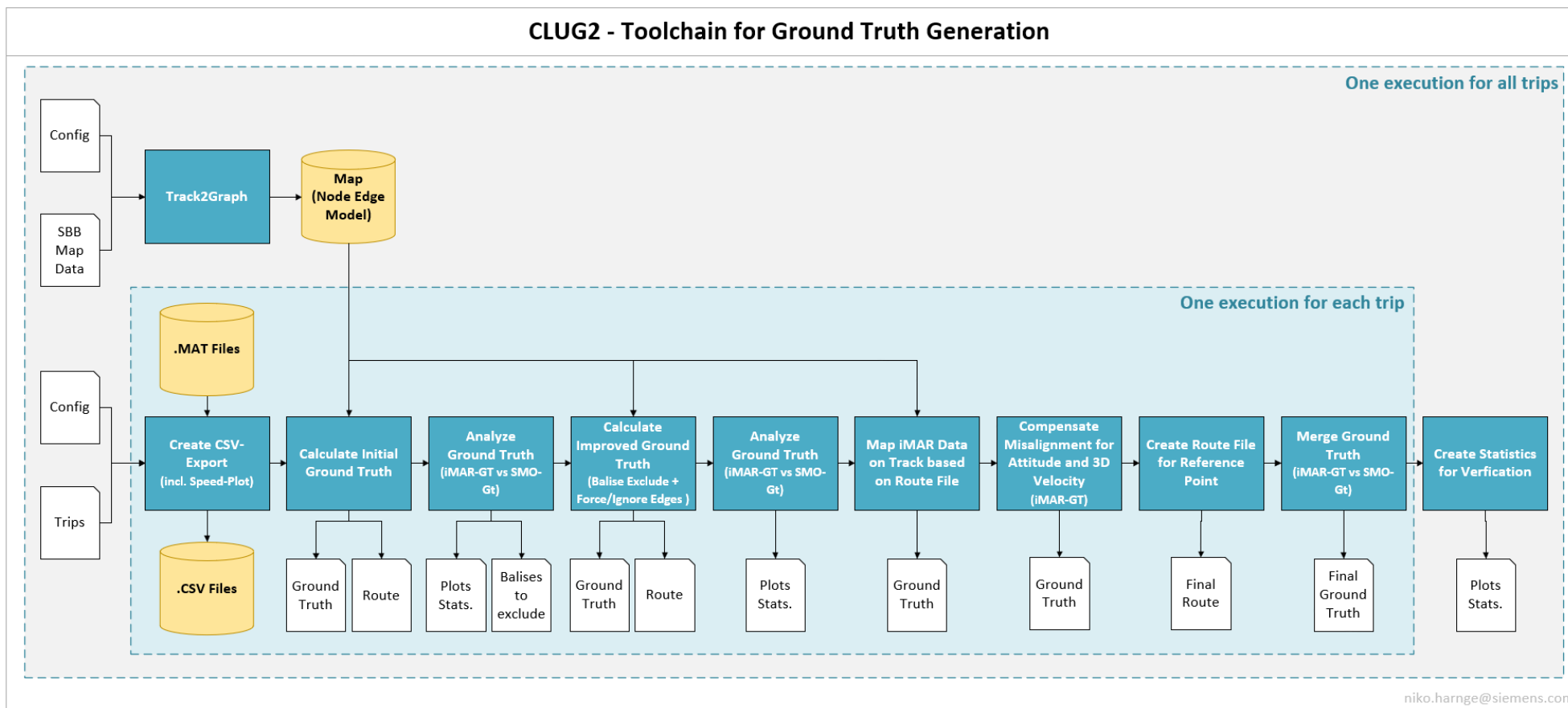


Figure 2-1: Toolchain for CLUG2-GT generation



Comparative Analysis and Validation: The two GT systems were systematically compared. SMO-GT, which relies on balises, wheel sensors, and track data, was validated against the iMAR-GT data. The goal was to identify faulty paths, invalid balises, and inconsistencies in positioning. SMO-GT was then iteratively updated based on the analysis results and re-evaluated against iMAR-GT to ensure high accuracy and alignment between the systems.

Compensation and Projection. A key step involved compensating for misalignments in the iMAR data, particularly in 3D velocity and attitude angles. To minimize cross-track errors, the iMAR position data were projected onto the track geometry. This projection enabled more accurate mapping of position data to the actual railway infrastructure and reduced systematic lateral deviations.

Reference Point Adjustment: To ensure consistency with LOC-OB outputs, the reference point for both GT systems was shifted from the balise location to the first bogie (Bogie #1). This adjustment aligned the GT data with the operational reference used by the LOC-OB system. A dedicated route file was generated for this new reference point to support downstream processing.

Fusion into CLUG2-GT: The final Ground Truth, referred to as CLUG2-GT, was created through intelligent fusion of the two systems. iMAR-GT served as the baseline for real-time and motion data, while SMO-GT contributed track-referenced parameters. Data gaps were filled using the complementary system where possible, and the validity of all data points was systematically checked and annotated. This fusion leveraged the strengths of both systems while mitigating their respective weaknesses.

CLUG2-GT provides a robust and highly accurate reference solution that remains reliable across diverse operational environments, including urban areas and tunnel segments. By combining the real-time, 3D-motion capabilities of iMAR-GT with the track-referenced localization of SMO-GT, the system compensates for GNSS shadowing and the lack of real-time data. The resulting GT ensures consistent data quality and serves as a dependable foundation for validating the LOC-OB system.

3 KNOWN LIMITATIONS OF THE LOC-OB SYSTEM

3.1 LOC-OB algorithm

- Problem with EGNOS DFMC corrections for satellites GAL PRN > 27

The provision of EGNOS augmentation to the LOC-OB post-processing prototype is performed through Rinex.B files produced by the EGNOS Emulator tool (Airbus Defence & Space proprietary tool).

Detailed information of the Rinex.B format can be found in [R10].

The ADS EGNOS Emulator can handle Galileo PRNs that get only up to 27. Therefore, the LOC-OB will not be provided with augmentation for Galileo satellites with PRN values larger than 27 that are observed during the experimentation. As a consequence, these satellites will be automatically excluded by the LOC-OB.

The impact of this limitation will be a slight reduction of Galileo satellites' visibility, with respect to the nominal scenario.

This limitation is planned to be corrected after CLUG 2.0.

- Confidence Interval: only fault-free CI is provided

As detailed in [R4], the Integrity monitoring function is designed in CLUG2.0 WP4 to compute three Confidence Intervals: one in the fault-free case, one assuming GNSS faults and one assuming tachometer faults.

In the fault-free case, the CI is represented by a single factor, which is the multiplication of a constant value (depending on the THR allocated to the fault-free case) and the standard deviation computed by the localization algorithm for the along-track distance and speed.

In the two faulty cases (GNSS/tacho), the CI is the sum of two components:

- Similar to the fault free case, formed by the product of a constant (depending on the THR allocated to that faulty condition) and the standard deviation computed by the localization algorithm for the along track distance and speed;
- And an inflation component that takes into account the impact on the estimated output of those GNSS faults and tacho faults that would pass undetected by the System FDE.

This latter inflation component has been observed to be clearly overestimating the possible errors of the LOC-OB and therefore, more work is needed to understand the source of such overestimation.

For this reason, in the CLUG2.0 LOC-OB prototype, only fault-free CIs are provided.

The impact of this limitation is that it could occasionally happen in the experimentation phase that the observed errors of the LOC-OB could over exceed the CIs. This could happen when GNSS and/or tacho measurements would be affected by minor biases that pass undetected through the respective data FDEs.

- THR and PFA budgets allocations and thresholds definitions are preliminary

The LOC-OB prototype needs to be configured with several input parameters that correspond to THR and PFA budget allocations to the system data FDE and the CI computation, as well as threshold values for several sensor data FDEs.

Some preliminary values are already set in the LOC-OB prototypes, but there is the need for additional validations to consolidate them.

3.2 GNSS data FDE

Post processing SW limitation:

- Use of the train ground truth

The current version of the post-processing software requires the receiver position as input to calculate the satellite position. It is achieved using the train ground truth data. This choice was historically made for the first software version developed in Python language. No evolution was possible in the CLUG2.0 project to limit the development and integration time. As already discussed with CLUG2.0 partners, the solution, instead of using the ground truth could be to calculate the receiver position using the least-square method and use it as input. This also implies that in case of missing ground truth data, we cannot compute the SBAS corrections. For real-life applications, missing approximate receiver position from least-square would be due to GNSS performance issues and not from another sensor.

- No “real time” data processing

Another limitation of the current post-processing software is the way data is processed. The software reads all the input files at once (GNSS observables data, PVT data and SBAS corrections data) to store them in RAM memory. As this solution fulfils the project's requirement for recorded data analysis, it could have scalability limitations for very large recordings. Also, the software output containing each observable associated with SBAS corrections and FDE flags is generated all at once. There is no “real-time” treatment of the data, meaning that the current tool has not been adapted and tested for real-time applications. However, the choice of C-code and software optimization ensures that the performance of the post-processing software meets the partner's needs. C-code is also easier to adapt for real-time embedded applications.

- SBAS correction and ephemeris reception

The post-processing software uses Ephemeris (Ephemeris refers to the orbital and clock data of GNSS satellites present in navigation messages), which is essential information that the GNSS receiver needs for determining the precise location of satellites at any given time. In the case of post-processing software, ephemeris tables are read from the RINEX files. In real-life applications, reproducing this behaviour would mean tracking, acquiring and decoding navigation messages without perturbations that could delay the update of the ephemeris data. Unlike pure radio frequency reception, for CLUG 2.0 experiment, the ephemeris table is always fully available according to the best scenario of reception. It is the same behaviour for the SBAS corrections availability, the post-processing software



uses RINEX format corrections file as input. This is an ideal scenario and no effect like noise that could occur using real radio-frequency satellite signals is introduced.

3.3 Tacho data FDE

As analysed and described in more detail in 5.4, the Tacho data FDE algorithm has its limitations and can have a negative influence on the LOC-OB output in a few situations. The algorithm has to decide based on a single OPG sensor in real-time if the speed information is valid or not, which is an extremely challenging task. The current version was able to detect 65 % of the invalid speed datapoints, while discarding 6.9 % of the valid samples, in the ten analysed trips. In some situations, the Tacho data FDE is clearly reacting too sensitively and discarding too much, which can have a bad influence on the LOC-OB output, mostly by slightly increasing the confidence interval and sometimes also the noise on the speed delta. Overall, the positive impact of a Tacho data FDE based on a single OPG sensor on a sensor level is very limited.

4 TRIP ANALYSIS SUMMARY

4.1 Introduction

The following subchapters provide a summary of the main findings for each dataset analysed during the last iteration of the project. These datasets have been created using the latest available versions of the algorithms developed within the CLUG2.0 project.

A dataset consists of one “Trip” (train running from A to B) processed using one specific set of sensor input and algorithm configuration. All the trips have been processed with the configuration C01, as defined in the test plan [R6]. The configuration C01 includes the following sensors:

- Speed sensor: HaslerRail wheel tachometer
- GNSS receiver: Septentrio Mosaic-X5
- IMU: Analog Devices ADIS 16545

The configuration of the algorithms is as follow:

- FDE IMU disabled
- FDE Tacho enabled
- FDE GNSS enabled
 - FDE GNSS ELV enabled (at GNSS FDE level)
 - FDE GNSS CN0 enabled (at GNSS FDE level)
 - FDE GNSS CSL enabled
 - FDE GNSS CMC enabled
- FDE System MHD enabled
- EGNOS DFMC enabled
- Track selectivity disabled (routing file used)

Furthermore, the Trips 45, 73 and 77 have been processed with 2 additional configurations C03 and C09.

- C03 is based on C01 with the difference that EGNOS DFMC+PR+PV is used instead of DFMC.
- C09 is based on C01 with the difference that Track Selectivity is used instead of a routing file.

The following table provides an overview of the 10 trips with the configurations used:

Table 5: Overview of the trips analysed

ID	Vehicle	Date	Start UTC	End UTC	Journey	Configuration
45	Domino	14.03.2025	06:28:00	07:28:00	Yverdon-Fribourg	C01
						C03
						C09
46	Domino	14.03.2025	05:30:00	06:27:00	Fribourg-Yverdon	C01
47	Domino	14.03.2025	07:30:00	08:28:00	Fribourg-Yverdon	C01
58	Domino	14.03.2025	15:30:00	16:40:00	Fribourg-Lausanne	C01
49	Domino	25.03.2025	08:40:00	11:00:00	Biel-Arth-Goldau	C01
57	Domino	27.03.2025	12:15:00	15:00:00	Effretikon-Biel	C01
73	Domino	25.03.2025	12:00:00	13:50:00	Arth-Goldau-Biasca	C01
						C03
77	Domino	27.03.2025	08:00:00	09:15:00	Bellinzona-Altdorf	C01
						C03
78	Domino	27.03.2025	09:17:00	10:20:00	Altdorf-Sihlbrugg	C01
79	Domino	27.03.2025	10:22:00	11:45:00	Sihlbrugg-Effretikon	C01

4.2 Trip 45 – C01

Date:	14.03.2025	Time:	06:40-07:28
Route:	Yverdon-Fribourg		
Weather:	No rain/snow		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV disabled FDE GNSS CN0 disabled FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled EGNOS DFMC Track selectivity disabled	
	Analysis scripts:	v1.0.0	
	Ground Truth:	CLUG2 V1-19	
Result summary:			
Distance Along Track Error < 1.25 m:		52.88 %	
Distance Along Track Error < 4 m:		99.98 %	
Distance Error < Distance CI:		100 %	
Distance CI < 60 m:		100 %	
Distance CI < 10 m:		90.78 %	
Speed Error < (± 1 km/h $v < 100$ km/h, ± 1 % $v > 100$ km/h):		99.95 %	
Speed Error < Speed CI:		100 %	
CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:		CLUG2: 12.03 %	
TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:		TSI/R2DATO: 98.57 %	
<p>Trip 45 between Yverdon and Fribourg (41 km in 46 min) represents favourable conditions in terms of local environment (flat, rural area, no tunnel) and GNSS availability (mainly open sky, availability of 34±3 frequencies).</p> <p>Therefore, the percentage of GNSS pseudo range measurements excluded due to FDE (ELV: 16 %; CN0: 13 %; CMC: 0 %; MHD: 4 %) and no EGNOS DFMC data (7 %) is relatively small. Most of the time measurements from 4 GPS and 5 GAL satellites can be used.</p>			

The requirement SpecSysReq[010] is fulfilled for speed accuracy, while the distance accuracy is only fulfilled for the 4m-limit requirement (SpecSysReq[006]) and not for the 1.25m-limit requirement (SpecSysReq[005]). The 95th percentile of the distance errors is 2.59 m and of the speed error 0.56 km/h. An unexplained yet offset of about 1 m had been identified between the distance of the LOC-OB and Ground Truth. Reason therefore seems to be a non-constant behaviour in the lever arm, which could be only observed for Trip 45. If for this trip the lever arm would be reduced by 90 cm, there would be no offset between LOC-OB and Ground Truth. The tool chain implemented in the project does not provide the capability to implement non constant lever arms. A further investigation of this issue is recommended in future project.

The safety CI requirements (SpecSysReq[007], SpecSysReq[011]), distance/speed inside the computed CIs, is fulfilled.

The distance CI fulfils the requirement SpecSysReq[004], it is always below the 60-limit, but it does not fulfil the requirement SpecSysReq[003], because 9.22 % of the datapoints are above the 10-limit. The speed CI does not fulfil the requirement SpecSysReq[009], but it just fulfils the TSI requirement as the associated requirement allows 1mn per 1h (i.e. 98.3%) where computed CI might exceed the required CI.

4.3 Trip 45 – C03

Date:	14.03.2025	Time:	06:40-07:28
Route:	Yverdon-Fribourg		
Weather:	No rain/snow		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV disabled FDE GNSS CNO disabled FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled EGNOS DFMC+PR+PV Track selectivity disabled	
	Analysis scripts:	v1.0.0	

Ground Truth:		CLUG2 V1-19
Result summary:		
Distance Along Track Error < 1.25 m:		74.89 %
Distance Along Track Error < 4 m:		99.99 %
Distance Error < Distance CI:		100 %
Distance CI < 60 m:		100 %
Distance CI < 10 m:		90.40 %
Speed Error < (± 1 km/h $v < 100$ km/h, ± 1 % $v > 100$ km/h):		100 %
Speed Error < Speed CI:		100 %
CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:		CLUG2: 27.76 %
TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:		TSI/R2DATO: 98.65 %
<p>Trip 45 between Yverdon and Fribourg (41 km in 46 min) with favourable GNSS local environment (flat, rural area, no tunnel, mainly open sky) and configuration EGNOS DFMC+PR+PV ensures the same level of requirement fulfilment for distance/speed accuracy, distance/speed CI and safety CI as Trip 45 with configuration EGNOS DFMC, see chapter 4.2. As described in chapter 5.2 in more details, the speed CI is significantly lower for EGNOS DFMC+PR+PV, while the use of DFMC+PR+PV does not have a significant impact on the distance CI. Regarding accuracy, no significant impact on the speed estimations could be identified. No analysis regarding distance accuracy is possible, because of the identified 1 m bias between LOC-OB and Ground Truth (see chapter 4.2).</p>		

4.4 Trip 45 – C09

Date:	14.03.2025	Time:	06:40-07:28
Route:	Yverdon-Fribourg		
Weather:	No rain/snow		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV disabled FDE GNSS CNO disabled FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled	

		EGNOS DFMC Track selectivity enabled
	Analysis scripts:	v1.0.0
	Ground Truth:	CLUG2 V1-19
Result summary:		
Distance Along Track Error < 1.25 m:		53.30 %
Distance Along Track Error < 4 m:		99.85 %
Distance Error < Distance CI:		99.90 %
Distance CI < 60 m:		100 %
Distance CI < 10 m:		90.86 %
Speed Error < (± 1 km/h $v < 100$ km/h, ± 1 % $v > 100$ km/h):		99.95 %
Speed Error < Speed CI:		100 %
CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:		CLUG2: 11.95 %
TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:		TSI/R2DATO: 98.57 %
<p>Trip 45 between Yverdon and Fribourg (41 km in 46 min) with favourable GNSS local environment (flat, rural area, no tunnel, mainly open sky) and configuration EGNOS DFMC plus track selectivity (TS) ensures the same level of requirement fulfilment for distance/speed accuracy, distance/speed CI and safety CI as Trip 45 with configuration EGNOS DFMC (chapter 4.2) expect the safety speed CI requirement is not met to 100 %. As described in more detail in chapter 5.1.3, the track edges estimated by TS coincide almost completely with the ones provided by the GT and no significant impact on the 1D localization/speed accuracy could be identified. Therefore, the LOC-OB performs as expected with TS.</p>		

4.5 Trip 46 – C01

Date:	14.03.2025	Time:	05:36 – 6:25
Route:	Givisiez – Yverdon-les-Bains		
Weather:	Partly cloudy, 4°C		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV enabled (at GNSS FDE level)	

		FDE GNSS CNO enabled (at GNSS FDE level) FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled EGNOS DFMC Track selectivity disabled
	Analysis scripts:	v1.0.0
	Ground Truth:	CLUG2 V1-19
Result summary:		
Distance Along Track Error < 1.25 m:		83.78 %
Distance Along Track Error < 4 m:		100 %
Distance Error < Distance CI:		100 %
Distance CI < 60 m:		100 %
Distance CI < 10 m:		98.55 %
Speed Error < (± 1 km/h $v < 100$ km/h, ± 1 % $v > 100$ km/h):		99.72 %
Speed Error < Speed CI:		100 %
CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:		CLUG2: 27.31 %
TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:		TSI/R2DATO: 99.51 %
<p>Trip 46 between Givisiez and Yverdon-les-Bains covers a distance of 46 km in 49 min. There are no tunnels along the route. This trip shows ideal conditions regarding GNSS signal reception.</p> <p>The delta in 1D distance between LOC-OB and Ground Truth is always below the 4m-limit specified in SpecSysReq[006], with only 16.22 % of the datapoints being above the 1.25m-limit from SpecSysReq[005]. Note that the distance accuracy is not always decreasing below 1.25 m when the train stops, as required by SpecSysReq[005].</p> <p>The computed confidence interval for the distance mostly fulfils the requirements:</p> <ul style="list-style-type: none"> - 0 % of the datapoints are above the 60m-limit from SpecSysReq[004] - 1.45 % of the datapoints are above the 10m-limit from SpecSysReq[003] (note, that some points are within ± 500 m of a stopping point) <p>The speed accuracy is also fulfilling the requirement SpecSysReq[010], with only 0.28 % of speed data points deviating from the Ground Truth by the specified limits.</p> <p>The computed speed confidence interval falls outside the CI limit defined in SpecSysReq[009] for 75.69 % of the time; however, overall, it remains very close to the specified limit throughout the entire trip.</p>		

4.6 Trip 47 – C01

Date:	14.04.2025	Time:	07:30 – 08:28 (UTC)
Route:	Fribourg - Yverdon		
Weather:	no rain, 6-16°C		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV enabled (at GNSS FDE level) FDE GNSS CNO enabled (at GNSS FDE level) FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled EGNOS DFMC Track selectivity disabled	
	Analysis scripts:	v1.0.0	
	Ground Truth:	CLUG2 V1-19	
Result summary:			
Distance Along Track Error < 1.25 m:	71.07 %		
Distance Along Track Error < 4 m:	100 %		
Distance Error < Distance CI:	100 %		
Distance CI < 60 m:	100 %		
Distance CI < 10 m:	95.71 %		
Speed Error < (± 1 km/h $v < 100$ km/h, $\pm 1\%$ $v > 100$ km/h):	99.88 %		
Speed Error < Speed CI:	100 %		
CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:	CLUG2: 26.28 %		
TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:	TSI/R2DATO: 96.0 %		
<p>Trip 47 represents a standard journey of the Domino serving for passenger transport between Fribourg and Yverdon. The environment is common for a rural area in Switzerland, and the line connects two smaller cities with no large stations in between. 71.07 % of the samples have a position error smaller than 1.25 m, but the analysis does not distinguish between operational surroundings, Stop and Open. All position errors are smaller than 4 m and position safety is guaranteed for every sample as the error is always bounded by the confidence interval. The confidence interval for position itself is always below 60 m and does not exceed 10 m in 95.71 % of the cases. Similarly, the speed error is always within the formulated requirement, except for 0.12 % of the samples. No safety violations are registered for this trip. The confidence interval for speed</p>			

is smaller than formulated in the requirement in CLUG 2.0 for 26.28 % of samples and the TSI requirement for speed CI for 96.00 %.

In general, the algorithm performs as expected and the relevant requirements are fulfilled.

4.7 Trip 49 – C01

Date:	25.03.2025	Time:	08:40-11:00
Route:	Biel/Bienne-Arth-Goldau		
Weather:	Partly cloudy, 8-12°C		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV enabled (at GNSS FDE level) FDE GNSS CN0 enabled (at GNSS FDE level) FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled EGNOS DFMC Track selectivity disabled	
	Analysis scripts:	v1.0.0	
	Ground Truth:	CLUG2 V1-19	
Result summary:			
Distance Along Track Error < 1.25 m:		73.48 %	
Distance Along Track Error < 4 m:		96.58 %	
Distance Error < Distance CI:		100 %	
Distance CI < 60 m:		100 %	
Distance CI < 10 m:		74.8 %	
Speed Error < (± 1 km/h $v < 100$ km/h, ± 1 % $v > 100$ km/h):		98.98 %	
Speed Error < Speed CI:		99.97 %	
CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:		CLUG2:18.8 %	
		TSI/R2DATO: 95.52 %	

TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47}(v + 64 \text{ km/h}))$):

Trip 49 between Biel/Bienne and Arth-Goldau is covering a distance of 136 km for a duration of 2:03. Two longer tunnels are passed, plus some additional shorter ones. The weather is partly cloudy. Therefore, these can be deemed as typical environmental conditions for railway operation in Switzerland.

This distance delta is for more than 95 % of the case within the 4m-limit defined in the requirement SpecSysReq[006]. Only 3 events have been detected for which the distance error is increasing above the 4m-limit:

1. At 09:55 which is correlated to a drop of number of satellite pseudoranges for GAL E5a after passing a tunnel 3 minutes earlier. The LOC-OB requires almost 4 min to recover the typical number of PSR after passing the tunnel.
2. At 10:33, however no external reasons for that event could be found. The tacho FDE set all measurements to valid and the number of GNSS satellites is typical. It can be noted that the train runs for 1 min at low speed < 5 km/h.
3. At 10:43, during a period when the number of satellite PSR for GAL E5a drops and the tacho FDE discards tachometer measurements.

Generally, the distance delta is often within the $\pm 1.25 \text{ m}$, but it is not correlated to the vehicle speed, i.e. the distance delta is not always within the $\pm 1.25 \text{ m}$ when the train stops as per the requirement SpecSysReq[005].

All the datapoints have a confidence interval for the distance below the required 60m-limit in SpecSysReq[004]. The confidence interval is almost centered on the 10m-limit, which leads to 25.30 % of the datapoints being above the 10m-limit. The confidence interval is not correlated to the vehicle speed, i.e. the confidence interval does not always decrease below the 10m-limit when the train stops as per the requirement SpecSysReq[003].

The speed accuracy is mostly within the specified limits, only a few outliers can be observed. In total 98.98 % of the datapoints are within the required limit, which is better than the required 95 % in SpecSysReq[010].

There is one event when speed error is outside the computed CI shortly before 09:23. By comparing the speed values provided by the LOC-OB, tachometer, doppler radar, optical speed sensor, it can be proven that the speed computed by the LOC-OB is deviating by approximately 2 km/h. Three seconds before this event the number of satellites dropped to 0 for 1 second, which could be the cause of this speed error. The tacho FDE did not discard measurements during this time.

The computed speed confidence interval falls outside the CI limit defined in SpecSysReq[009] for 81.2 % of the time; however, overall, it remains very close to the specified limit throughout the entire trip.

4.8 Trip 57 – C01

Date:	27.03.2025	Time:	12:31-14:49
Route:	Zürich Stadelhofen-Biel		
Weather:	Partly cloudy, 8-12°C		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV enabled (at GNSS FDE level) FDE GNSS CN0 enabled (at GNSS FDE level) FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled EGNOS DFMC Track selectivity disabled	
	Analysis scripts:	v1.0.0	
	Ground Truth:	CLUG2 V1-19	
Result summary:			
Distance Along Track Error < 1.25 m:			62.28 %
Distance Along Track Error < 4 m:			87.8 %
Distance Error < Distance CI:			99.74 %
Distance CI < 60 m:			99.97 %
Distance CI < 10 m:			58.22 %
Speed Error < (± 1 km/h $v < 100$ km/h, ± 1 % $v > 100$ km/h):			99.39 %
Speed Error < Speed CI:			100 %
CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:			CLUG2: 33.76 %
TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:			TSI/R2DATO: 94.75 %
<p>Trip 57 between Zürich Stadelhofen and Biel/Bienne is covering a distance of 116 km for a duration of 2:18. Two longer tunnels are passed. The weather is partly cloudy. The challenging condition in this trip is the fact that the algorithm is initialized in Stadelhofen, which is a place with very poor satellite reception, and after leaving the Stadelhofen station the train enters a long tunnel until it leaves Zürich main station. Probably due to this reason, the LOC-OB algorithm starts providing output only at 12:42 when the train leaves the tunnel from Zurich HB.</p>			

The delta of the 1D distance between LOC-OB and Ground Truth mostly remains within the limits ± 4 m specified in SpecSysReq[006]. Two phases can be observed when the performance decrease:

1. at the beginning of the trip
2. between Aarau and Olten

A decrease of the distance delta below 1.25 m when the train reduces its speed and/or reaches standstill, as specified in SpecSysReq[005], cannot be always verified. For instance, there is a phase that lasts almost 5 min when the train is at standstill during which the distance delta is slightly above the 1.25m-limit.

The drop in distance accuracy at the beginning of the trip is correlated to a decrease of number of satellite pseudorange measurements for GAL E5a after system FDE. In addition, the Tacho FDE discards many measurements during this phase.

The drop in distance accuracy between Aarau and Olten is correlated to a decrease of number of satellite pseudorange measurements for GPS L1 after system FDE. However, the Tacho FDE does not discard many measurements during this phase.

In addition, there is one event lasting 15 s between Aarau and Olten during which the delta distance is outside the computed confidence interval.

The computed confidence interval for the distance remains almost always (99.97 %) within the 60m-limit from SpecSysReq[004], the remaining 0.03 % are occurring at initialization phase and shall be ignored. The confidence interval is mostly centered on the 10m-limit, with 41.78 % of the data points above the 10m-limit. During the longer standstill phases of the trip, the confidence interval decreases below the 10m-limits. Otherwise, it remains above the 10m-limit during the shorter standstill phases. Therefore, the requirement SpecSysReq[003] is not met.

With only 0.61 % of the datapoints having a speed delta outside the limit specified in SpecSysReq[010], the speed accuracy fully fulfils the specification.

The same two phases as for the distance accuracy can be observed during which the speed accuracy slightly drops. Most of these speed deviations are below 2 km/h. Further investigations tend to show that a tuning of the algorithm to detect standstill faster could help to further improve the speed accuracy.

The computed speed confidence interval falls outside the CI limit defined in SpecSysReq[009] for 66.24 % of the time; however, overall, it remains very close to the specified limit throughout the entire trip.

At standstill, the speed confidence interval is mostly within the specified limit. Otherwise, no outlier can be observed, except during the initialization phase.

4.9 Trip 58 – C01

Date:	14.03.2025	Time:	15:30 – 16:40 (UTC)
Route:	Fribourg - Lausanne		
Weather:	No rain, 2-18°C		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV enabled (at GNSS FDE level) FDE GNSS CNO enabled (at GNSS FDE level) FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled EGNOS DFMC Track selectivity disabled	
	Analysis scripts:	v1.0.0	
	Ground Truth:	CLUG2 V1-19	
Result summary:			
Distance Along Track Error < 1.25 m:		79.11 %	
Distance Along Track Error < 4 m:		100 %	
Distance Error < Distance CI:		100 %	
Distance CI < 60 m:		100 %	
Distance CI < 10 m:		92.16 %	
Speed Error < (± 1 km/h $v < 100$ km/h, ± 1 % $v > 100$ km/h):		98.47 %	
Speed Error < Speed CI:		99.87 %	
CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:		CLUG2: 20.22 %	
TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:		TSI/R2DATO: 98.08 %	
<p>Trip 58 is a regular train journey of the Domino for passenger service between the city of Fribourg and Lausanne in the western part of Switzerland. The line is standardly equipped as a dual line without any environmental specialties. The journey does not contain any longer tunnels or passages in larger cities. The performance is as expected. The exceedance of the position error of 20.89 % is because the analysis does not distinguish between the areas around stops and stations where this requirement is applicable. The error is always below 4 m, the confidence interval is below 60 m,</p>			

and the confidence interval envelopes the position error well. Similar to the lower position error requirement, 92.16 % of the samples have a smaller confidence interval than 10 m. 98.47 % of the samples have a speed error smaller than the stated requirement. Concerning the safety, for 0.13 % of the trip dataset, the speed error is larger than the computed confidence interval. Similarly to the other trips, the confidence interval for speed is nearly always larger than the formulated requirement by CLUG 2.0 D2.4 [R1]. The TSI requirement regarding the speed CI [R5] on the other hand, is fulfilled by 98.08 % of the samples.

4.10 Trip 73 – C01

Date:	25.03.2025	Time:	12:12 – 13:46
Route:	Art Goldau – Biasca		
Weather:	Partly cloudy		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV enabled (at GNSS FDE level) FDE GNSS CNO enabled (at GNSS FDE level) FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled EGNOS DFMC Track selectivity disabled	
	Analysis scripts:	v1.0.0	
	Ground Truth:	CLUG2 V1-19	
Result summary:			
Distance Along Track Error < 1.25 m:		57.97 %	
Distance Along Track Error < 4 m:		97.56 %	
Distance Error < Distance CI:		99.58 %	
Distance CI < 60 m:		99.95 %	
Distance CI < 10 m:		16.48 %	
Speed Error ($\pm 1\text{ km/h}$ <math>v < 100\text{ km/h}</math>, $\pm 1\%$ $v > 100\text{ km/h}$):		99.49 %	
Speed Error < Speed CI:		99.82 %	

CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:	CLUG2: 14.24 %
TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:	TSI/R2DATO: 72.59 %

Trip 73 is a challenging scenario regarding the dynamic (high speed / acceleration / high angular speed) as well as the variety of environment.

The beginning of the trip starts in Art Goldau and travels through tunnels, cities and rural areas until reaching the Gotthard tunnel. Then, the train leaves the tunnel and crosses cities, tunnels (some spinning) and canyons.

Despite this, LOC-OB's performance with DFMC configuration (C01) is good. Excepted the tunnel where the position error grows up to 10 m and speed error to 10 km/h (tacho failure undetected), accuracy limit is respected up to 97.66 % for position at 4 m and 99.42 % for speed. Less than 58.87 % of position samples are inferior to 1.25 m, which makes this requirement a bit difficult to fulfil (no distinction between stopping point and other areas as per SpecSysReq[005] and SpecSysReq[006]). Position CIs are almost always inferior to 60 m (99.95%, see SpecSysReq[004]), and 16.48 % of the time inferior to 10 m (SpecSysReq[003]). It should be noticed that position CI is usually ranging from 10 to 15 m so the gap with SpecSysReq[003] is not big. About speed, CI is superior to SpecSysReq[009] limit 85.76 % of the time, but this should be underlined that it varies between 2 km/h and 3 km/h. A common point between position and speed is, with GNSS reception or when leaving tunnels, CIs are subject to important variations which is not in line with SpecSysReq[025]. Some integrity events are also seen, 0.42 % of samples for position and 0.21 % for speed which is in contradiction with SpecSysReq[007] and SpecSysReq[011].

4.11 Trip 73 – C03

Date:	25.03.2025	Time:	12:12 – 13:46
Route:	Art Goldau – Biasca		
Weather:	Partly cloudy		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV enabled (at GNSS FDE level) FDE GNSS CNO enabled (at GNSS FDE level)	

		FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled EGNOS DFMC + PR + PV Track selectivity disabled
	Analysis scripts:	v1.0.0
	Ground Truth:	CLUG2 V1-19
Result summary:		
Distance Along Track Error < 1.25 m:		46.61 %
Distance Along Track Error < 4 m:		95.06 %
Distance Error < Distance CI:		99.07 %
Distance CI < 60 m:		100 %
Distance CI < 10 m:		23.31 %
Speed Error < (± 1 km/h $v < 100$ km/h, ± 1 % $v > 100$ km/h):		99.49 %
Speed Error < Speed CI:		99.82 %
CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:		CLUG2: 19.54%
TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:		TSI/R2DATO: 89.57 %

Trip 73 is a challenging scenario regarding the dynamic (high speed / acceleration / high angular speed) as well as the variety of environment. The beginning of the trip starts in Arth Goldau and travels through tunnels, cities and rural areas until reaching the Gotthard tunnel. Then, the train leaves the tunnel and crosses cities, tunnels (some spinning) and canyons.

In this simulation, LOC-OB performance with DFMC+PR+PV is good. Similarly to C01 configuration, only the Gotthard tunnel is challenging for LOC-OB. Again, the position error grows up to more than 10 m and speed error to 10 km/h (tacho failure undetected).

Despite this, over the whole trip, accuracy limit is respected up to 95.04 % for position at 4 m and 99.49 % for speed. Less than 45.61 % of position samples are inferior to 1.25 m without distinction between stopping point and other areas as depicted in SpecSysReq[005] and SpecSysReq[006]. Position CIs are always inferior to 60 m (100 %, see SpecSysReq[004]), and 23.31 % of the time inferior to 10 m (see SpecSysReq[003]). Position CI usually varies in the range from 10 to 15 m, so it is closed to SpecSysReq[003] and a major improvement is the stability of position CI especially under GNSS coverage or when leaving tunnels. About speed, CI is superior to SpecSysReq[009] limit 80.46 % of the time but mainly remains under 3 km/h. In comparison with C01, this is more compliant with SpecSysReq[007] and SpecSysReq[011] which ask to limit important variations for whether speed or position CI to avoid emergency braking. As for position, speed CI does not vary as much as in C01.

4.12 Trip 77 – C01

Date:	27.03.2025	Time:	08:00-09:15 (UTC)
Route:	Bellinzona - Altdorf		
Weather:	No Rain, partly cloudy, 2 - 20°C		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV enabled (at GNSS FDE level) FDE GNSS CN0 enabled (at GNSS FDE level) FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled EGNOS DFMC Track selectivity disabled	
	Analysis scripts:	v1.0.0	
	Ground Truth:	CLUG2 V1-19	
Result summary:			
Distance Along Track Error < 1.25 m:		49.02 %	
Distance Along Track Error < 4 m:		64.57 %	
Distance Error < Distance CI:		100 %	
Distance CI < 60 m:		98.29 %	
Distance CI < 10 m:		53.07 %	
Speed Error < (± 1 km/h $v < 100$ km/h, ± 1 % $v > 100$ km/h):		99.93 %	
Speed Error < Speed CI:		100 %	
CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:		CLUG2: 20.16 %	
TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:		TSI/R2DATO: 89.9 %	
Trip 77 and configuration C01 is analyzed in detail in Section 5.3.2 Trip 77 through the Gotthard base tunnel.			

4.13 Trip 77 – C03

Date:	27.03.2025	Time:	08:15-09:15 (UTC)
Route:	Pollegio - Altdorf		
Weather:	No Rain, partly cloudy, 2 - 20°C		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV enabled (at GNSS FDE level) FDE GNSS CNO enabled (at GNSS FDE level) FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled EGNOS DFMC+PR+PV Track selectivity disabled	
	Analysis scripts:	v1.0.0	
	Ground Truth:	CLUG2 V1-19	
Result summary:			
Distance Along Track Error < 1.25 m:		46.23 %	
Distance Along Track Error < 4 m:		58.11 %	
Distance Error < Distance CI:		100 %	
Distance CI < 60 m:		99.87 %	
Distance CI < 10 m:		50.08 %	
Speed Error < (± 1 km/h $v < 100$ km/h, ± 1 % $v > 100$ km/h):		100 %	
Speed Error < Speed CI:		100 %	
CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:		CLUG2: 48.8 %	
TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:		TSI/R2DATO:98.5 %	

Trip 77 is a special scenario that starts in Pollegio, travels for 25 min in a tunnel to finish in Altdorf. This scenario is unique in the way the domino dynamic phase mainly takes place in the tunnel.

In this simulation, LOC-OB performance with DFMC+PR+PV is good. Similarly to Trip 73, only the tunnel is challenging for LOC-OB (25 min long, 57 km).

This has obviously an impact on performance requirement compliance:

Regarding position accuracy limit SpecSysReq[006] (4-m limit), only 58.11 % for position are compliant. For SpecSysReq[005] (1.25 m), it is less than 46.23 % (no distinction between stopping point and other areas as expected in SpecSysReq[005] and SpecSysReq[006]). On the contrary, speed accuracy is respected all the time (SpecSysReq[010]).

Position CIs are always inferior to 60 m (100 %, see SpecSysReq[004]), and 23.31 % of the time inferior to 10 m (see SpecSysReq[003]). It linearly increases in straight line and shrinks a bit in curves. Speed CI is half the time above SpecSysReq[009] limit but is very stable in time and not that far from the requirement (most time between 2 km/h and 3 km/h).

No integrity event is triggered neither for position nor speed.

Overall, even if performances are not fulfilled, these results are very positive in regard to this challenging environment.

4.14 Trip 78 – C01

Date:	27.03.2025	Time:	9:36 – 10:15
Route:	Brunnen - Sihlbrugg		
Weather:	Partly cloudy, 5°C		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV enabled (at GNSS FDE level) FDE GNSS CNO enabled (at GNSS FDE level) FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled	

		EGNOS DFMC Track selectivity disabled
	Analysis scripts:	v1.0.0
	Ground Truth:	CLUG2 V1-19
Result summary:		
Distance Along Track Error < 1.25 m:		20.07 %
Distance Along Track Error < 4 m:		100 %
Distance Error < Distance CI:		100 %
Distance CI < 60 m:		100 %
Distance CI < 10 m:		54.85 %
Speed Error < (± 1 km/h $v < 100$ km/h, ± 1 % $v > 100$ km/h):		97.9 %
Speed Error < Speed CI:		99.55 %
CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:		CLUG2: 13.03 %
TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:		TSI/R2DATO: 88.65 %
<p>Trip 78 between Brunnen and Sihlbrugg covers a distance of 36 km in a duration of 39 min. The route includes few short tunnels and a longer tunnel toward the end of the journey. Therefore, these can be deemed as typical environmental conditions for railway operation in Switzerland.</p> <p>The delta in 1D distance between LOC-OB and Ground Truth is fulfilling the 4m-requirement SpecSysReq[006], with only 0.02 % of the datapoints outside the specified ± 4 m limit, which seems to be caused by an artefact in the Ground Truth.</p> <p>However, 19.93 % of the datapoints have a distance delta above 1.25 m, including a significant section during the first long standstill phase, thus the 1.25m-requirement SpecSysReq[005] is not fulfilled.</p> <p>The confidence Interval for the distance is always below the 60m-limit from SpecSysReq[004]. However, 45.15 % of the data points have a confidence interval above the 10m-limit, a significant part of it occurs during the second long standstill phase. Thus, the requirement SpecSysReq[003] is not fulfilled.</p> <p>The speed accuracy is mostly within the specified limits, only a few outliers can be observed. In total 97.1 % of the datapoints are within the required limit, which is better than the required 95 % in SpecSysReq[010]. Two events have been detected for which the speed error is outside of the computed confidence interval. Both events indicate that the LOC-OB speed deviates by approximately 2 km/h from the other speed sensors, including the wheel tachometer used by the LOC-OB algorithm.</p> <p>The computed speed confidence interval falls outside the CI limit defined in SpecSysReq[009] for 86.97 % of the time; however, overall, it remains very close to the specified limit throughout the entire trip.</p>		

4.15 Trip 79 – C01

Date:	27.03.2025	Time:	10:31 – 11:34
Route:	Thalwil - Effretikon		
Weather:	Clear day		
Configuration:	HW:	HaslerRail wheel tachometer, Septentrio Mosaic-X5 receiver, Analog Devices ADIS 16545 IMU	
	SW:	ADS CLUG2 post processing V3.1.5 CAF IMU FDE V1.0.5 SMO Tacho FDE V2.0.1 SYN Post Processing V1.3.8 SYN rinex2csv V1.2.2	
	Config. parameters:	FDE IMU disabled FDE Tacho enabled FDE GNSS enabled FDE GNSS ELV enabled (at GNSS FDE level) FDE GNSS CN0 enabled (at GNSS FDE level) FDE GNSS CSL enabled FDE GNSS CMC enabled FDE Syst MHD enabled EGNOS DFMC Track selectivity disabled	
	Analysis scripts:	v1.0.0	
	Ground Truth:	CLUG2 V1-19	
Result summary:			
Distance Along Track Error < 1.25 m:		40.38 %	
Distance Along Track Error < 4 m:		71.66 %	
Distance Error < Distance CI:		99.71 %	
Distance CI < 60 m:		100 %	
Distance CI < 10 m:		62.36 %	
Speed Error < (± 1 km/h $v < 100$ km/h, ± 1 % $v > 100$ km/h):		96.57 %	
Speed Error < Speed CI:		99.85 %	
CLUG2: half Speed CI < $\max(1 \text{ km/h}, \frac{1}{2} * \frac{1}{47} (v + 64 \text{ km/h}))$:		CLUG2: 40.58 %	
TSI/R2DATO: half Speed CI < $\max(2 \text{ km/h}, \frac{1}{47} (v + 64 \text{ km/h}))$:		TSI/R2DATO: 62.12 %	
<p>Trip 79 covers a distance of 32.5 km between Thalwil and Effretikon, with a total duration of 1 hour and 3 min. The route passes entirely through urban areas, including the city center of Zurich. As a result, the train had to pass through four tunnels, creating a challenging environment for GNSS signal reception. After 10 min, directly after the second short tunnel, the train stopped for around 22 min. The trip took place on a sunny and clear day.</p>			

During the first 5 min of the trip, the LOC-OB algorithm experiences difficulties in providing an accurate position. Although the number of satellites should be sufficient, the 1D position error consistently exceeds 4 m and occasionally reaches up to 20 m, when compared to the ground truth (GT). Following this initial phase, during the long standstill after the two short tunnels, the positioning accuracy improves and remains relatively stable within 2 m. As the train proceeds, passes through the underground station at Zurich HB and continues to Zurich Oerlikon, in a longer tunnel, the position error typically ranges between 4 and 10 m. In the final section, through the underground station at Zurich Airport and the second long tunnel, the algorithm performs the best, achieving an accuracy of approximately 1.25 m for most of the time. Overall, the 1D distance error remains within the 1.25m-limit for 40.38 % of the trip and within the 4m-limit for 71.66 % of the trip.

The computed confidence interval (CI) for the position error consistently remains below the 60m-limit specified in SpecSysReq[004], peaking at 50 m during the first 5 min. During the long standstill, the CI remains within 10 meters, and afterward, it generally fluctuates between 10 and 20 m. After the standstill, 0.29 % of the LOC-OB position data points fall outside of the confidence interval.

The 1D speed information from LOC-OB initially shows a deviation of approximately 3 km/h from the GT but gradually decreases to 0 km/h before the long stop at the 10-minute mark. During the standstill, the computed speed remains nearly constant at zero, never exceeding 0.25 km/h. After the stop, the speed deviation between LOC-OB and GT stays within the 1 km/h limit, except for some short section, where LOC-OB shows some small oscillation in the range of 2 km/h. Overall, 96.57 % of the LOC-OB speed information fall within the 1 km/h threshold, surpassing the 95 % requirement stated in SpecSysReq[010].

The confidence interval for speed is while 59.42 % outside of the CLUG2.0 requirement, defined in SpecSysReq[009]. Most of the part where the CI is within the limit occurs during the long standstill. The biggest outliers occur at the beginning, reaching 8 km/h, while elsewhere it is typically between 2 and 4 km/h.

5 COMPREHENSIVE ANALYSIS

5.1 Detailed analysis of Trip 45

5.1.1 Overview

Trip 45 had been analysed for three different configurations:

- **C01:** EGNOS DFMC (see chapter 4.1),
- **C03:** EGNOS DFMC+PR+PV (see chapter 4.2),
- **C09:** EGNOS DFMC plus track selectivity (see chapter 4.3).

Furthermore, 2 “fake” tunnels had been introduced in order to investigate the performance of the LOC-OB in GNSS denied areas.

For comparison reasons Table 6 provides the corresponding key GNSS performance indicators for the safe 1D localization/speed parameters. Note that within this table the probability speed CI inside [2 12] km/h half-MCI is provided with respect to the TSI requirement [R5]. Detailed descriptions can be found in the subsequent chapters (5.1.2, 5.1.3, 5.2).

Table 6: Overall performance and GNSS availability for the different configurations of Trip 45

Key GNSS safety performance indicators Safe 1D localization parameters after first 60 s		Trip #45			Trip #49 „fake“ tunnels		
		C01 (DFMC)	C03 (DFMC+PR+PV)	C09 (DFMC, TS)	C01 (DFMC) All trip	C01 (DFMC) No tunnel parts	C01 (DFMC) Tunnel parts
ACCURACY	Along track pos error mean (m)	0.93	0.71	0.93	0.93	1.01	0.46
	Along track pos error 2-sigma (m)	2.98	2.48	2.96	3.02	3.02	2.86
	Along track pos error inside 1.25m 95% (1s occurrences / total / %)	6651 / 13560 / 49.05	7963 / 13560 / 58.72	6717 / 13560 / 49.54	6527 / 13560 / 48.13	5082 / 11587 / 43.86	1445 / 1973 / 73.24
	Along track pos error inside 4m 95% (1s occurrences / total / %)	13434 / 13560 / 99.07	13537 / 13560 / 99.83	13429 / 13560 / 99.03	13416 / 13560 / 98.94	11461 / 11587 / 98.91	1955 / 1973 / 99.09
	Along track speed error mean (km/h)	0.08	-0.01	0.08	0.07	0.07	0.07
	Along track speed error 2-sigma (km/h)	0.48	0.45	0.48	0.46	0.47	0.37
	Along track speed error inside [1 5]km/h 95% (1s occurrences / total / %)	13553 / 13560 / 99.95	13560 / 13560 / 100	13553 / 13560 / 99.95	13559 / 13560 / 99.99	11586 / 11587 / 99.99	1973 / 1973 / 100
INTEGRITY	Along track pos half CI mean (m)	7.88	7.38	7.87	8.22	7.98	9.65
	Along track pos half CI 2-sigma (m)	2.8	2.81	2.79	3.3	2.96	3.69
	Along track pos error inside CI (1s occurrences / total / %)	13560 / 13560 / 100	13560 / 13560 / 100	13560 / 13560 / 100	13560 / 13560 / 100	11587 / 11587 / 100	1973 / 1973 / 100
	Along track pos CI inside 10m half-MCI 99% (1s occurrences / total / %)	12299 / 13560 / 90.7	12282 / 13560 / 90.58	12308 / 13560 / 90.77	11428 / 13560 / 84.28	10319 / 11587 / 89.06	1109 / 1973 / 56.21
	Along track pos CI inside 60m half-MCI 99% (1s occurrences / total / %)	13560 / 13560 / 100	13560 / 13560 / 100	13560 / 13560 / 100	13560 / 13560 / 100	11587 / 11587 / 100	1973 / 1973 / 100
	Along track speed half CI mean (km/h)	1.69	1.5	1.68	1.73	1.69	2.01
	Along track speed half CI 2-sigma (km/h)	0.72	0.5	0.72	0.75	0.73	0.64
	Along track speed error inside CI (1s occurrences / total / %)	13560 / 13560 / 100	13560 / 13560 / 100	13560 / 13560 / 100	13560 / 13560 / 100	11587 / 11587 / 100	1973 / 1973 / 100
	Along track speed CI inside [2 12]km/h half-MCI 99% (1s occurrences / total / %)	13366 / 13560 / 98.57	13377 / 13560 / 98.65	13366 / 13560 / 98.57	13108 / 13560 / 96.67	11400 / 11587 / 98.39	1708 / 1973 / 86.57
GNSS AVAILABILITY AFTER FDE & EGNOS	GNSS DF GPS L1&L5 satellite (PSR) unavailability (%)	2.08	2.22	2.08	14.73	2.42	100
	GNSS DF GAL E1&E5a satellite (PSR) unavailability (%)	2.11	2.11	2.11	14.73	2.42	100
	Mean number of DF GPS L1&L5 satellite (PSR)	4	4	4	4	4	0
	Standard deviation number of DF GPS L1&L5 satellite (PSR)	1	1	1	2	1	0
	Mean number of DF GAL E1&E5a satellite (PSR)	5	5	5	4	5	0
	Standard deviation number of DF GAL E1&E5a satellite (PSR)	1	1	1	2	1	0

5.1.2 Trip 45 with fake tunnels

Trip 45 (favourable GNSS local environment) had also been analysed with 2 “fake” tunnels (1 linear, 1 curve) in order to investigate the performance and safety or when no GNSS is available. Note the entry and exit local environments of the tunnels are less representative due to the absence of multipath and GNSS satellite shadowing caused by mountains (see Figure 5-1).

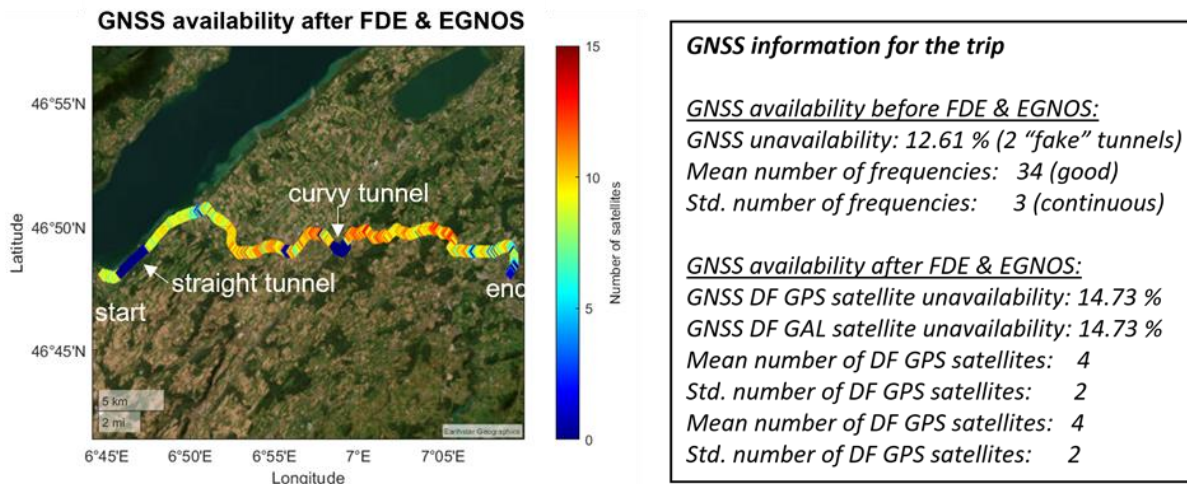


Figure 5-1: GNSS availability before and after FDE & EGNOS for Trip 45 with 2 “fake” tunnels

The performance for the whole trip is not negatively impacted by these tunnels, see Table 7. The requirements are still partly fulfilled as described in chapter 4.2. Whereas the performance within the tunnels and about 500 to 850 s after the tunnels is slightly worse than it would be in the case without a tunnel (GNSS availability), see Figure 5-2 and Table 7. The FDE MHD recovers already 2 s after the tunnels. This example shows that the LOC-OB can handle tunnels in a good manner.

Table 7: Performance impact on position and speed during and after straight and curvy tunnels

	Performance impact	
	Position	Speed
During 1 straight tunnel	Maximum 1.1 m	Maximum 0.4 km/h
After 1 straight tunnel	Low	Max. 0.2 km/h for about 500 s
During 1 curvy tunnel	Maximum 2.8 m	Maximum 0.6 km/h
After 1 curvy tunnel	Max. 0.8 m for about 850 s	Max. 0.6 km/h for about 850 s

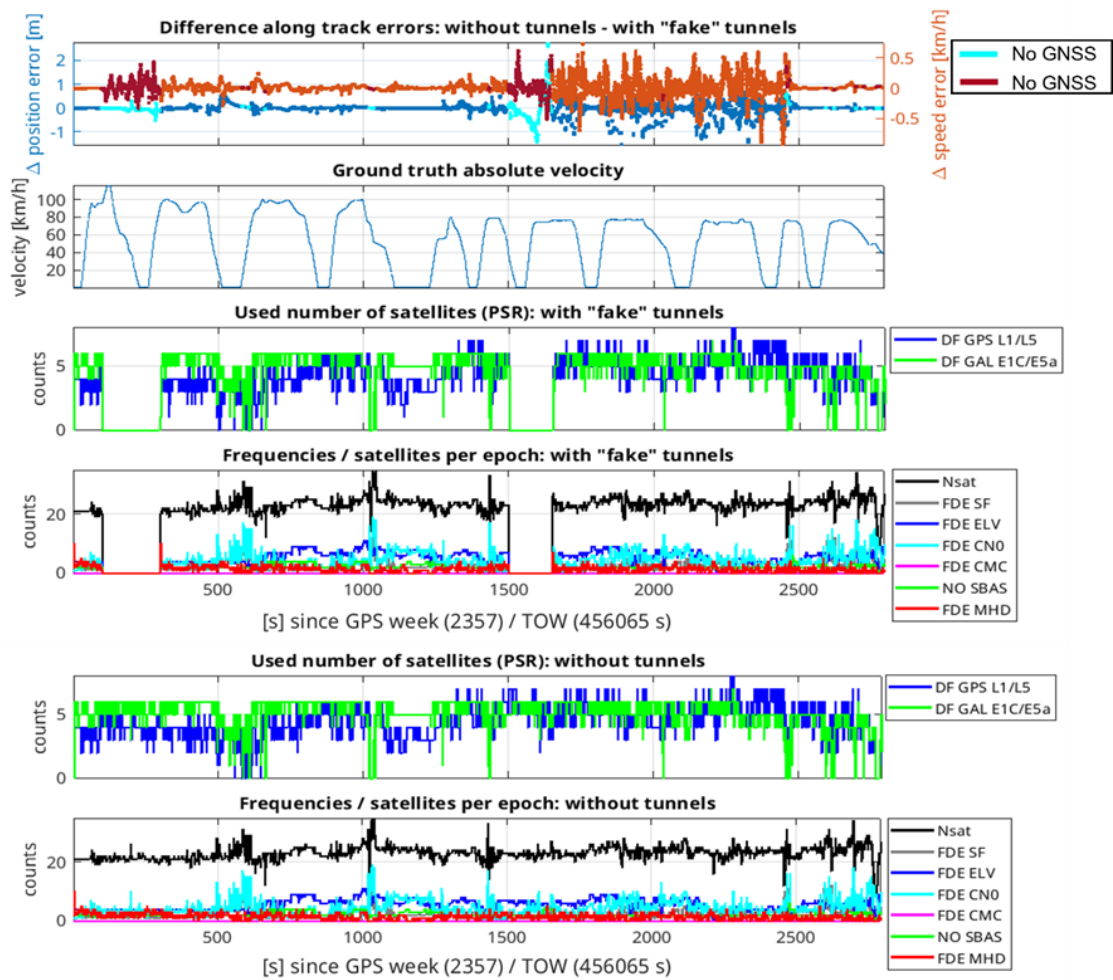


Figure 5-2: Along track position and speed error differences without tunnels and with "fake" tunnels together with GT velocity, used number of GNSS satellites pseudo range measurements and applied FDE & EGNOS.

In



Table 8 and Figure 5-3, the impact on integrity due to the 2 “fake” tunnels is presented. The position CI increases significantly nearly linearly within a straight tunnel, while within a curvy tunnel, it first increases and then decreases around the angular point. The impact on the speed CI within tunnels is significantly lower. For straight tunnels, the impact is a bit higher than for curvy tunnels. In both cases, the behaviour of the CI with tunnels is similar to the behaviour of the CI without tunnels. The position and speed CI recovers already after 9 s, directly after the straight and curvy tunnels. This shows that the LOC-OB can handle the CI estimation correctly during and after tunnels.

Table 8: Integrity impact on CI position and speed during and after straight and curvy tunnels

	Integrity impact	
	CI position	CI speed
During 1 straight tunnel	CI range in [9 14] m, linear increase	Mean 2 km/h, increase slightly wrt EGNOS DFMC
After 1 straight tunnel	Recovers after 9 s	Recovers after 9 s
During 1 curvy tunnel	Mean 8 m, increase and decrease wrt to EGNOS DFMC	Range [1 3] km/h, increase very little wrt EGNOS DFMC
After 1 curvy tunnel	Recovers after 9 s	Recovers after 9 s

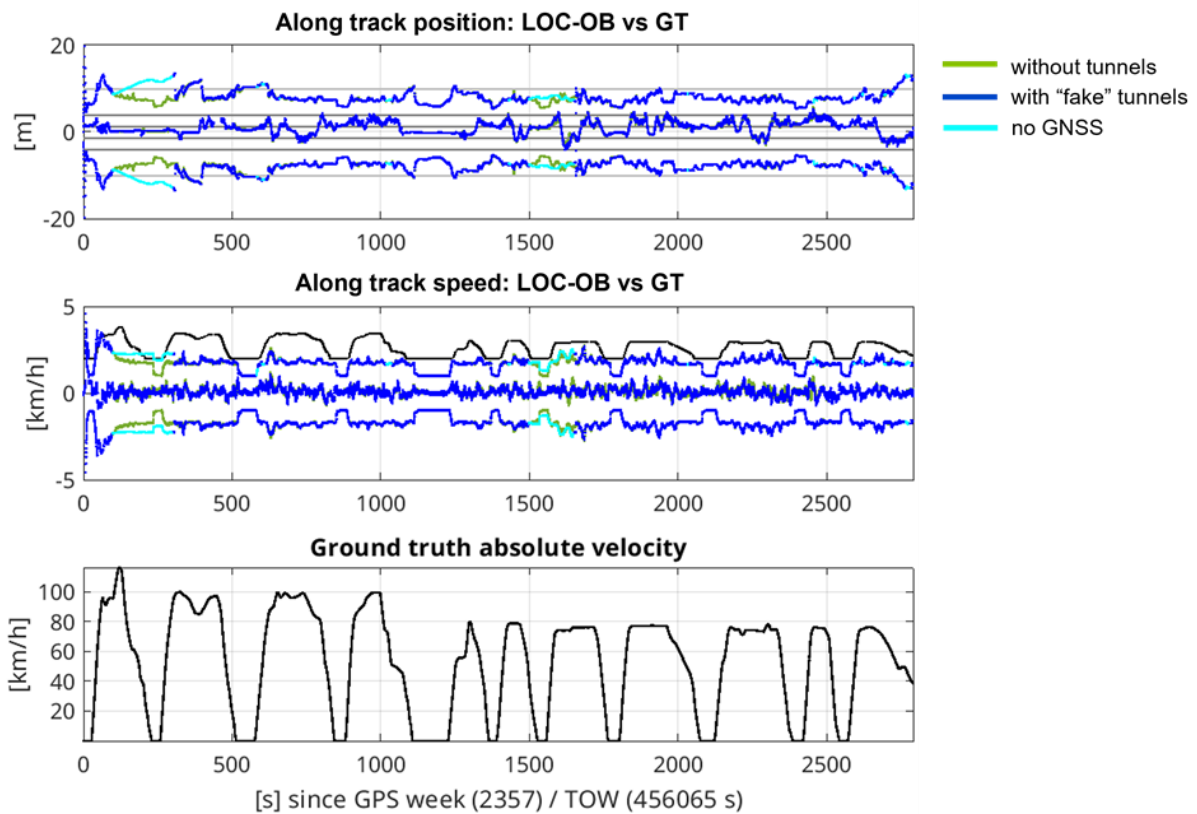


Figure 5-3: Along track position and speed: LOC-OB vs GT together with CI position and speed for Trip 45 without tunnels and with 2 "fake" tunnels

5.1.3 Track Selectivity algorithm

The LOC-OB allows for applying track selectivity (TS) in order to autonomously estimate the track edge ids to be independent from external information. In Figure 5-5, the distance delta, together with the track edge ids are shown for both configurations: (1) DFMC without TS and (2) DFMC with TS. The track edges estimated by the TS coincide almost completely with the ones provided by the GT, except very few timesteps (0.58 %). This means that the TS module is making the right decision at each track switch encountered and, in turn, enables an overall operation mode which is independent from the GT track edge ids.

In Figure 5-4, an example of a working scenario of the TS is provided.

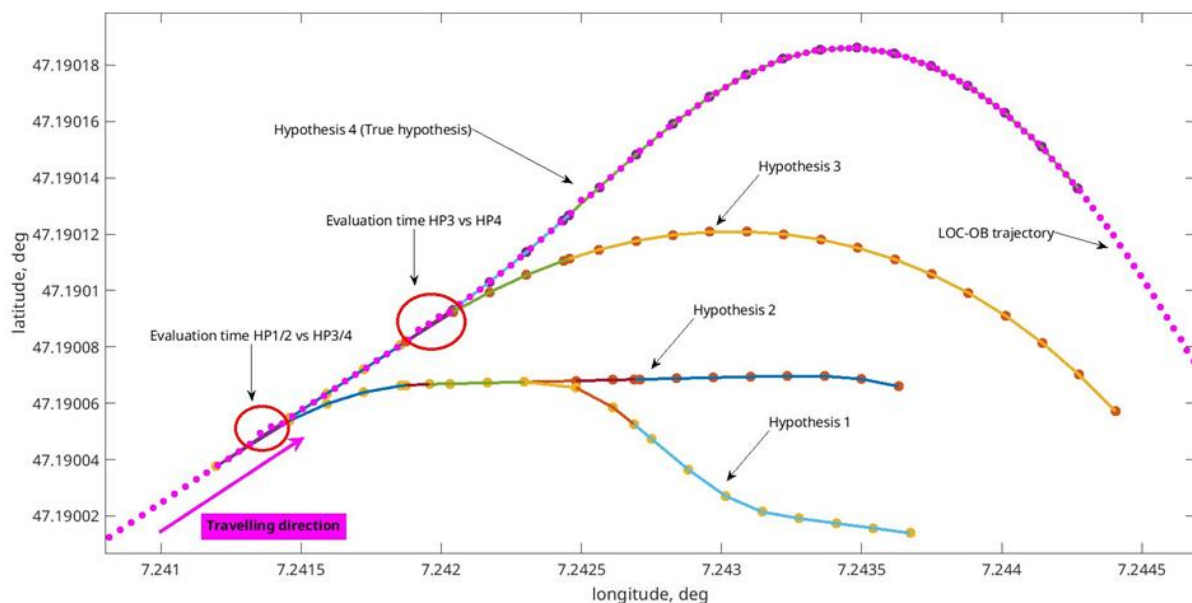
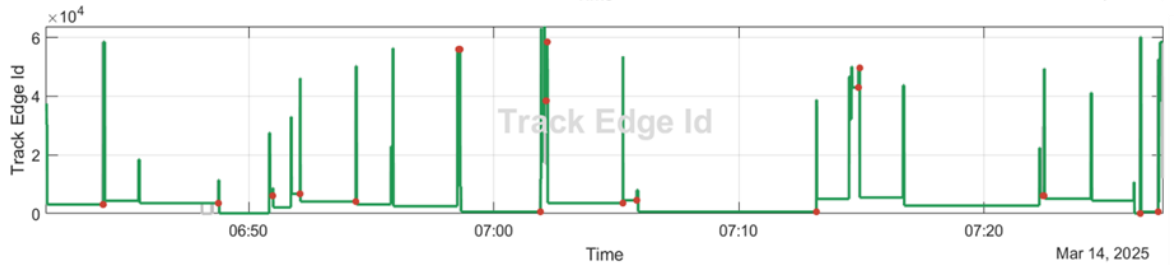
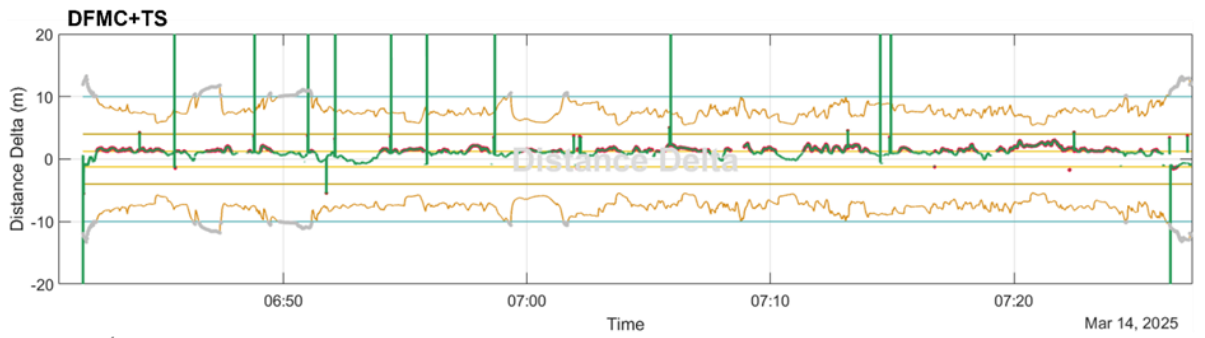
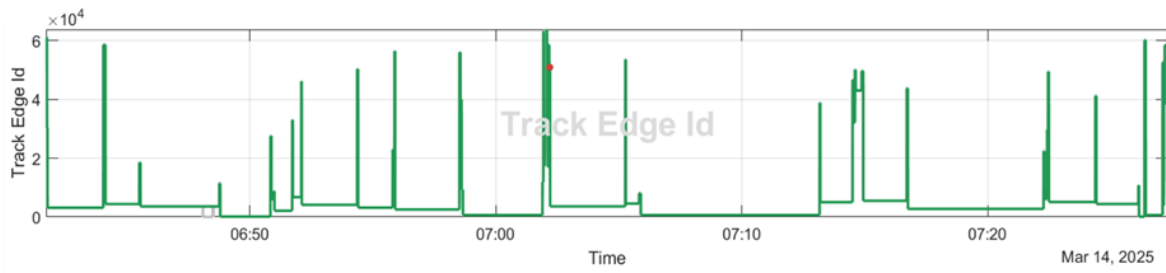
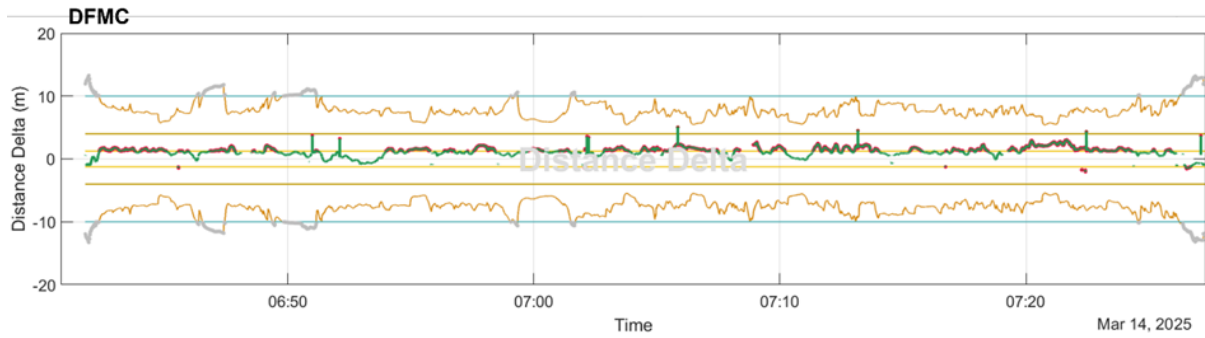


Figure 5-4: Example of the TS operation

In the presented track switch, the LOC-OB encounters four possible hypotheses. The LOC-OB trajectory (pink dots) follows Hypothesis 4, which is actually the correct one. This behavior is possible only because, in the background, the TS module has detected within a short time the right track edge. The phases in which the TS is evaluating the different hypotheses are highlighted with red circles. In these phases, it can be seen that the LOC-OB 3D trajectory is not exactly on the track map. This is due to the fact that, since the TS is not yet sure about what track edge will be taken, no projection of the 3D position on the track map is performed. Such transitions represent those short time spans (< 2 s) in which the TS track edge id estimation does not coincide with the GT track edge id, see Figure 5-4. This is a nominal behavior and fully acceptable. It is noted that in these occurrences, the old track edge id is still conserved in order to keep a safe overall 1D position report of the LOC-OB.

The good performance of the TS can also be seen from the fact that there is no significant impact on the 1D localization/speed accuracy, see Figure 5-6 and Table 6, when the track edge ids are estimated autonomously from the TS. The differences of the along-track errors between DFMC and DFMC with TS are very small (Δ position error: -0.0025 ± 0.06 m; Δ speed error: 0.0005 ± 0.02 km/h). This is further proof that the TS of the LOC-OB is performing very well.



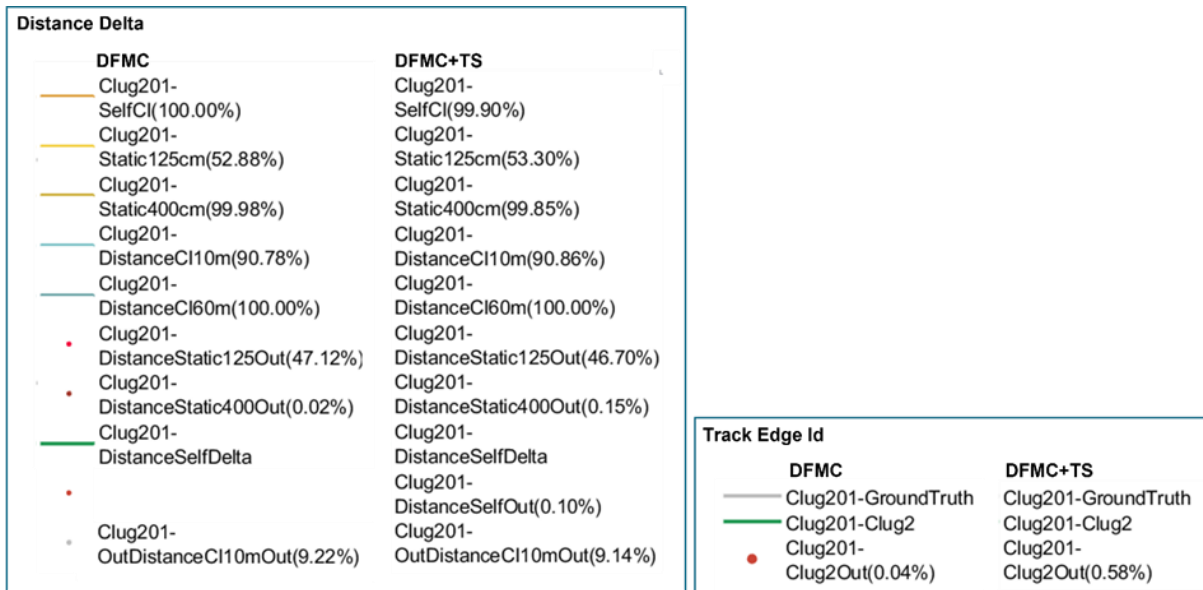


Figure 5-5: Comparison of the distance delta and track edge id for Trip 45 with EGNOS DFMC without TS and EGNOS DFMC with TS

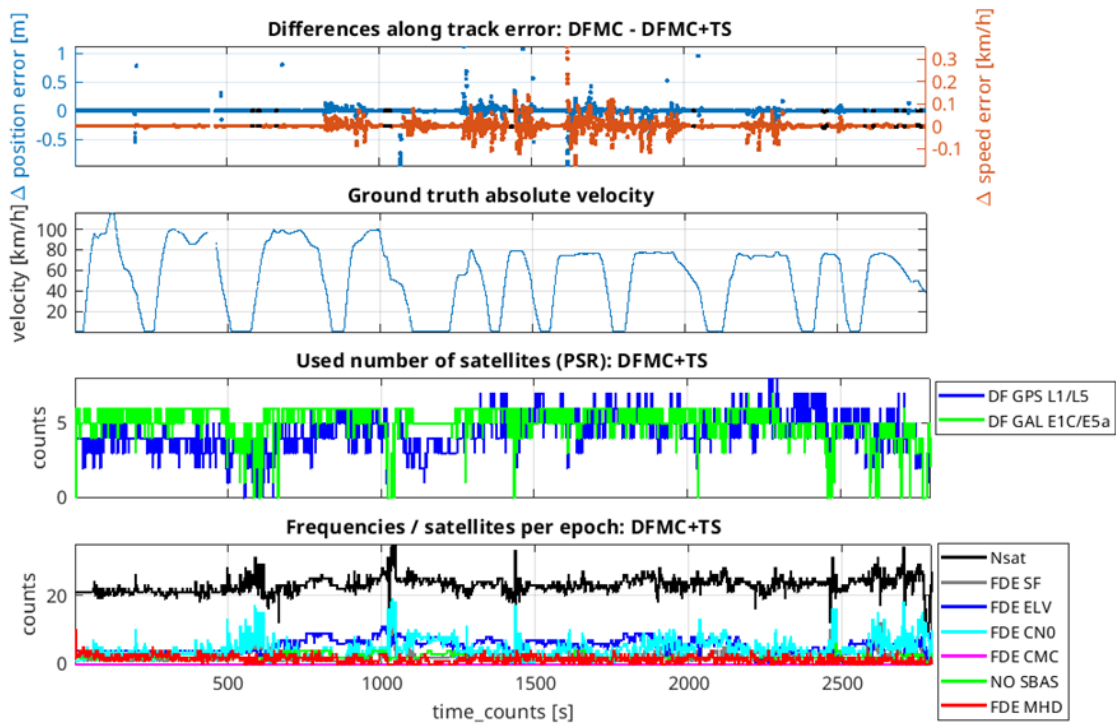


Figure 5-6: Along track position and speed error differences without TS and with TS together with GT velocity, used number of GNSS satellites pseudo range measurements and applied FDE & EGNOS

5.2 Comparison of the performance between DFMC and DFMC+PR+PV

In the framework of this project, three trips, namely Trip 45, Trip 73 and Trip 77, with different local environments (no tunnel/flat; multiple tunnels/mountains; one long tunnel/mountains) and GNSS availability (34 ± 3 ; 20 ± 4 ; 28 ± 3 GNSS frequencies before FDE and EGNOS in none tunnel parts of the trips) had been analysis in order to investigate the 1D localization/speed performance (accuracy/integrity) based on the two configurations:

- **C01:** EGNOS DFMC (see chapter 4.1)
- **C03:** EGNOS DFMC+PR+PV (see chapter 4.2)

Table 9 provides the corresponding key GNSS performance indicators for the safe 1D localization/speed parameters for all three trips separately for non-tunnel parts of the trips and for tunnels. Note that within this table the probability speed CI inside [2 12] km/h half-MCI is provided with respect to the TSI requirement [R5].

According to Table 9, EGNOS DFMC+PR+PV yields a significant improvement of the CI for challenging railway trips in mountainous areas with tunnels and worse GNSS availability (e.g. Trip 73 and Trip 77). With EGNOS DFMC+PR+PV, the fault-free CI is for the non-tunnel parts of the trips about 4 to 12 % and in the tunnel parts about 14 to 27 % more often inside the [2 12] km/h half-MCI (TSI requirement [R5]) than it would be the case for EGNOS DFMC. Due to the fact that the CI is lower and less noisy before entering and after exiting a tunnel, the CI is also lower and more stable in tunnels, see Figure 57. Nevertheless, using EGNOS DFMC+PR+PV, the CI speed availability 99 % requirement (SpecSysReq[048]) is still not fulfilled for all trips expect for Trip 77 within the 57 km long Gotthard base tunnel, see Table 9. For Trip 73 about 7 % (no tunnel parts) and 3 % (tunnel parts) are more often inside the 10 m half-MCI. This is based on the fact that, in contrast to EGNOS DFMC, EGNOS DFMC+PR+PV provides significantly lower variances for the Doppler measurements, which mainly impacts the speed CI and not the distance CI. Regarding accuracy, no significant impact on the speed estimations could be identified for all three trips, while for the distance, a slight degradation could be identified except for Trip 45, which might be less representative due to the mentioned 1 m bias between LOC-OB and GT in chapter 4.2. The reason therefore might be that FDE MHD exclusions are a bit higher for EGNOS DFMC+PR+PV than for DFMC (Trip 45: 5 % vs 4 %; Trip 73: 15 % vs 13 %; Trip 77: 12 % vs 10 %). Thus, sometimes fewer GNSS measurements are used for the safe 1D localization/speed estimation. But due to the fact that the distance accuracy degradation is smaller compared to the large improvement in integrity, it is recommended to use EGNOS DFMC+PR+PV in the future.

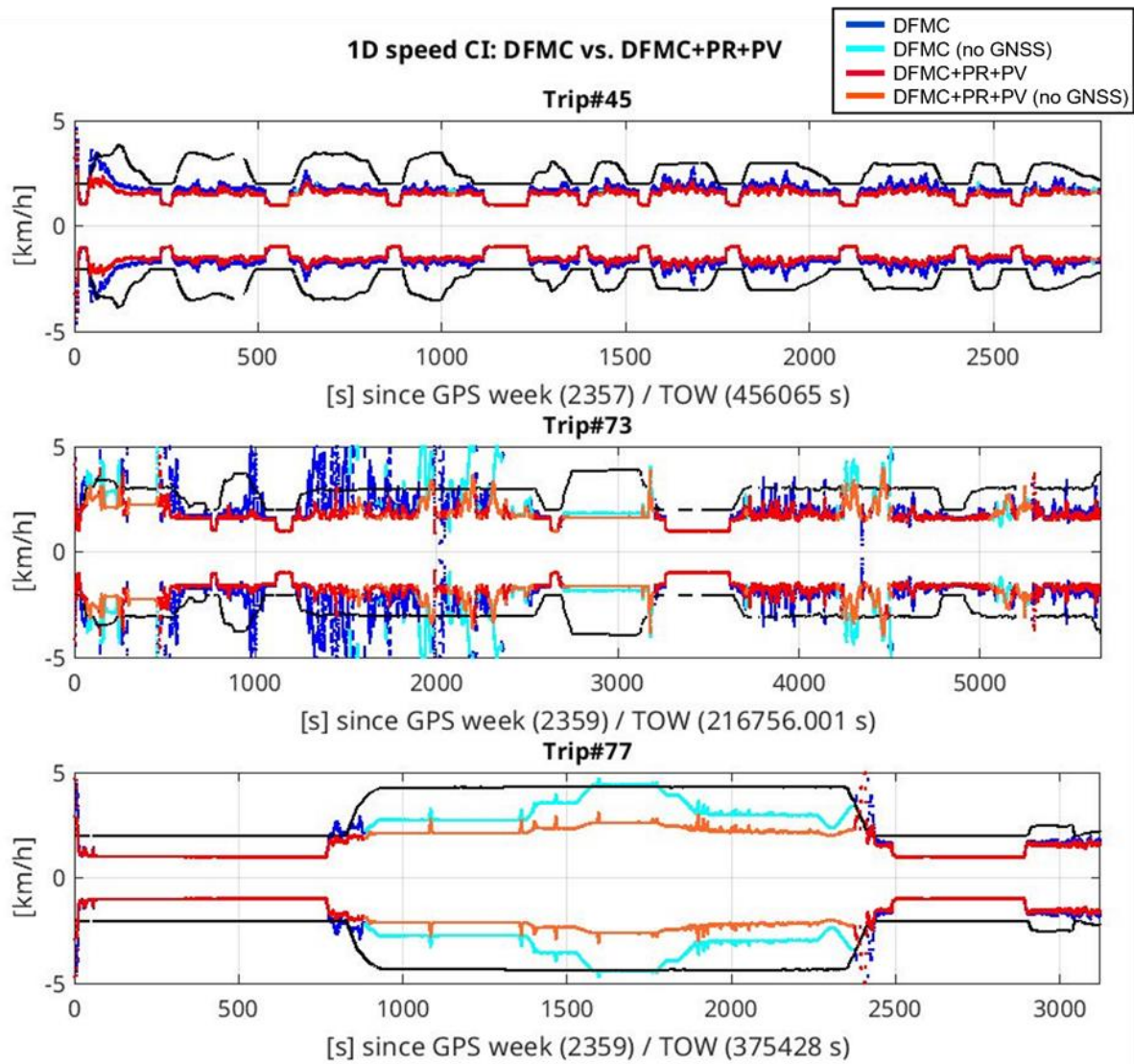


Figure 5-7: Speed CI for respectively Trip 45, Trip 73 and Trip 77

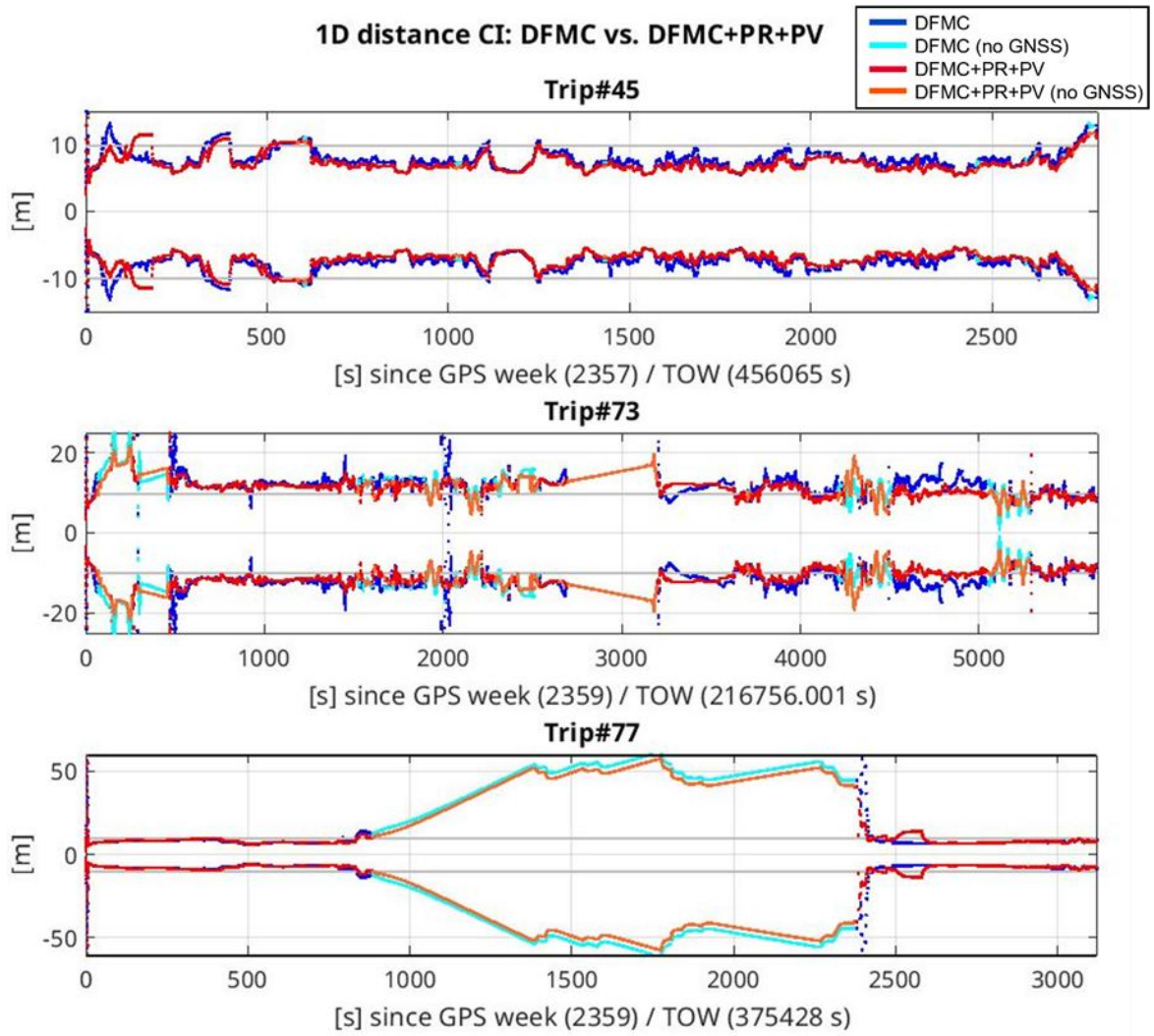


Figure 5-8: Position CI for respectively Trip 45, Trip 73 and Trip 77

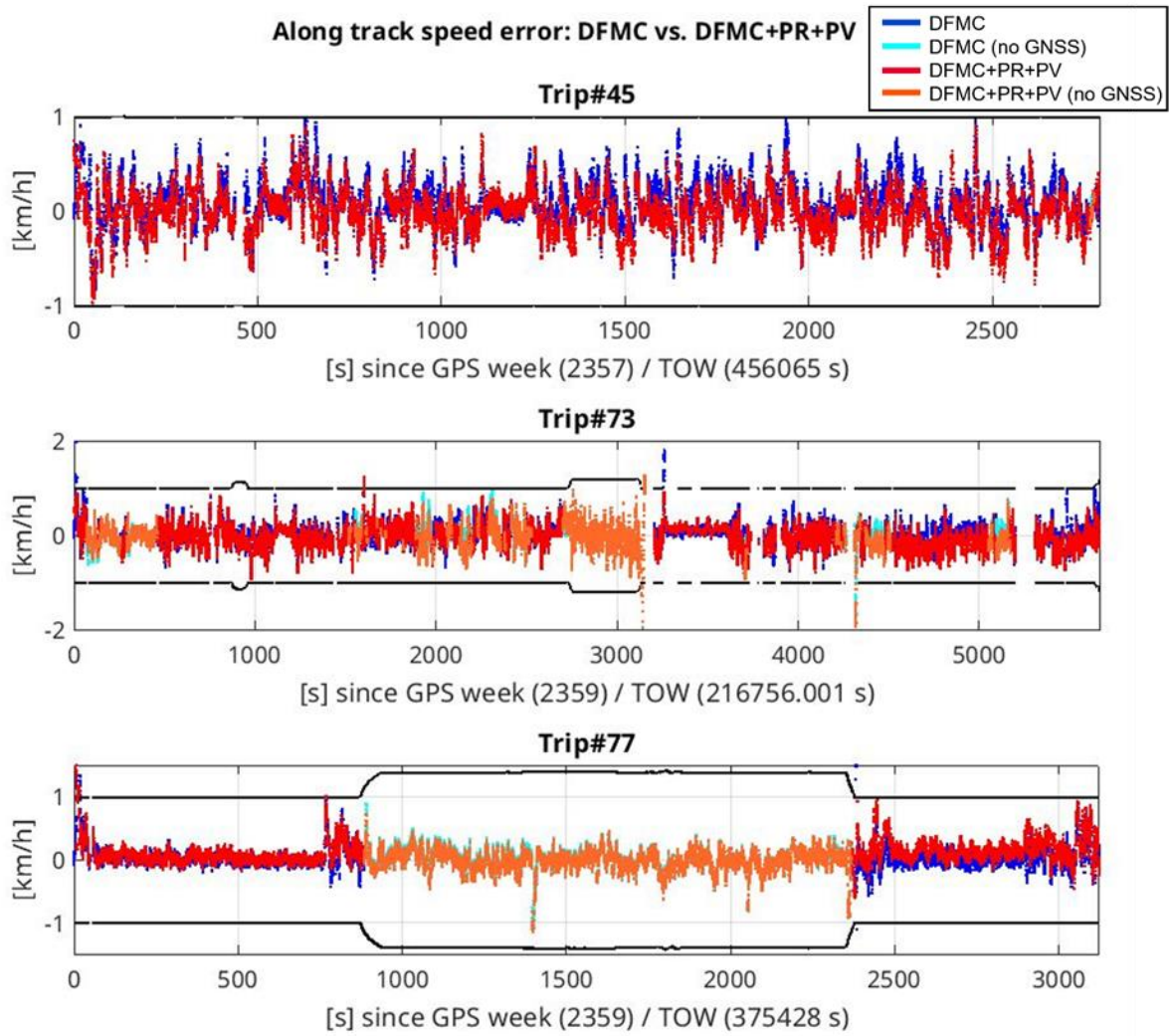


Figure 5-9: Speed error for respectively Trip 45, Trip 73 and Trip 77

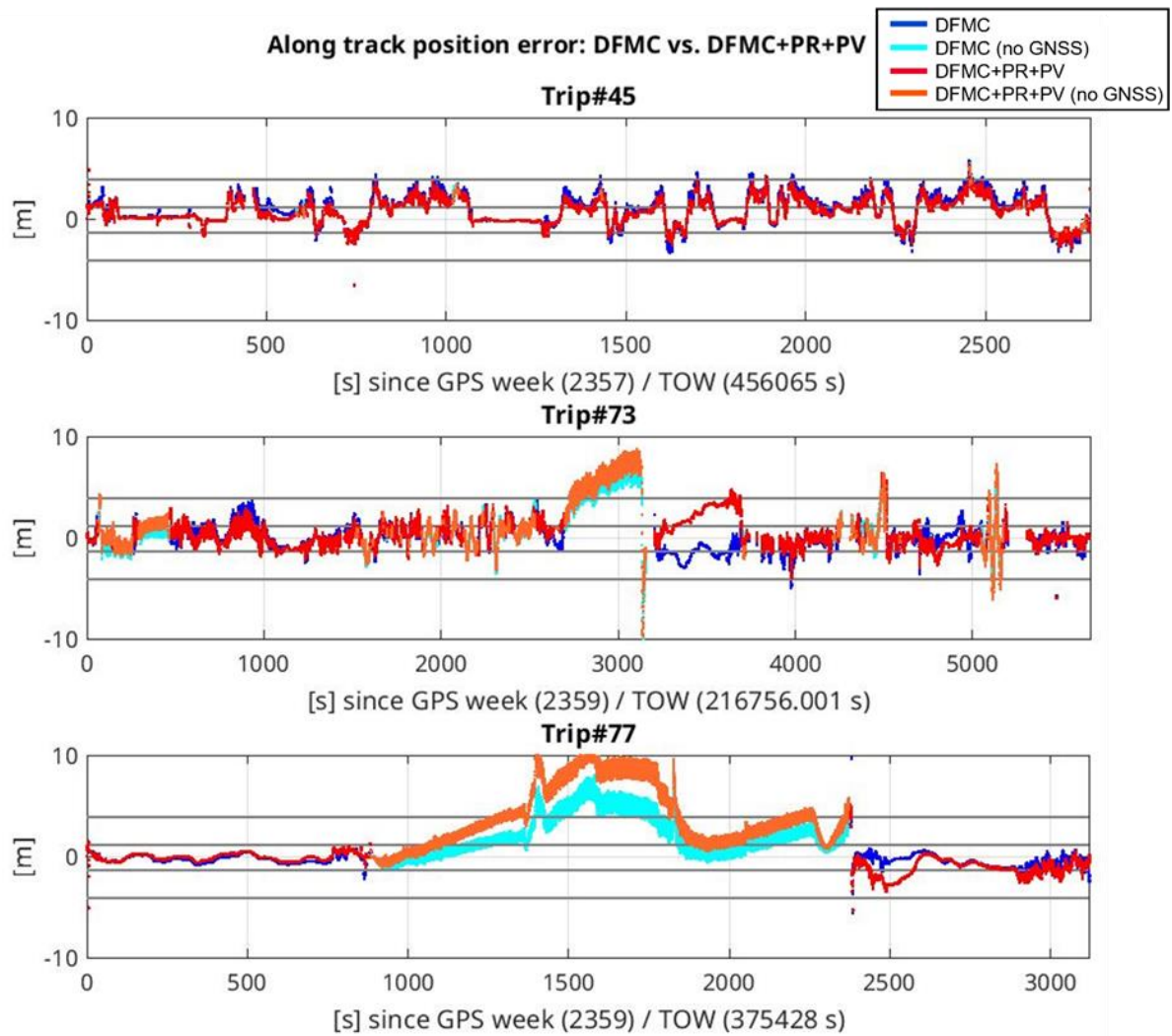


Figure 5-10: Position error for respectively Trip 45, Trip 73 and Trip 77

Table 9: Overall performance and GNSS availability for Trip 45, Trip 73 and Trip 77. Improvements w.r.t. another configuration are highlighted with green ellipses

Key GNSS safety performance indicators Safe 1D localization parameters after first 60 s		Trip #45		Trip #73				Trip #77			
		C01 (no tunnel)	C03 (no tunnel)	C01 (no tunnel)	C03 (no tunnel)	C01 (tunnel)	C03 (tunnel)	C01 (no tunnel)	C03 (no tunnel)	C01 (tunnel)	C03 (tunnel)
ACCURACY	Along track pos error mean (m)	0.93	0.71	-0.1	0.32	1.38	1.68	-0.38	-0.58	2.09	3.99
	Along track pos error 2-sigma (m)	2.98	2.48	2.32	2.5	5.74	6.27	1.69	1.87	4.1	6.17
	Along track pos error inside 1.25m 95% (1s occurrences / total / %)	6651 / 13560 / 49.05	7963 / 13560 / 58.72	14678 / 19305 / 76.03	14796 / 19248 / 76.87	4799 / 8519 / 56.33	4429 / 8576 / 51.64	7450 / 7823 / 95.23	6252 / 7821 / 79.94	3144 / 7391 / 42.54	1381 / 7393 / 18.68
	Along track pos error inside 4m 95% (1s occurrences / total / %)	13434 / 13560 / 99.07	13537 / 13560 / 99.83	19220 / 19305 / 99.56	19120 / 19248 / 99.33	6684 / 8519 / 78.46	6471 / 8576 / 75.45	7790 / 7823 / 99.58	7792 / 7821 / 99.63	5711 / 7391 / 77.27	4641 / 7393 / 62.78
	Along track speed error mean (km/h)	0.08	-0.01	0	-0.05	-0.04	-0.08	0.03	0.11	0	-0.02
	Along track speed error 2-sigma (km/h)	0.48	0.45	0.46	0.47	1.24	1.24	0.33	0.34	0.35	0.34
	Along track speed error inside [1 5]km/h 95% (1s occurrences / total / %)	13553 / 13560 / 99.95	13560 / 13560 / 100	19272 / 19305 / 99.83	19237 / 19248 / 99.94	8410 / 8519 / 98.72	8466 / 8576 / 98.72	7813 / 7823 / 99.87	7819 / 7821 / 99.97	7391 / 7391 / 100	7393 / 7393 / 100
INTEGRITY	Along track pos half CI mean (m)	7.88	7.38	12.14	11.05	13.18	12.93	11.53	8.7	44.75	41.69
	Along track pos half CI 2-sigma (m)	2.8	2.81	8.14	3.67	7.14	6.71	179.41	13.13	24.27	23.44
	Along track pos error inside CI (1s occurrences / total / %)	13560 / 13560 / 100	13560 / 13560 / 100	19233 / 19305 / 99.63	19222 / 19248 / 99.86	8458 / 8519 / 99.28	8524 / 8576 / 99.39	7823 / 7823 / 100	7821 / 7821 / 100	7391 / 7391 / 100	7393 / 7393 / 100
	Along track pos CI inside 10m half-MCI 99% (1s occurrences / total / %)	12299 / 13560 / 90.7	12282 / 13560 / 90.58	3654 / 19305 / 18.93	4971 / 19248 / 25.83	1483 / 8519 / 17.41	1734 / 8576 / 20.22	7284 / 7823 / 93.11	6904 / 7821 / 88.28	0 / 7391 / 0	0 / 7393 / 0
	Along track pos CI inside 60m half-MCI 99% (1s occurrences / total / %)	13560 / 13560 / 100	13560 / 13560 / 100	19222 / 19305 / 99.57	19248 / 19248 / 100	8514 / 8519 / 99.94	8576 / 8576 / 100	7728 / 7823 / 98.79	7801 / 7821 / 99.74	7253 / 7391 / 98.13	7393 / 7393 / 100
	Along track speed half CI mean (km/h)	1.69	1.5	2.31	1.66	3.07	2.08	3.64	1.29	3.23	2.27
	Along track speed half CI 2-sigma (km/h)	0.72	0.5	3.97	0.81	3.48	0.96	94.24	2.04	1.22	0.38
	Along track speed error inside CI (1s occurrences / total / %)	13560 / 13560 / 100	13560 / 13560 / 100	19244 / 19305 / 99.68	19248 / 19248 / 100	8474 / 8519 / 99.47	8530 / 8576 / 99.46	7823 / 7823 / 100	7821 / 7821 / 100	7391 / 7391 / 100	7393 / 7393 / 100
	Along track speed CI inside [2 12]km/h half-MCI 99% (1s occurrences / total / %)	13366 / 13560 / 98.57	13377 / 13560 / 98.65	15290 / 19305 / 79.2	17635 / 19248 / 91.62	4907 / 8519 / 57.6	7287 / 8576 / 84.97	7319 / 7823 / 93.56	7613 / 7821 / 97.34	6358 / 7391 / 86.02	7373 / 7393 / 99.73
GNSS AVAILABILITY AFTER EDE & EGNOS	GNSS DF GPS L1&L5 satellite (PSR) unavailability (%)	2.08	2.22	11.42	9.61	100	100	0.55	0.67	100	100
	GNSS DF GAL E1&E5a satellite (PSR) unavailability (%)	2.11	2.11	6.87	19.89	100	100	1.03	1.03	100	100
	Mean number of DF GPS L1&L5 satellite (PSR)	4	4	2	2	0	0	4	3	0	0
	Standard deviation number of DF GPS L1&L5 satellite (PSR)	1	1	1	1	0	0	1	1	0	0
	Mean number of DF GAL E1&E5a satellite (PSR)	5	5	3	3	0	0	4	4	0	0
	Standard deviation number of DF GAL E1&E5a satellite (PSR)	1	1	1	2	0	0	1	1	0	0

5.3 Detailed analysis of Trip 73 and 77 through the Gotthard tunnels

The following section analyses the behaviour of the algorithm in both Gotthard tunnels. The Gotthard is a mountain pass between the northern and southern parts of Switzerland, used for both rail and road traffic. For rail transportation, two different tracks can be used:

- 1) The historic Gotthard railway opened in 1882 with multiple spiral tunnels on both sides of the pass and a peak tunnel with a length of 15 km analysed in 5.3.1; and
- 2) the Gotthard base tunnel opened in 2016 with a length of 57 km, being the longest railway tunnel in the world analysed in 5.3.2.

5.3.1 Trip 73 through the Gotthard mountain tunnels

5.3.1.1 Trip description

Trip 73 took place from Arth Goldau and ended in Biasca. It lasts an hour and a half (see Table 10). The travelled distance is approximatively 120 km, the trip presents a high dynamic (see Table 11 and Figure 5-11) with multiple loops (Figure 5-12) and a maximum speed equal to 118 km/h.

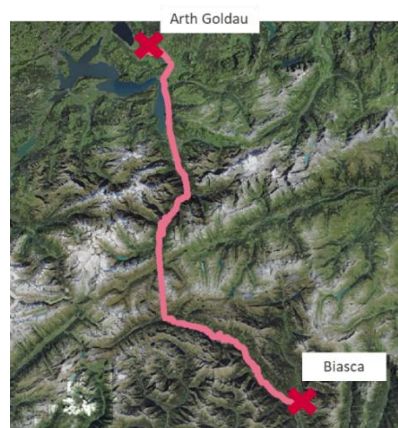


Figure 5-11: Trip 73 Trajectory



Figure 5-12: Trip 73 Loop section

Table 10: Trip 73 General Information

Information	Values
To	2025-03-25 12:12:23 UTC
Tf	2025-03-25 13:46:37 UTC
Duration	90~ min
Starting city	Arth-Goldau
Ending point	Biasca
Train	DOMINO

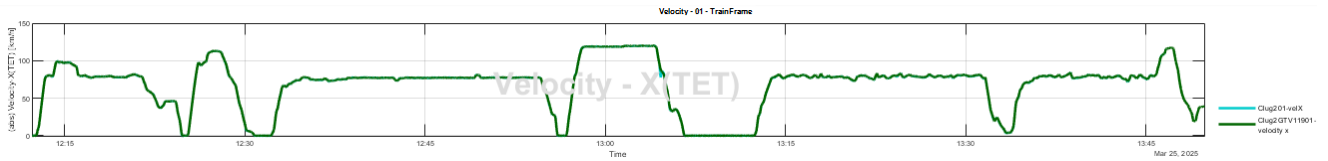


Figure 5-13: Trip 73 Velocity

Table 11: Trip 73 Attitude dynamic

Information	Values
Heading variation	$\pm 360^\circ$ in curves (up to $4^\circ/s$ angular speed)
Roll variation	$\pm 5^\circ$ in curves
Pitch variation	$\pm 2^\circ$

In the trip, the Domino train penetrates at 12:52 the Gotthard tunnel (see Figure 5-14), which is around 15 km long, for a duration equal to 8 min.

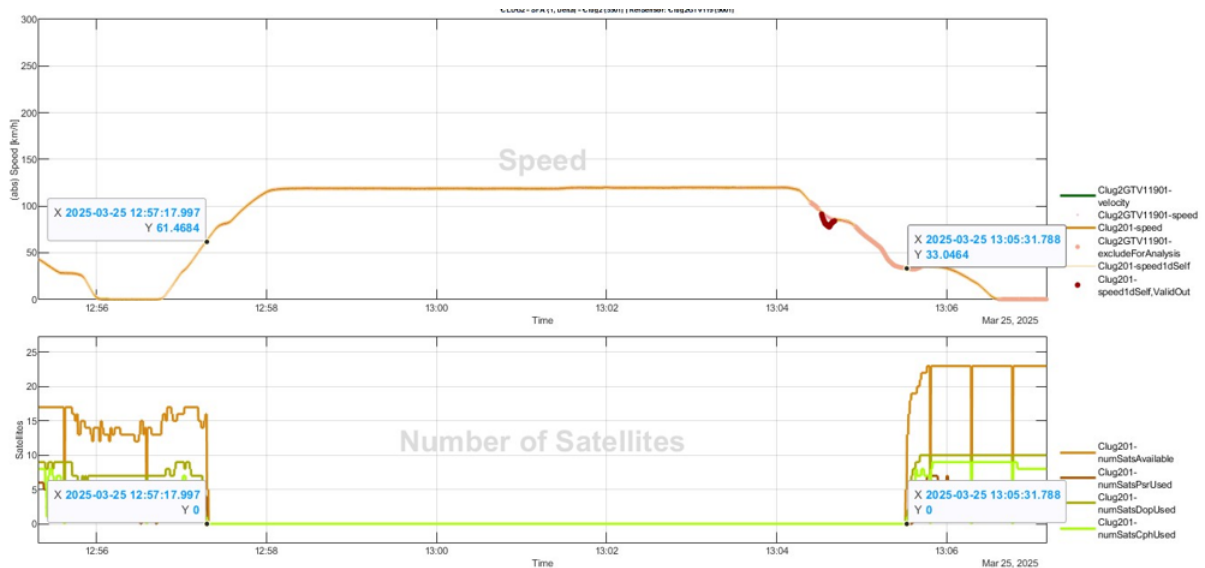


Figure 5-14: Trip 73 Gotthard Tunnel speed

The tunnel is a straight line (which is unfavourable for LOC-OB) crossed at a mean speed equal to 117 km/h.

Before entering the tunnel, GNSS reception is altered, with the number of available satellites perturbed which translates in the navigation filter as:

- C01 (EGNOS DFMC) → a poor application of pseudo ranges (≤ 6 , 3 most time) during the minute preceding the tunnel (see Figure 5-15).
- C03 (EGNOS DFMC+PR+PV) → a poor application of pseudo ranges (≤ 5 , 2 to 3 most time) during the minute preceding the tunnel (see Figure 5-16).

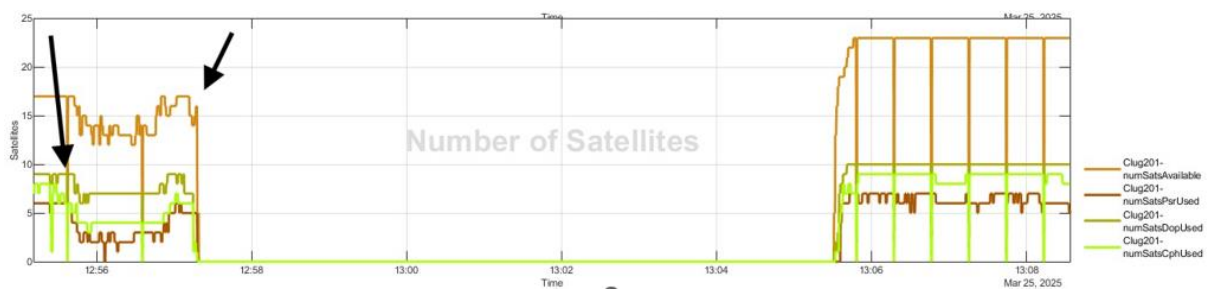


Figure 5-15: Trip 73, available and applied GNSS measurement C01 (EGNOS DFMC)

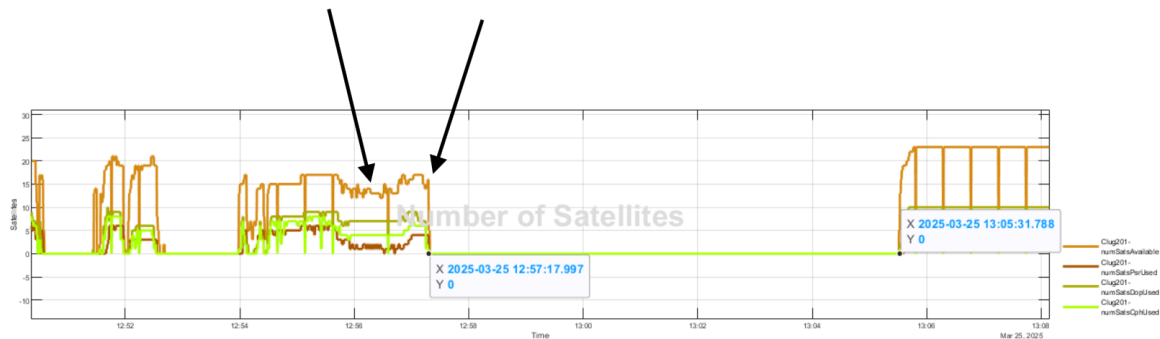


Figure 5-16: Trip 73, available and applied GNSS measurement C03 (EGNOS DFMC+PR+PV)

Despite this, a reduction of both C03 and C01 speed CI is seen around 12:57 (see Figure 5-17), surely thanks to doppler observations that are more available.

5.3.1.2 Analysis

Between C01 (EGNOS DFMC) and C03 (EGNOS DFMC+PR+PV), no major differences in speed error are seen for the whole trips. Regarding the tunnel, for both simulations, speed error does not act differently from other sections of the trip if the tacho failure is excluded (see jump at 13:04:30 in Figure 5-18) which might be related to tacho FDE misdetection (see Figure 5-18):

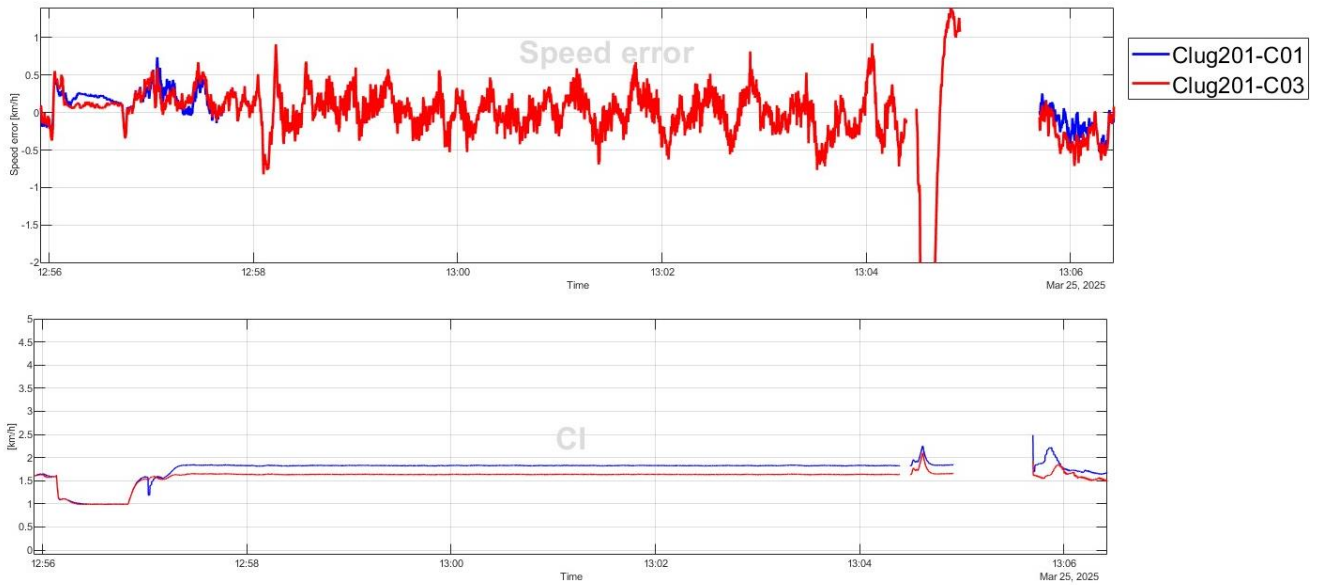


Figure 5-17: Trip 73, C01 and C03, Speed error and CI, zoom on Gotthard tunnel

Results can be better than those with GNSS reception. Speed error remains between ± 0.5 km/h and speed CI is very constant with 1.8 km/h for C01 and 1.6 km/h for C03. That means accuracy limit is respected SpecSysReq[009]. However, CI availability is just above SpecSysReq[010] limit expectations.

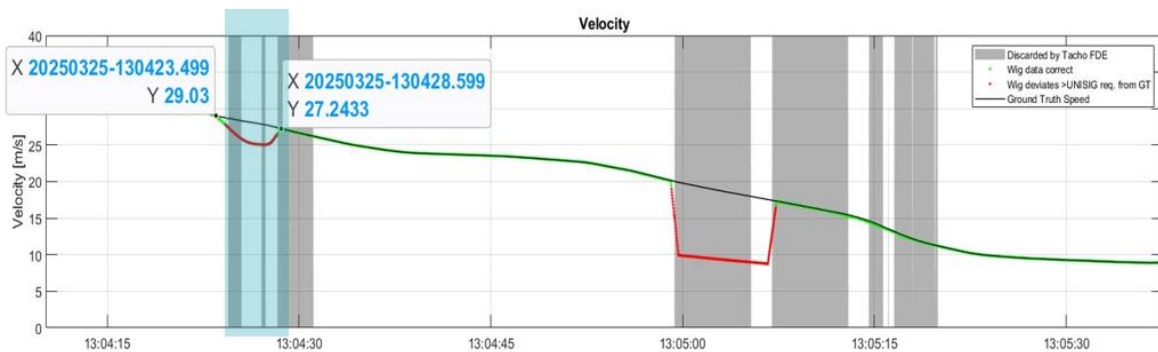


Figure 5-18: Trip 73 Tacho FDE. Tacho missed detection between 13:04:23 and 13:04:29 is followed by a wrong exclusion until 13:04:31

For position, both along track position error and position CI are very similar and both follows a linear curve (if the event at 13:04 is discarded). Position error remains under 10 m (accuracy limits are not respected, neither the 4 m nor 1.25 m) and CI remains under 20 m which is encouraging (as a reminder only Fault free CI is shown here, see Figure 5-19). Therefore, position CI is compliant with the 60 m limit (SpecSysReq[004], not the 10 m limit from SpecSysReq[003]).

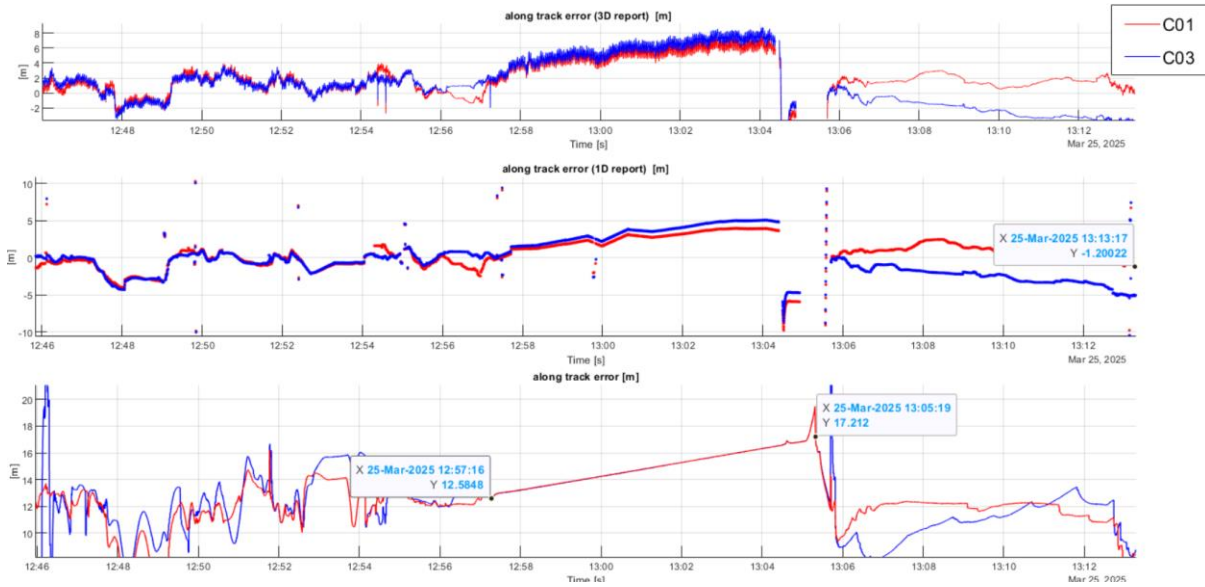


Figure 5-19: Trip 73, Gotthard tunnel, C01 and C03, position error and CI

For position error, the slope is equal to 0.01 m/s. By distance, the error slope is equal to 0.38 m/km. For CI, the error slope is equal to 0.11 m/s. By distance, the error slope is equal to 0.31 m/km.

Probably, a general mathematical rule derived from navigation model can be obtained so that performances on straight line can be predicted (or from simulation). As it can be seen, the slope for the error and the CI are very similar which shows the coherence of the model with the error.

To conclude, performances shown in this simulation do not fulfil D2.4 requirements [R1] but are very positive regarding the challenging environment of Trip 73.

5.3.2 Trip 77 through the Gotthard base tunnel

Trip 77 started in Pollegio shortly before entering the tunnel. The train was at a standstill, accelerated, entered the tunnel, and drove with approximately 135 km/h through the 57 km long tunnel at constant speed. At the end of the tunnel, the train started braking, exited the tunnel, and came to a standstill short before the station of Altdorf. After a short stop, the train accelerated again, and the trip ended in Altdorf. An illustration of the Trip 77 on a map can be seen in Figure 5-20.

Map

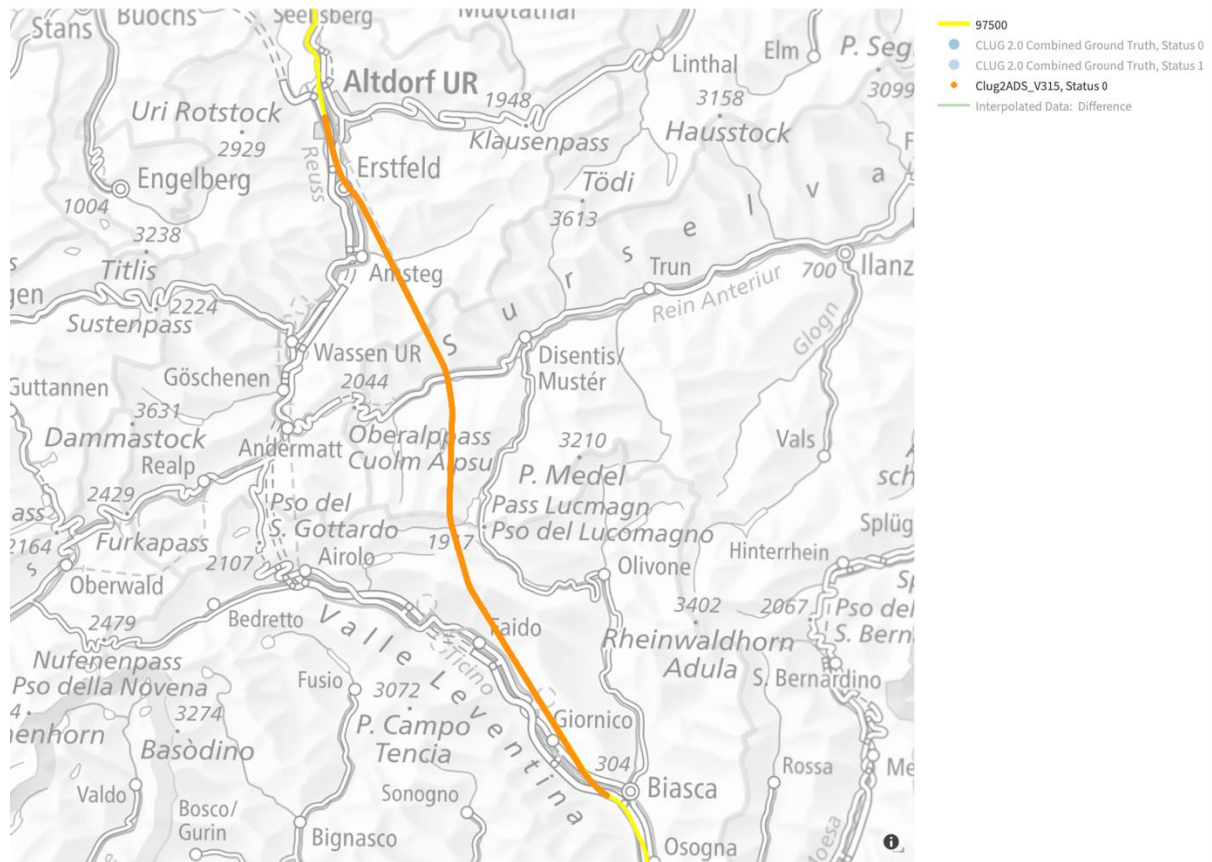


Figure 5-20: Visualization of the Trip 77 through the Gotthard Base Tunnel

Figure 5-21 shows the speed, distance, the distance confidence interval, and the distance error of the trip over time. The top plot shows the acceleration phase after 08:30 and the constant speed until 08:57 at the exit of the tunnel. In the second plot, the distance (Clug201-Distance) is visualized over time. The tunnel consists of three larger track edges which each of them having a length between 15 and 20 km. The plot in the middle shows the confidence interval for the distance computed by the algorithm (Clug201-SelfCI), the two limits for the error at 1.25 m respectively 4 m (Clug201-Static125/400cm), the limits for the distance confidence interval at 10 m and 60 m (Clug201-DistanceCI10/60m) according to the requirements and the difference in distance between the algorithm and ground truth (Clug201-DistanceSelfDelta).

For two periods of the trip (08:32 to 08:35 and 08:40 to 08:42), the ground truth is not available, and therefore, the error cannot be computed.

According to the plots, we observe that the confidence interval strongly increases while entering the tunnel and losing GNSS reception. Nevertheless, also illustrated in the results table in 0, the confidence interval for distance exceeds the 60 m limit only for 1.71 % of the samples. The distance error is nearly all the time larger than 4 m while driving but always bounded by the confidence interval for the complete trip and below 10 m. Inside a tunnel of this length, the error is operationally acceptable. As

soon as the train leaves the tunnel and the algorithm can use GNSS information again, the parameters are within the requirements.

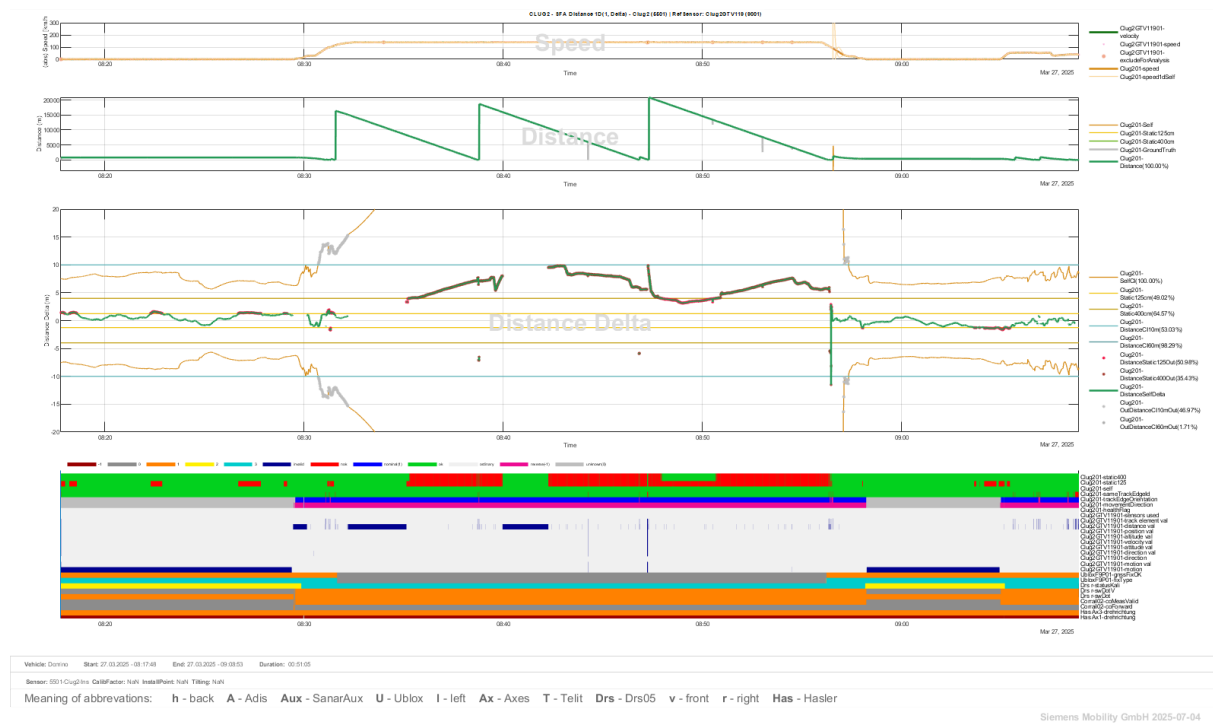


Figure 5-21: Visualization of the speed, distance, the confidence interval and error of the distance including the requirements

Figure 5-22 shows in the top plot the ground truth speed (Clug2GTV11901-velocity), the outputted speed of the algorithm (Clug201-speed), and the confidence interval (Clug201-speed1dSelf). Similarly to the plot before, we see the acceleration phase while entering the tunnel and the braking at the exit of it. The plot below shows the speed error (Clug201-deltaSpeed), again the confidence interval of the speed (Clug201-speed1dSelf), the limit for the speed error (SpeedStaticCI01-staticSpeedErrorLim), and the limit for the confidence interval (SpeedCILimit01-SpeedCILimit) according to the specified requirements. As observable in the table of chapter 4.12, the speed error is only in 0.07 % of the cases larger than the requirement; the confidence interval always bounds the speed error, and with this, all samples are safe in speed. The confidence interval is most of the time too large with respect to the specification, 79.84 % of the samples have a confidence interval larger than required.

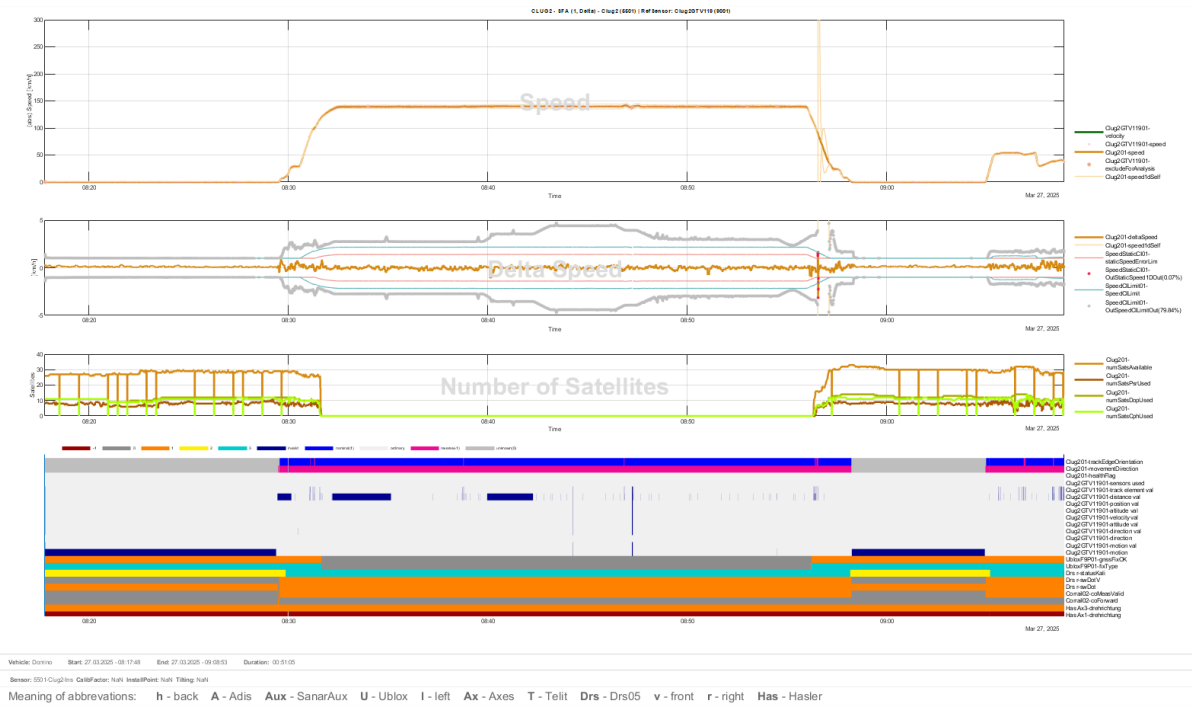


Figure 5-22: Visualization of the speed, confidence interval and error of the distance including the requirements

In general, one can conclude from this trip that it is one of the most challenging trips in railway for such an algorithm, which primarily relies on GNSS. During the journey in the tunnel, driving at constant speed in a harsh environment, the system has to rely on IMU and speed measurements only. Regarding this, the confidence interval for distance is larger than for other trips under optimal conditions, but still, most of the time, within the requirements. The position error exceeds in the tunnel the limit 4 m but is always below 10 m and bounded by the confidence interval in any case. Consequently, one can conclude that the algorithm is challenged by this trip, but the performance is within expectations.

5.4 Detailed analysis of tachometer FDE algorithm

In this chapter, the performance of the tachometer Fault Detection and Exclusion (FDE) algorithm for the Odometer Pulse Generator (OPG) sensor is analysed. To evaluate this, the speed data from the OPG sensor is compared with the speed reference from the Ground Truth. A measurement is considered as correct if the deviation is within the TSI requirements [R5] (± 2 km/h for speeds below 30 km/h, increasing linearly up to ± 12 km/h at 500 km/h). It should be noted that the Tacho FDE algorithm is designed to operate on a single OPG sensor at the sensor level using live data, which makes it a challenging task.

A comprehensive mass data analysis was conducted across all simulated trips, and the results are summarized in the confusion matrix shown in Table 12. The green-highlighted cells represent cases where the Tacho FDE made correct decisions, while the red-highlighted cells indicate incorrect classifications. 92.75 % of the data points are true positives, meaning they are correct and were also identified as valid by the Tacho FDE. True negatives refer to instances where the OPG sensor speed was incorrect and appropriately flagged as invalid by the Tacho FDE. On the other hand, 6.84 % of the data points are marked as invalid despite being correct (false negative) and 0.14 % were incorrect but not detected by the Tacho FDE, and thus wrongly marked as valid (false positives).

Table 12: Confusion matrix of mass data analysis from Tacho FDE over all ten Trips

		OPG Data (Actual)	
		True Positive (TP) 92.75 %	False Positive (FP) 0.14 %
Tacho FDE (Predicted)	True Positive (TP) 92.75 %	True Positive (TP) 92.75 %	False Positive (FP) 0.14 %
	False Negative (FN) 6.84 %	False Negative (FN) 6.84 %	True Negative (TN) 0.27 %

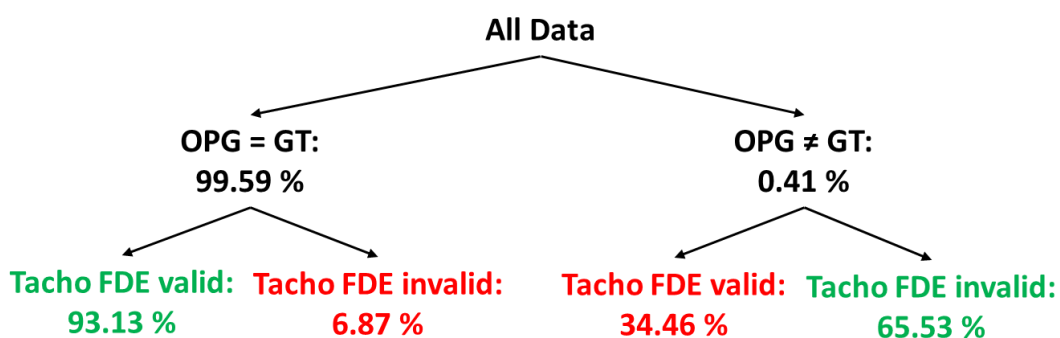


Figure 5-23: Results from Tacho FDE mass data analysis over all ten trips

Another perspective to look at the results from the mass data analysis is presented in Figure 5-23. It can be observed that 99.59 % of the OPG speed data meets the TSI requirements [R5] and is therefore considered correct, while 0.41 % is classified as incorrect. From the correct data points 93.13 % were also correctly marked as valid by the Tacho FDE, whereas 6.87 % were incorrectly discarded. Among

the 0.41 % of incorrect data points, 65.13 % were correctly detected and discarded by the Tacho FDE, while 34.46 % were not detected and were erroneously retained as valid.

Overall, it can be concluded that the Tacho FDE is capable of detecting nearly two-thirds of the incorrect data points from the OPG speed sensor, while **only discarding 7.11 % of the data**.

Detailed Analysis:

In the ten different trips analyzed in this report, the Tacho FDE algorithm has been performing differently. Figure 5-24 shows the result for Trip 57, where the algorithm has performed on average.

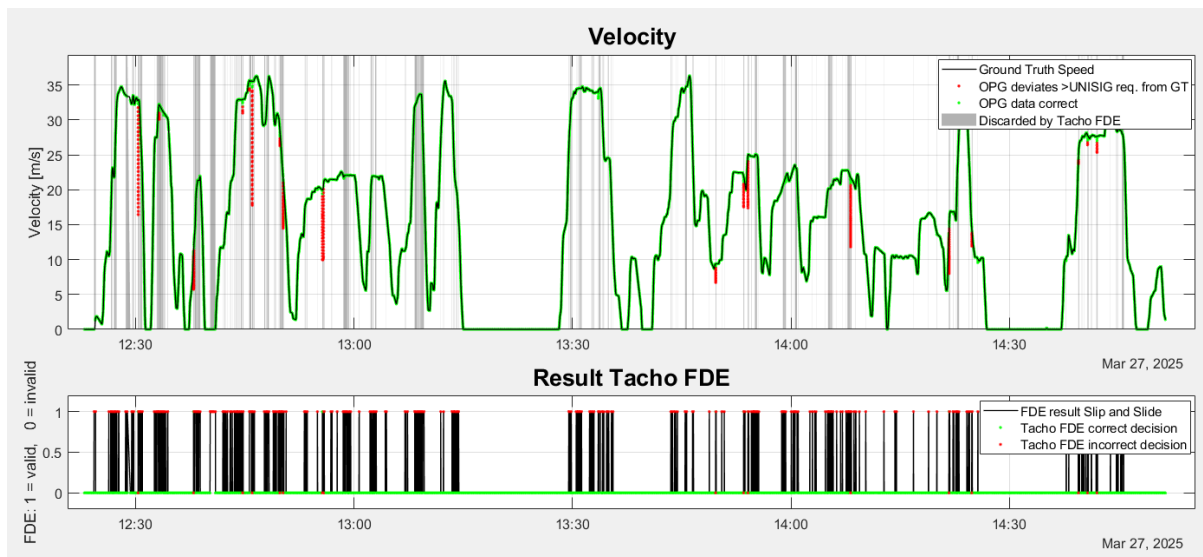


Figure 5-24: Result of Tacho FDE for Trip 57. Incorrect OPG data points: 0.4 %. Therefore, 74.6 % is correctly detected by the Tacho FDE, while 9.7 % of the overall data is discarded

Generously, it can be observed that the Tacho FDE is discarding many, but mostly only very short sections of a few seconds.

In many cases where the OPG speed sensor delivers incorrect data, the speed curve exhibits a trapezoidal shape, characterized by a sudden step drop, a brief plateau for a few seconds, and then a rapid return to the correct speed value. Which is not looking like a typical slip or slide event of the wheel, more like a sensor error or an issue encountered while recording the data. Two of these typical errors are shown in Figure 5-25 from Trip 57. It can be also observed that the Tacho FDE often reacts a little late on an OPG error and afterwards discards too much.

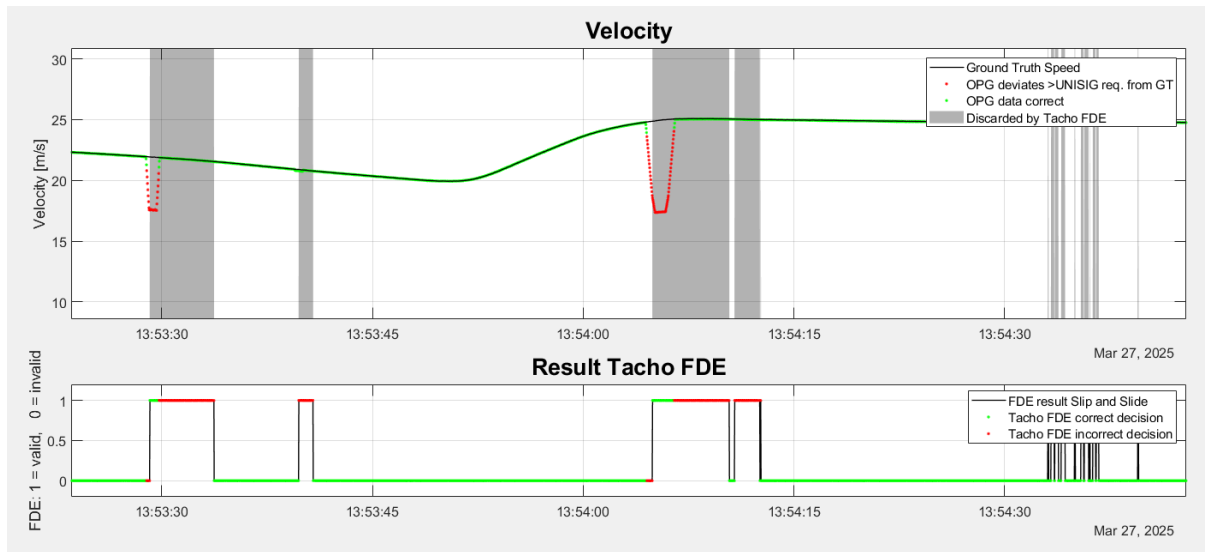


Figure 5-25: Zoom plot from Trip 57 showing two typical error behaviours of the OPG sensor

When longer errors occur, such as in Trip 49, the Tacho FDE is often unable to discard the entire faulty segment. Typically, one section is marked as invalid during the steep decrease in speed, and a second section during the subsequent speed increase, see Figure 5-26.

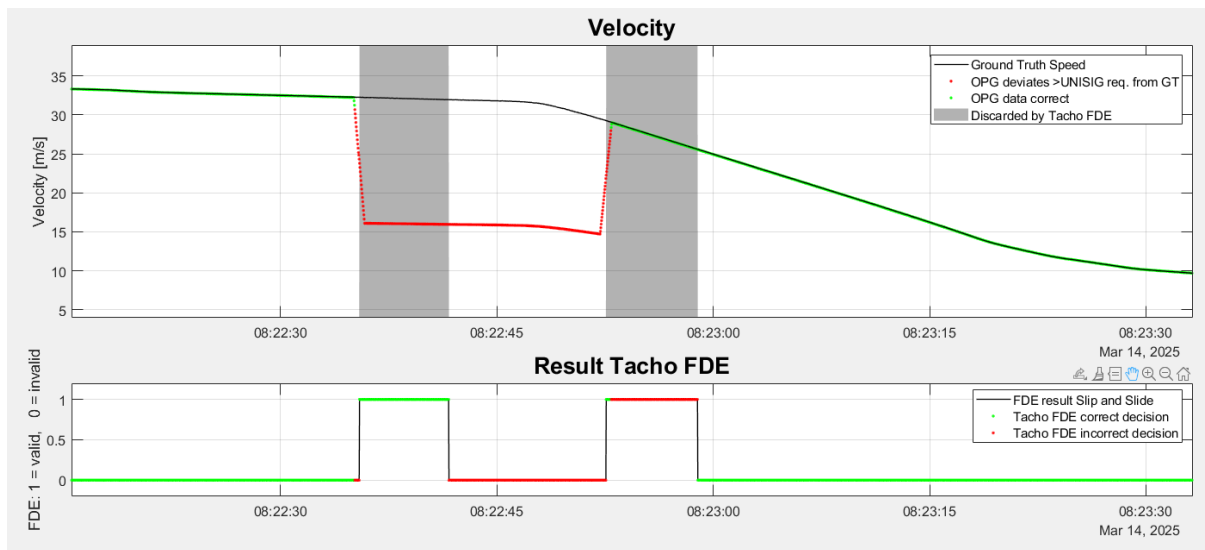


Figure 5-26: Zoom on a longer error section in Trip 49, with two discarded sections by the Tacho FDE

Trip 45 exhibited the best performance of the Tacho FDE, see Figure 5-27. In this trip, 88.8 % of the incorrect speed data points were successfully detected, while only 0.5 % of the overall data was discarded.

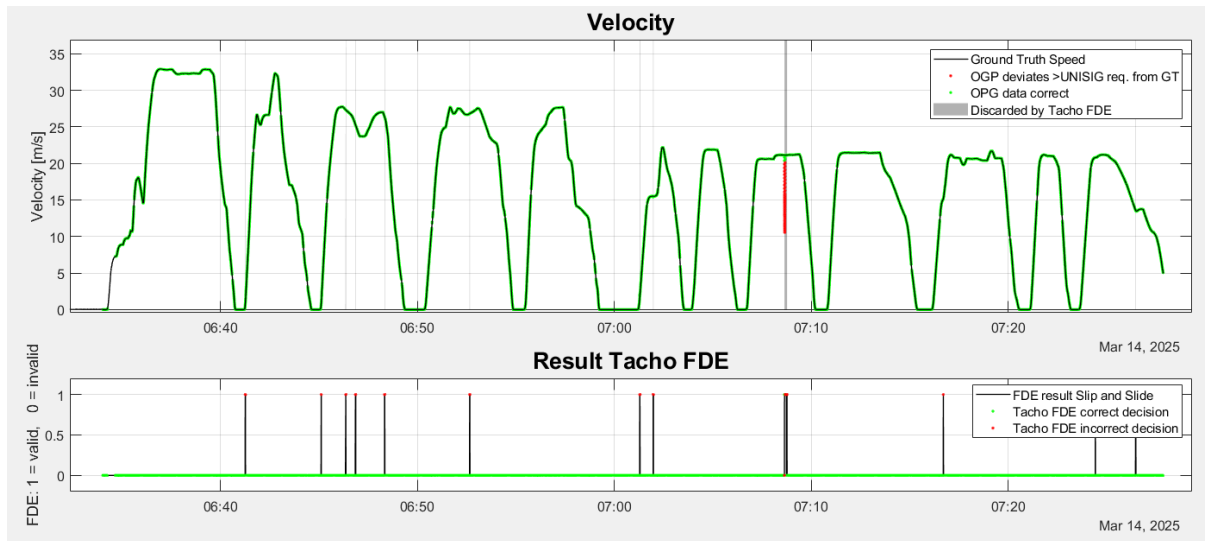


Figure 5-27: Result of Tacho FDE for Trip 45. Incorrect OPG data points: 0.1%. Therefore, 88.8% is correctly detected by the Tacho FDE, while 0.5% of the overall data is discarded

On the other hand, the Tacho FDE has also performed poorly in a few trips. The worst example is Trip 78, where only 0.2 % of the OPG speed data is actually faulty, but 24.4 % of the overall data is marked as invalid by the Tacho FDE. In this case, the Tacho FDE reacted far too sensitively, even though the same configuration was used as in all the other trips.

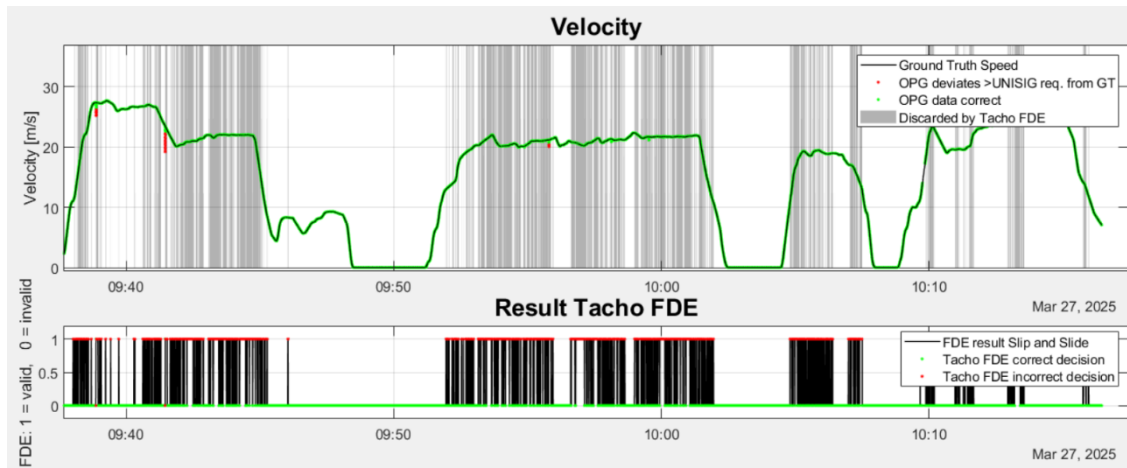


Figure 5-28: Result of Tacho FDE for Trip 78. Incorrect OPG data points: 0.2 %. Therefore, 90.5 % is correctly detected by the Tacho FDE, while 24.4 % of the overall data is discarded

The limited availability of OPG speed information in Trip 78 negatively impacts the performance of the LOC-OB algorithm. Figure 5-29 to Figure 5-32 present a comparison of the LOC-OB results with and without the use of the Tacho FDE. In the red-marked sections, the Tacho FDE decreases the performance of the LOC-OB algorithm, while in the green-marked areas, it improves it. In Figure 5-29 and Figure 5-30 it is clearly visible that, particularly in sections with low availability of OPG speed information, the confidence interval increases significantly when the Tacho FDE is applied, and the

speed delta also increases slightly. Similar effects can be observed in the 1D position results shown in Figure 5-31 and Figure 5-32.



Figure 5-29: Trip 78 results from LOC-OB speed **with** Tacho FDE

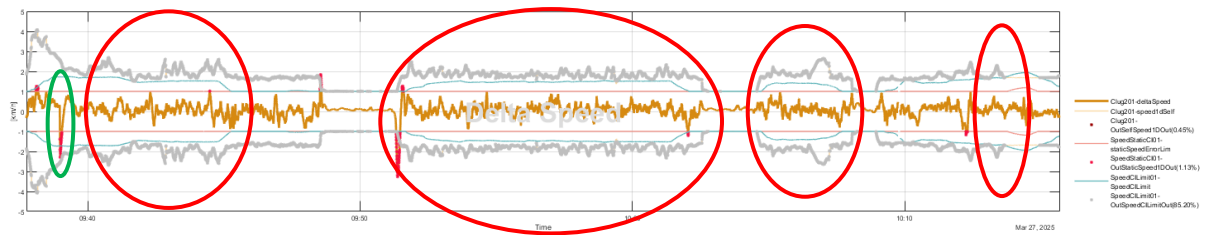


Figure 5-30: Trip 78 results from LOC-OB speed **without** Tacho FDE

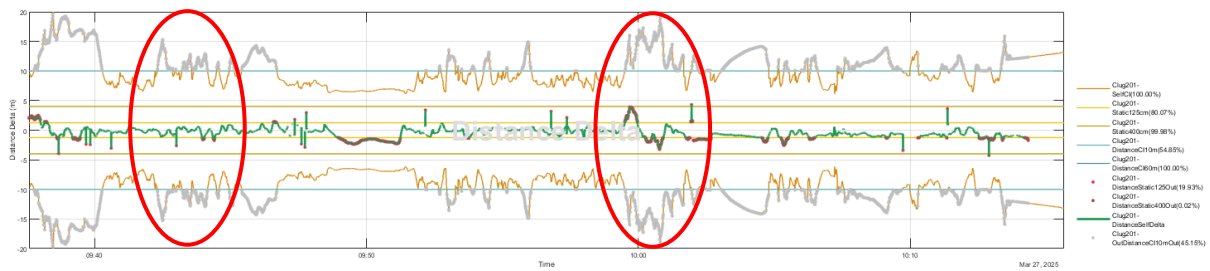


Figure 5-31: Trip 78 results from LOC-OB 1D position delta **with** Tacho FDE



Figure 5-32: Trip 78 results from LOC-OB 1D position delta **without** Tacho FDE

In summary, the Tacho FDE performs reasonably well on its own, as it detects most of the errors in the OPG data. However, its positive impact on the LOC-OB results is limited, as it improves accuracy only in a few short sections. In a few trips, the Tacho FDE reacts too sensitively and discards too much of the OPG speed data, leading to an increased confidence interval in the LOC-OB results and sometimes slightly higher speed delta. But in most of the analysed trips, the Tacho FDE has no significant influence at all.

5.5 Statistical analysis

The following chapter describes the statistical analysis of the trips presented in the previous part of this document. Aggregated results of all the journeys are presented in the form of cumulative distributions, and Stanford diagrams and analyse the results against the requirements.

5.5.1 Methodology

The statistical analysis uses the same datasets as the ones presented for the single-trip analysis. Only journeys with configuration C01 (EGNOS DFMC) are included. For the analyses, a few assumptions have been made:

- The first 60 seconds of a trip are not part of the statistical analysis. This is due to the initialization phase of the algorithm in order to ensure that the LOC-OB algorithm is converged, and the results are not meaningful to analyse.
- The ground truth, as well as the algorithm output, are filtered for only valid timestamps. For the ground truth, the validity fields are used and for the algorithm output, the health flag.
- The analysis focuses on the 1D output, e.g. the relative distance on the track edge with respect to the start node and the speed.

To compare the algorithm output with the ground truth, we interpolate the ground truth in time to the timestamps of the algorithm output. If the two ground truth samples have a difference in time larger than 2 seconds, the output is not analysed, during this period to avoid interpolation of large time gaps. Edge cases that occur during the passage between two track edges are discarded.

5.5.2 Definitions

Error

The error e of a measured or estimated value $\hat{n} \in \mathbb{R}$ and the true value $n \in \mathbb{R}$ is defined as

$$e = \hat{n} - n$$

The *absolute* error $|e| \in \mathbb{R}^+$ is the non-negative value of e without regard to its sign.

An accuracy requirement defines a range for which the error e is acceptable.

Example: The error e of the estimated value \hat{n} shall not exceed $\pm a$.

This results in $e = \hat{n} - n \in [-a, a]$ or can be expressed by the absolute error as $|e| \leq a$.

Confidence Interval

The confidence interval

$$\mathcal{C} = [a, b] = [\hat{n} - l, \hat{n} + u]$$

is used to describe the trustworthiness or estimated uncertainty of a sensor or algorithm regarding a measured or estimated value \hat{n} .

The confidence interval is often expressed relatively by a lower $l \in \mathbb{R}^+$ and upper $u \in \mathbb{R}^+$ bound or in the railway context by an over- l and underestimate u .

Example: The confidence interval \mathcal{C} shall not exceed $\pm k$. The result is that $l \leq k$ and $u \leq k$ or

$$\mathcal{C}_{\hat{n}} \subseteq [\hat{n} - k, \hat{n} + k]$$

Position 1D (Relative Distance)

- The estimated position is denoted by \hat{p} and the reference position by p .
- The absolute over- and underestimated position is expressed as \hat{p}^+ resp. \hat{p}^- .
- The relative over- and underestimation of the position can be calculated as $u_p = \hat{p}^+ - \hat{p}$ and $l_p = \hat{p} - \hat{p}^-$ where $l_p, u_p \geq 0$ per definition.
- The position error is defined as the difference between estimate and reference position $e_p = \hat{p} - p$.

Speed (1D Velocity)

- The estimated speed is denoted by \hat{v} and the reference speed by v .
- The absolute over- and underestimated speed is expressed as \hat{v}^+ resp. \hat{v}^- .
- The relative over- and underestimation of the speed can be calculated as $u_v = \hat{v}^+ - \hat{v}$ and $l_v = \hat{v} - \hat{v}^-$ where $l_v, u_v \geq 0$ per definition.
- The speed error is defined as the difference between estimate and reference speed $e_v = \hat{v} - v$.

Operational Surrounding

Some requirements which are analyzed below differentiate between two operational surroundings. According to the system requirements, the operational surrounding *Stop* is defined as ± 500 m around an operational stop, speed limitation, or a train station stop. For the statistical analyses, we distinguish between

1. the operational surrounding *Stop* for each sample within ± 500 m where the reference velocity $v < 0.1$ m/s, and
2. the operational surrounding *Open* everywhere else.

5.5.3 Cumulative distribution of errors

In the following section, we analyze the cumulative error distributions for position and speed. These plots characterize the magnitude of the differences and their statistical distribution.

Position Error Operational Surrounding *Stop / Open*

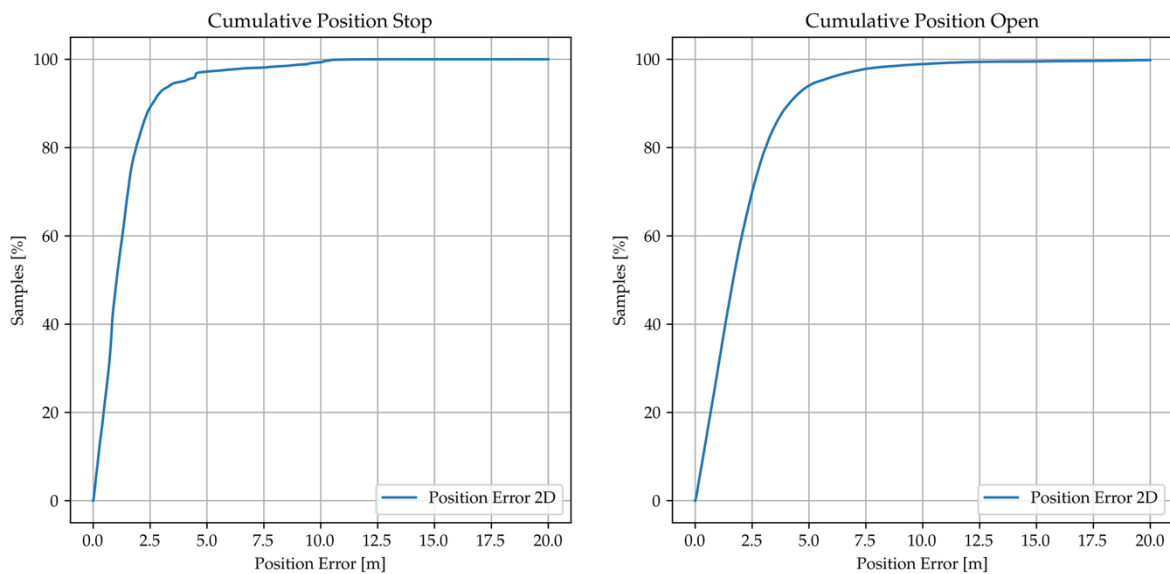


Figure 5-33: Cumulative distribution of the position error for operational surroundings Stop and Open

Figure 5-33 shows the error characteristics of the position in the operational surroundings, Stop and Open, as introduced in the previous sections. For both scenarios, 80 % of the samples have an error below 2 m for Stop, respectively below 3 m for Open. The cumulative distribution reaches 95 % around an error of 5 m for the surrounding Stop and 7.5 m for Open.

Speed Error Operational Surrounding Stop / Open

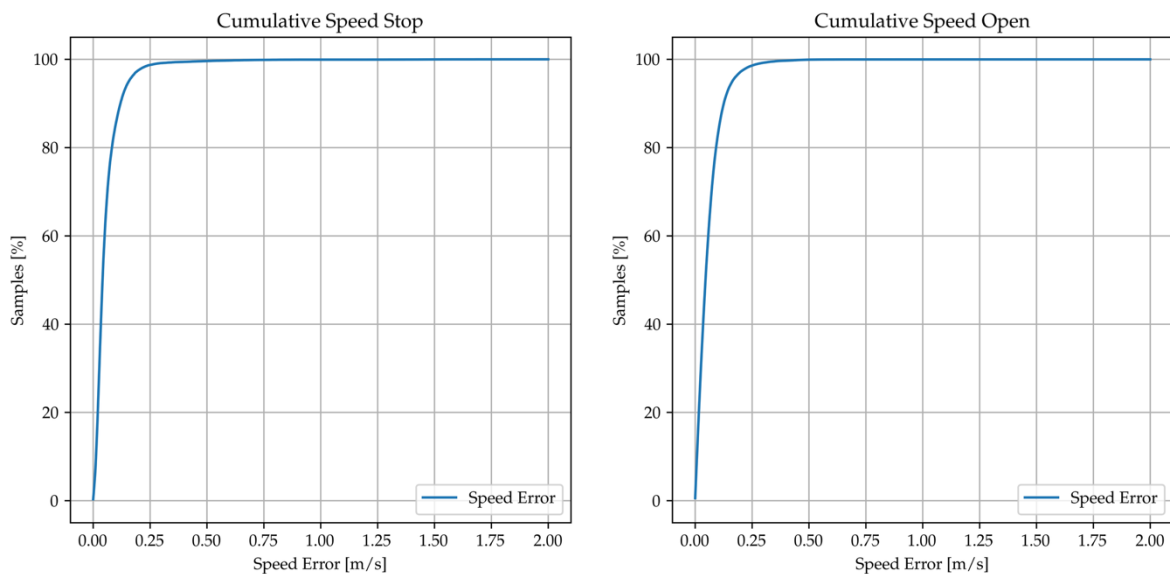


Figure 5-34: Cumulative distribution of the speed error for operational surroundings Stop and Open

The cumulative distribution of the speed error is shown in Figure 5-34. There is no visible difference between the curves for operational surroundings Stop and Open. More than 95 % of the samples have a speed error below 0.25 m/s, and there are no observable outliers in the distribution plot.

5.5.4 Stanford diagrams

In the section below, we analyse the safety and performance, which is defined by the size of the confidence interval, using the Stanford diagram. This is a well-established plot in aviation and is used to classify samples for safety and availability. The plot is a two-dimensional histogram with safety and availability limits.

Position Error Operational Surrounding Stop / Open

Figure 5-35 shows the Stanford diagrams for the position error and its confidence interval for the operational surrounding Stop (i.e. constrained areas) and Open (i.e. non constrained areas). They have two different availability limits: 10 m for Stop and 60 m for Open. The more challenging surrounding Stop has 80.67 % of the samples in a safe and available state, while 19.2 % are still safe but unavailable, with a confidence interval exceeding the 10 m availability limit. There are some samples (0.13 %) that are unsafe but also unavailable. There are no samples claiming full availability but with an error larger than the confidence interval. The results are very similar for the surrounding Open: 99.56 % of the samples are safe and available. 0.2 % of the samples have a confidence interval exceeding 60 m. Contrary to the Stop case, there are 0.24 % of the samples with an error larger than the confidence interval, which is below the availability limit. These very few unsafe samples are isolated, and root cause(s) have not yet been explained; it could come from sensor data FDE not excluding properly invalid data or undetected cumulative errors on both LOC-OB outputs and computed Ground Truth.

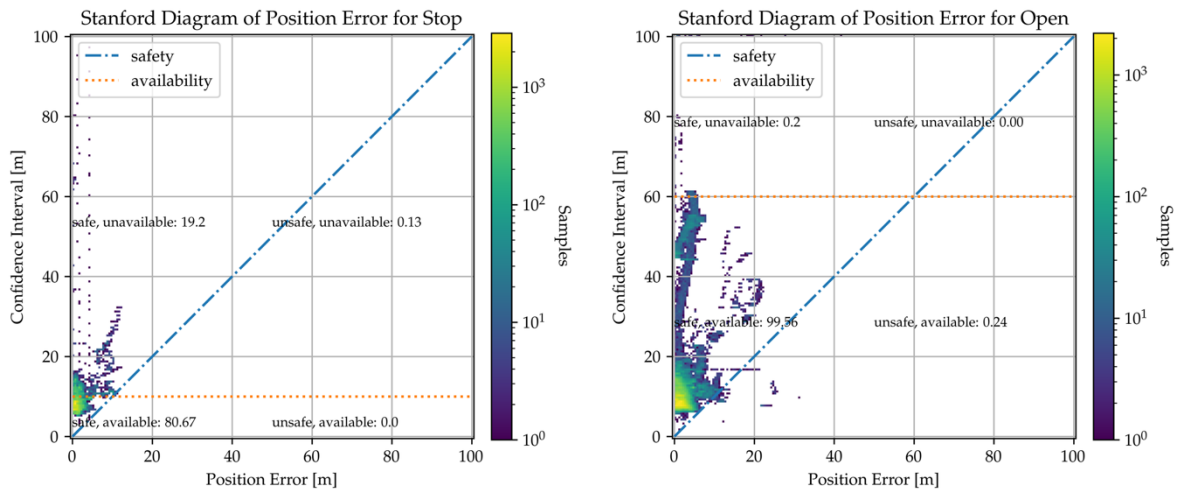


Figure 5-35: Stanford Diagram of the position error for operational surroundings Stop and Open

Speed Error Operational Surrounding Stop / Open

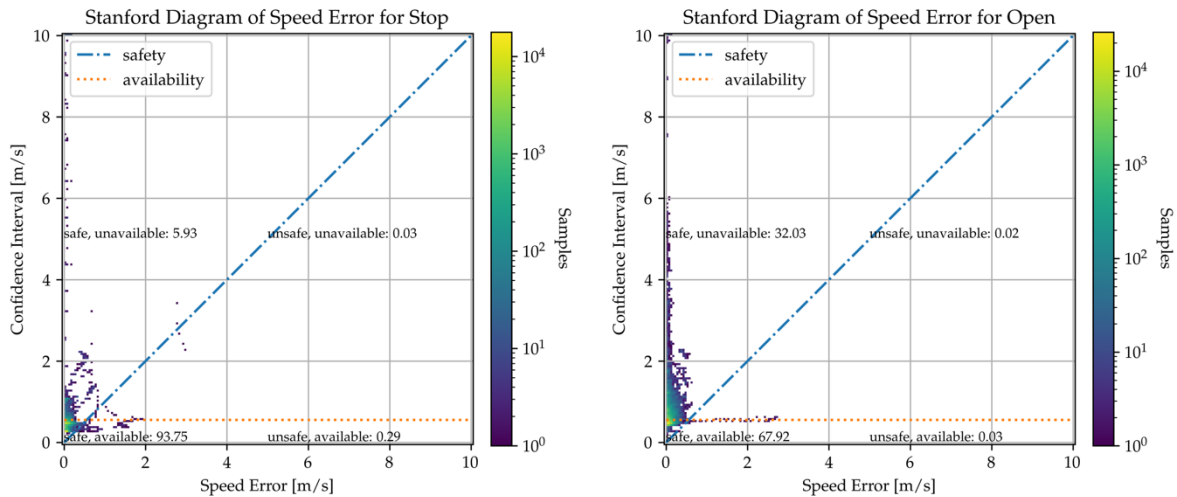


Figure 5-36: Stanford Diagram of the speed error for operational surroundings Stop and Open

Figure 5-36 shows similarly to the plots above the Stanford diagram for speed instead of position. Again, we distinguish between the operational surroundings. The availability limit is in contrast to the position formulated relatively to the reference speed: $l_v, u_v < \max(2 \text{ km/h}, 1/47(v + 64 \text{ km/h}))$. For the Stanford diagrams presented here for speed, we use a fixed availability limit of 2 km/h (0.56 m/s), which is the lower and more challenging boundary of the requirement, just because variable requirement towards speed is not visualizable in the Stanford diagram. Furthermore,

we used only the absolute speed error and the upper bound of the confidence interval, the overestimation of the speed. For the surrounding Stop, 93.75 % of the samples are safe and available. The majority of the other samples, 5.93 %, are unavailable but still safe with a speed error bounded by the confidence interval. 0.03 % of the evaluated speed estimates have a confidence interval larger than the hardened availability limit while the error exceeds it. The most dangerous case is if the confidence interval is within the availability limit, but the speed estimate is unsafe. This is the case for 0.29 % of the samples for the Stop surrounding. For the scenario Open, the availability decreases. 67.92 % of the samples are available and safe, whereas 32.03 % of the dataset has a speed confidence exceeding the limit of 2 km/h while still being safe. In total, 0.05 % of the samples are unsafe for the operational surrounding Open, 0.03 % of them below, and 0.02 % above the availability limit. Like for the position analysis, these very few unsafe samples are isolated and root cause(s) not yet explained; it could come from sensor data FDE not excluding properly invalid data or undetected cumulative errors on both LOC-OB outputs and computed Ground Truth.

5.5.5 Requirements testing

SpecSysReq[003]			
Definition	<p>The absolute value of the Overestimation related to the estimated distance and the absolute value of the Underestimation related to the estimated distance shall be lower than ten meters. Surrounding:</p> <ul style="list-style-type: none"> - An operational stop or speed limitation. - A stop in train station. <p>Surrounding shall be interpreted as $\pm 500m$ of a stopping point.</p> <p>Note: cf CI<MCI availability SpecSysReq[048], at least 99.2% (i.e. 1mn/2h) is assumed passed.</p>		
Criterion	$l_p, u_p < 10 m$		
Results	Open	Stop	Total
Samples	N/A	54970	N/A
Passed/Failed	N/A	80.664 % / 19.336 %	N/A

SpecSysReq[004]

Definition The absolute value of the Overestimation related to the estimated distance and the absolute value of the Underestimation related to the estimated distance shall be lower than sixty meters anywhere the SpecSysReq[003] requirement is not requested.

Note: cf CI<MCI availability SpecSysReq[048], at least 99.2% (i.e. 1mn/2h) is assumed passed.

Criterion $l_p, u_p < 60 \text{ m}$

Results	Open	Stop	Total
Samples	111415	N/A	166385
Passed/Failed	99.804 % / 0.196 %	N/A	99.843 % / 0.157 %

SpecSysReq[005]

Definition The absolute error of the estimated distance to the reference location shall not exceed 1.25m, for at least 95% of the cases. Surrounding:

- An operational stop or speed limitation.
- A stop in train station.

Surrounding shall be interpreted as $\pm 500\text{m}$ of a stopping point.

Criterion $\Pr(|e_p| \leq 1.25 \text{ m}) \geq 95\%$

Results	Open	Stop	Total
Samples	N/A	54970	N/A
Passed/Failed	N/A	58.774 % / 41.226 %	N/A

SpecSysReq[006]			
Definition	The absolute error of the estimated distance calculated by LOC-OB shall not exceed 4m (for at least 95% of the cases), anywhere the SpecSysReq[005] requirement is not requested.		
Criterion	$\Pr(e_p \leq 4\text{ m}) \geq 95\%$		
Results	Open	Stop	Total
Samples	111491	N/A	166461
Passed/Failed	89.140 % / 10.860 %	N/A	91.096 % / 8.904 %

SpecSysReq[007]			
Definition	The train front end true position shall be included in the LOC-OB computed confidence interval towards the train front end position within the most constraining user exported THR. Train true position is within [(Reference location id + Estimated distance - Overestimation of the estimated distance); (Reference location id + Estimated distance + Underestimation of the estimated distance)].		
Criterion	$e_p \in [-l_p, u_p]$		
Results	Open	Stop	Total
Samples	111415	54970	166385
Passed/Failed	99.758 % / 0.240 %	99.865 % / 0.135 %	99.793 % / 0.207 %

SpecSysReq[009]

Definition The confidence interval calculated by LOC-OB (Underestimation of the estimated train speed - Overestimation of the estimated train speed) toward estimated speed shall be better than 2 km/h for speeds lower than 30 km/h, and increasing linearly up to 12 km/h for speeds between 30 km/h and 500 km/h.

Note: The test for the requirement was integrated as specified in TSI SS-041 5.3.1.2 [R5]. Accuracy of speed known on-board and differs to the CLUG 2.0 interpretation.

Note: cf CI<MCI availability SpecSysReq[048], at least 99.2% (i.e. 1mn/2h) is assumed passed.

Criterion

$$l_v, u_v < \max\left(2 \text{ km/h}, \frac{1}{47}(v + 64 \text{ km/h})\right)$$

Results	Open	Stop	Total
Samples	111491	54970	166461
Passed/Failed	92.749 % / 7.251 %	96.491 % / 3.509 %	93.985 % / 6.015 %

SpecSysReq[010]

Definition The absolute error of the estimated train speed provided by LOC-OB shall not exceed ± 1 km/h for speeds from 0 km/h to 100 km/h and $\pm 1\% \cdot v$ for speeds from 100 km/h to 500 km/h for at least 95% of the cases.

Criterion

$$\Pr(|e_v| \leq \max(1 \text{ km/h}, 1\% \cdot v)) \geq 95\%$$

Results	Open	Stop	Total
Samples	111491	54970	166461
Passed/Failed	99.094 % / 0.906 %	99.001 % / 0.999 %	99.063 % / 0.937 %

SpecSysReq[011]			
Definition	The train true speed shall be lower than the LOC-OB computed max safe speed (Estimated train speed + Underestimation train speed) within the most constraining user exported THR.		
Criterion	$e_v \in [-l_v, u_v]$		
Results	Open	Stop	Total
Samples	111491	54970	166461
Passed/Failed	99.896 % / 0.104 %	99.680 % / 0.320 %	99.825 % / 0.175 %

5.6 Overview plots about all trips: GNSS availability, accuracy and integrity

This chapter provides overview plots about:

1. GNSS availability after FDE & EGNOS (Figure 5-37),
2. accuracy & integrity probabilities with respect to the requirements (Figure 5-38),
3. and mean and 2-sigma of the 1D localization/speed parameters and the corresponding CIs (Figure 5-39).

for all trips that had been analysed in chapter 4 including additional information regarding the behaviour in non-tunnel parts and tunnel parts of the individual trips.

In total :

- three trips: Trip 45, Trip 46 and Trip 47 had been analysed without tunnels,
- five trips: Trip 45 (fake tunnels), Trip 49, Trip 57, Trip 58 and Trip 78 with less than 20 % of the trip are tunnels,
- and three trips: Trip 73, Trip 77 and Trip 79 with more than 30 % up to 47 % of the trip are tunnels.

Generally, more GAL satellites are available than GPS satellites although:

- for GPS: an L2C to L5 extrapolation had been applied to the GPS satellites that do not yet broadcast in L5, i.e. the expected operational 24 GPS constellation not yet in orbit;
- for GAL: PRN larger than 27 are not considered due to the issue mentioned in chapter 3 with the Airbus EGNOS Emulator.

Furthermore, it can be observed that the GNSS availability (no tunnel parts) for trips without tunnels is higher than for trips with tunnels. The reason therefore is that most of the time, the local environment is more challenging for trips with tunnels. The GNSS availability after FDE & EGNOS is generally not very high, which might be due to the FDE threshold being set too strictly. For no tunnel trips, 9 ± 1 GNSS satellites are available, while for medium and maximum tunnel trips, only 7 ± 2 and 4 ± 2 GNSS satellites are available, respectively.

The requirement SpecSysReq[005] (1.25 m distance accuracy for 95 % of the case) is not fulfilled for all trips (too strict requirement), while the requirement SpecSysReq[006] (4 m distance accuracy for 95 % of the case) is fulfilled for most of the trips for the non-tunnel parts, except for Trip 49, Trip 57 and Trip 79. Within tunnels, only for 50 % of the trips, the 4 m requirement is met, which is acceptable because in GNSS-denied areas, the accuracy is lower and can be achieved with some rare Eurobalises.

Requirement SpecSysReq[010] ([1 5] km/h speed accuracy for 95 % of the case) is always fulfilled not only in the non-tunnel parts but also in tunnels.

Regarding the safety CI requirements, i.e. real along track position/speed are inside the computed CIs, except rare observations to be further analysed and explained, it is fulfilled or very close to 100 %.

Regarding CI<MCI at 99 % requirements:

- The position CI inside 60 m half-MCI requirement is always met;
- The position CI inside 10 m half-MCI requirement is only met for Trip 46; for all other trips for the non-tunnel parts, the probability is about 75 % \pm 25 % and for tunnel parts, about 47 % \pm 27 %, respectively;
- The speed CI inside [2 12] km/h half-MCI requirement is met for trips with favourable GNSS local environment. The more challenging the trip, the lower the probability not only in the tunnel parts but also in the non-tunnel parts of the trips.

Looking at the mean and 2-sigma plots in Figure 5-39, the mean along-track position error plus/minus 2-sigma in no tunnel parts and tunnel parts would be 0.47 ± 3.06 m versus 1.45 ± 4.35 m and for the along-track speed error, it would be 0.06 ± 0.53 km/h versus 0.04 ± 0.61 km/h. It signifies that the accuracy for position is significantly more impacted by GNSS denied areas than the accuracy for speed. The mean position CI plus/minus 2-sigma is about 9.12 ± 5.17 m (no tunnel parts) versus 14.30 ± 7.18 m (tunnel parts), while for the speed CI it is about 1.71 ± 1.25 km/h versus 2.21 ± 1.22 km/h. This clearly shows that the 10 m requirement is not

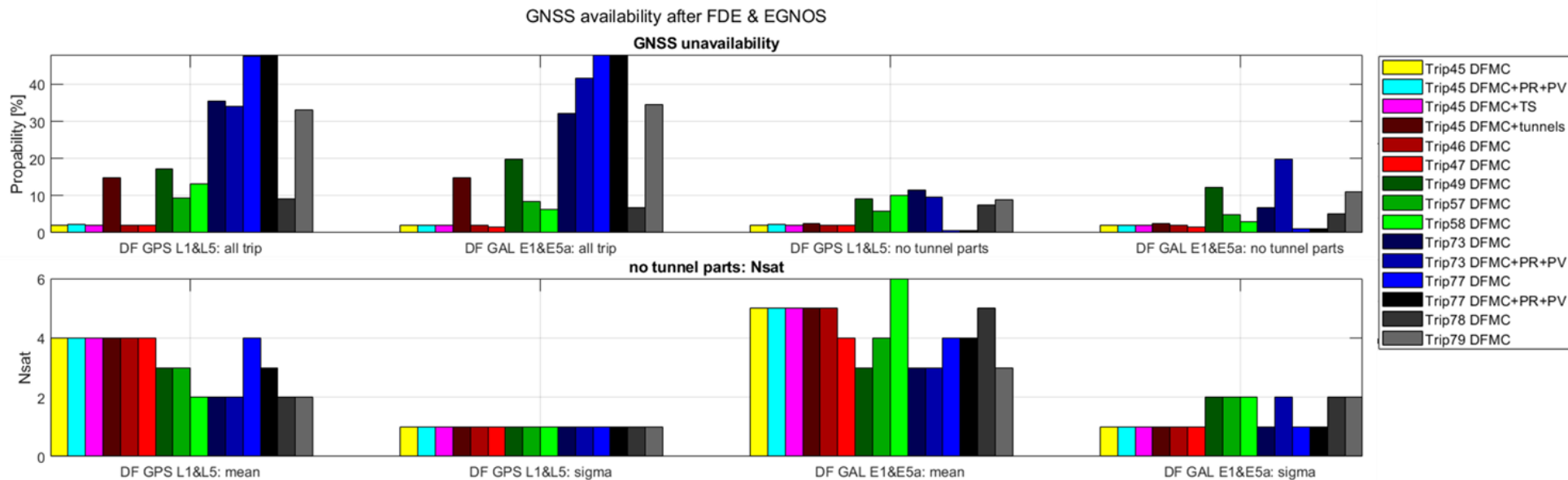


Figure 5-37: Overview plot about all trips: GNSS availability after FDE & EGNOS

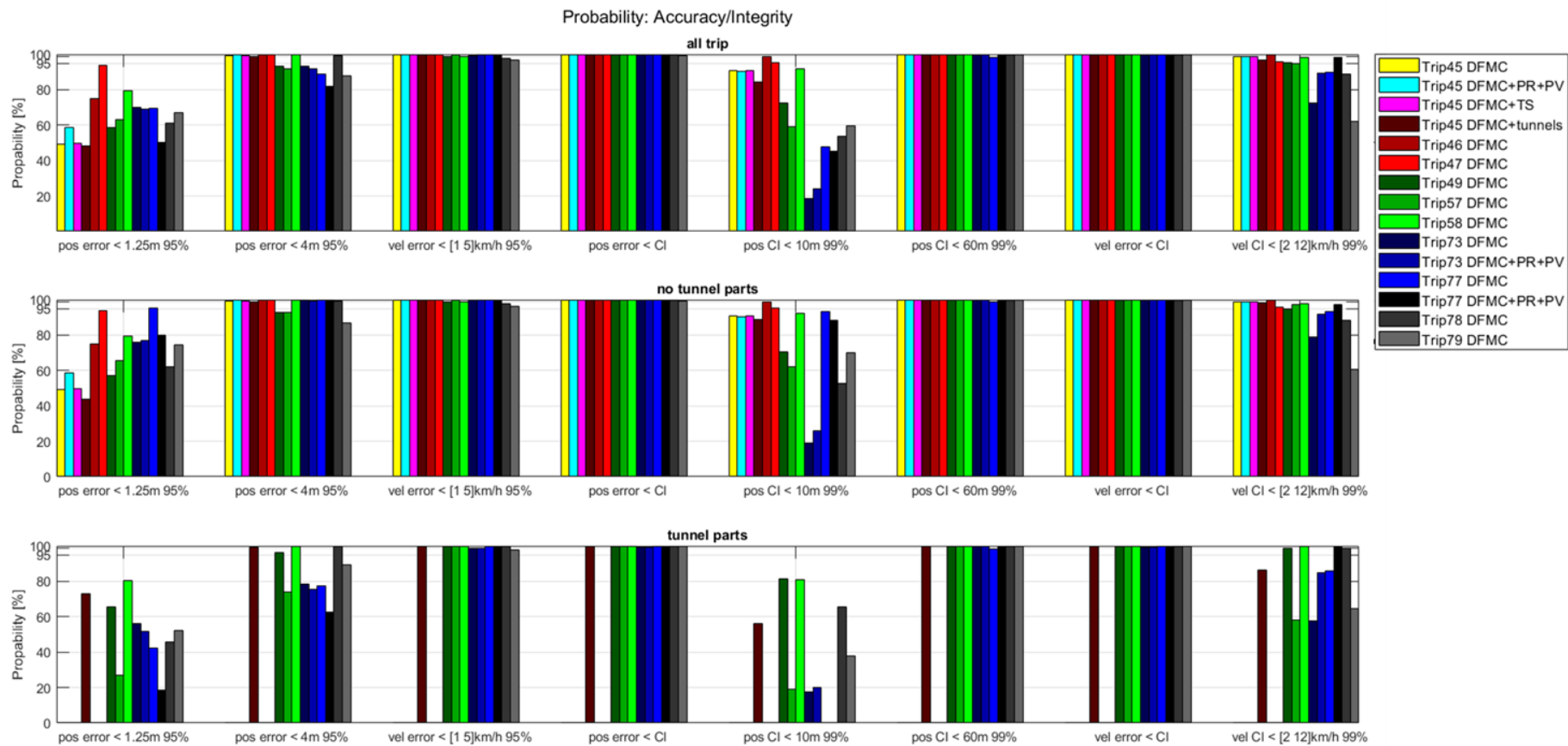


Figure 5-38: Overview plot about all trips: accuracy & integrity probabilities

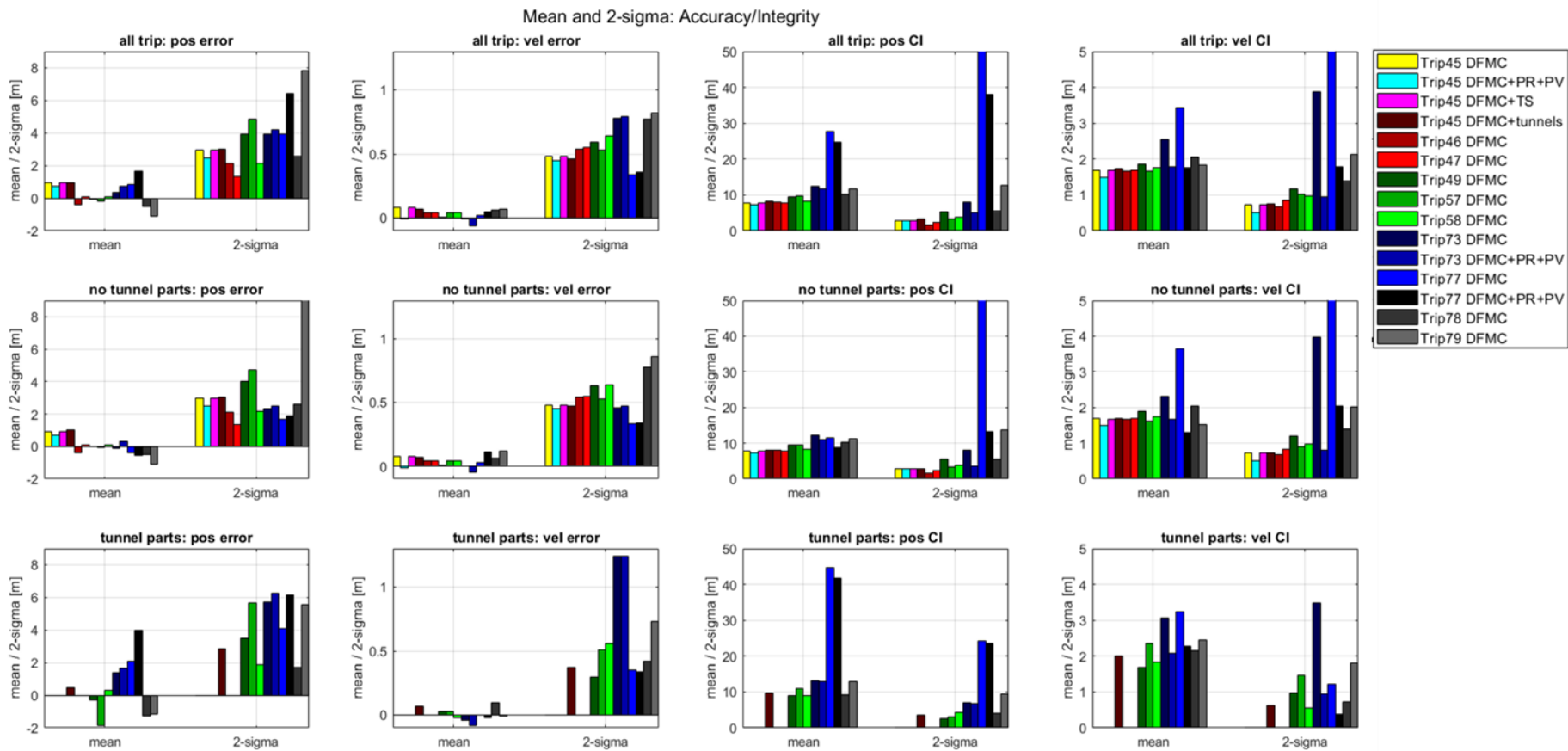


Figure 5-39: Overview plot about all trips: mean and 2-sigma of position/velocity errors and the corresponding CIs



5.7 Compliance statement to the system requirements

The compliance statements in Table 13 are valid for the test configuration C01 (EGNOS DFMC) according to chapter 4.1.

The Table 13 lists only the requirements which were planned to be covered by test and analysis done in work package 5 according to the CLUG2.0 Test Plan [R6].

Table 13: Test coverage of the system requirements

Requirement	Description	Compliance Level	Comments
SpecSysReq[001]	The 1D localisation dataset toward the train front end provided by LOC-OB shall include: <ul style="list-style-type: none"> - Reference location id - Train orientation - Position qualifier (w.r.t. to the reference location) - Estimated distance - Underestimation of the estimated distance - Overestimation of the estimated distance - Track edge id - Validity timestamp 	Fulfilled	-
SpecSysReq[002]	LOC-OB shall provide the track edge ID where the train front end position is.	Fulfilled	-
SpecSysReq[003]	The absolute value of the Overestimation related to the estimated distance and the absolute value of the Underestimation related to the estimated distance shall be lower than ten meters. surrounding: <ul style="list-style-type: none"> - An operational stop or speed limitation. - A stop in train station. Surrounding shall be interpreted as +- 500m of a stopping point.	Not fulfilled	According to chapter 0, 80.664 % of the samples are passed, which is less than the required 99% defined based on SpecSysReq[048].
SpecSysReq[004]	The absolute value of the Overestimation related to the estimated distance and the absolute value of the Underestimation related to the estimated distance shall be lower than sixty meters anywhere the SpecSysReq[003] requirement is not requested.	Fulfilled	According to chapter 0, 99.804 % of the samples are passed, which is more than the required 99% defined based on SpecSysReq[048].

Requirement	Description	Compliance Level	Comments
SpecSysReq[005]	The absolute error of the estimated distance to the reference location shall not exceed 1.25m, for at least 95% of the cases, surrounding: - An operational stop or speed limitation - A stop in train station. Surrounding shall be interpreted as +/- 500m of a stopping point.	Not fulfilled	According to chapter 0, 58.774 % of the samples are passed, which is less than the required 95%.
SpecSysReq[006]	The absolute error of the estimated distance calculated by LOC-OB shall not exceed 4m (for at least 95% of the cases), anywhere the SpecSysReq[005] requirement is not requested.	Not fulfilled	According to chapter 0, 89.140 % of the samples are passed, which is less than the required 95%.
SpecSysReq[007]	The train front end true position shall be included in the LOC-OB computed confidence interval towards the train front end position within the most constraining user exported THR. Train true position is within [(Reference location id + Estimated distance - Overestimation of the estimated distance); (Reference location id + Estimated distance + Underestimation of the estimated distance)].	Not fulfilled	According to chapter 0, 99.748 % of the samples are passed, which is less than the required TFFR $\leq 10^{-9}$ /h defined in D3.7 [R7].
SpecSysReq[008]	The 1D speed (along the track) dataset provided by LOC-OB shall include: - Movement direction - Estimated train speed - Underestimation train speed - Overestimation train speed - Validity timestamp	Fulfilled	-
SpecSysReq[009]	The confidence interval calculated by LOC-OB (Underestimation of the estimated train speed - Overestimation of the estimated train speed)	Not fulfilled	According to chapter 0, 93.985 % of the samples are passed, which is less than the

Requirement	Description	Compliance Level	Comments
	toward estimated speed shall be better than 2 km/h for speeds lower than 30 km/h, and increasing linearly up to 12 km/h for speeds between 30 km/h and 500 km/h.		required 99% defined based on SpecSysReq[048].
SpecSysReq[010]	The absolute error of the estimated train speed provided by LOC-OB shall not exceed ± 1 km/h for speeds from 0 km/h to 100 km/h and $\pm 1\% * v$ for speeds from 100 km/h to 500 km/h for at least 95% of the cases.	Fulfilled	According to chapter 0, 99.063 % of the samples are passed, which is more than the required 95%.
SpecSysReq[011]	The train true speed shall be lower than the LOC-OB computed max safe speed (Estimated train speed + Underestimation train speed) within the most constraining user exported THR.	Not fulfilled	According to chapter 0, 99.825 % of the samples are passed, which is less than the required $TFFR \leq 10^{-9}/h$ defined in D3.7 [R7].
SpecSysReq[048]	If the confidence intervals are larger than the acceptable position confidence interval (position), maximum acceptable speed confidence interval (speed) or maximum acceptable acceleration confidence interval (acceleration) for a cumulative 60 seconds (or more) for two hours, the time is accounted in the overall LOC-OB unavailability.	Not fulfilled	As a result of the computed confidence interval above the required CI for the distance according to SpecSysReq[003] (+/- 10 m) and for the speed according to SpecSysReq[009].
SpecSysReq[071]	LOC-OB shall take into consideration each sensor specific challenging environmental condition and each sensor failure mode to perform in all situations not considered as incredible or Improbable.	Fulfilled	As far as it could be observed with the data analyzed, the performance of the LOC-OB is not heavily impacted by environmental conditions, refer to analysis of Trip 73 (4.10) and Trip 77 (4.12) presenting challenging environmental conditions.
SpecSysReq[072]	If the LOC-OB is not providing data at the defined rate, the LOC-OB is considered as unavailable during this time.	Fulfilled	LOC-OB provides data at constant rate.

5.8 Open points and recommendations for follow-up projects

5.8.1 Integration into analysis tool chain

The open points and recommendations described in this section are intended for entities focused on the verification and validation of localization algorithms for railway applications.

- Challenges and Future Directions in Defining Ground Truth for Railway Applications

Establishing a reliable ground truth (GT) in railway environments presents a fundamental challenge, particularly in the context of validating positioning and navigation systems under diverse operational conditions. A GT must be consistently available across a wide range of environments—including tunnels, urban areas, and open tracks—while maintaining sufficient accuracy and independence from the device under test (DUT). This independence is crucial to avoid systematic errors caused by common-cause effects, where both the system under test and the reference system are influenced by the same external factors.

As the precision requirements for railway localization systems continue to increase, the demands placed on the GT used for their validation also increase. Traditional reference systems, often based solely on GNSS, are no longer adequate in complex railway scenarios. This trend underscores the need for a more robust and scalable approach to GT definition.

To address this, it would be beneficial to develop a foundational concept for GT generation that can be applied across future research and development projects. Such a concept should aim to produce high-quality GT data that is cost-neutral and achievable with manageable effort. It should include methodological guidelines for sensor selection, data fusion strategies, and environmental considerations, ensuring that the GT remains valid and reliable regardless of the specific test conditions.

Moreover, the validation and verification of the GT itself must be considered an integral part of the process. Currently, there is a lack of standardized procedures for assessing the integrity and accuracy of GT data, which limits the comparability and credibility of evaluation results. Establishing a formalized validation framework—potentially in the form of a modular and adaptable standard—could significantly enhance the reliability of GT-based assessments. This framework should encompass both quantitative accuracy metrics and qualitative assessments of data consistency, and it should support transparent documentation of uncertainties.

In the long term, such a standardized GT concept could not only improve the scientific rigor of railway research projects but also facilitate broader industrial adoption. It would provide a solid foundation for certification processes, safety assessments, and the development of autonomous railway technologies, thereby contributing to the advancement of innovation and operational safety in the rail sector.

- Optimizing Data Processing Through Field-Aligned Data Formats

A key aspect in the validation of railway localization algorithms is the efficient processing of sensor data recorded in the field. In practice, however, converting this raw data into a unified format suitable for both analysis and as input for the LOC-OB system can be time-consuming and computationally intensive. This is particularly true when dealing with large volumes of data and heterogeneous sensor types, where pre-processing pipelines often involve multiple transformation steps and extended runtimes.

To reduce this overhead, alternative approaches should be considered—specifically, the direct use of raw field data in its original format as input to the algorithms. By bypassing extensive conversion steps, not only processing loops can be eliminated, but potential error sources introduced during pre-processing can also be avoided. Furthermore, this approach brings the algorithm development process closer to real-world deployment conditions, which is especially beneficial for the design of robust, real-time systems.

An ideal scenario would involve both the post-processing environment and the real-time demonstrator using the exact same input data—processed in the same structure and format as recorded in the field. This alignment ensures that system behaviour observed in the field can be reproduced one-to-one in simulation or analysis environments. Such fidelity is particularly critical when investigating edge cases or failure scenarios, where even minor deviations in pre-processing can lead to significant differences in algorithm performance.

In the long term, this strategy could not only improve the efficiency of data handling but also enhance the comparability between different test environments. Moreover, it would lay the foundation for a standardized, field-oriented validation methodology for localization algorithms—an increasingly important requirement as future systems grow in complexity and demand higher levels of real-time performance.

5.8.2 LOC-OB

The open points and recommendations described in this section are intended for companies of the railway industry focused on the development of localization algorithms for railway applications.

- Exclusion of too many satellites shall be checked and further improved

A common observation in all datasets is that the discarding rate of GNSS measurement is relatively high: even in datasets with relatively good GNSS visibility conditions (for example Trip 45), about half of the GNSS measurements are discarded.

It would be interesting to gain more insight on this experimental evidence. On the one hand, it could be that this behaviour is indeed ensuring accurate and safe operation of the LOC-OB. On the other hand, it might also result that the exclusion rate is a bit too pessimistic.

A possible way forward would be to set up an evaluation platform that would compute pseudorange errors, by comparing the GNSS observations with respect to the expected measurements, computed through the knowledge of the satellite positions and the ground truth position.

By matching the pseudorange errors with the exclusion behaviour (per FDE) the performance level could then be characterized, leading to identify and adjust the possible over-pessimistic behaviour being observed the dated

- Potential relaxation of Time To Alert (TTA) requirements for GNSS and Tacho FDE

In the current design of the LOC-OB, the SBAS TTA (assumed as 6 s) is compensated by running the EKF six seconds in the past and coasting the output to the current time instant thanks to the IMU measurement.

This mechanism would enable a relaxation of the Time To Alert requirements also for all the Tacho and GNSS FDE, that has not been exploited in the current LOC-OB design and prototype. It is stressed that this relaxation would not be applicable to the IMU data, since the propagation ahead of the old localization output is based on the IMU data itself.

For GNSS DATA FDE, no major advantage is expected for CN0 and elevation masks, given the simplicity of the detection scheme. Also, for Cycle slips no major advantage is foreseen, given the fact that these FDE are intended to detect only instantaneous events on the carrier phase.

Some advantage might be observed in the Code-Minus-Carrier and Doppler-based FDEs.

For the Tacho FDE having the ability to look six seconds into the future may offer advantages for a new algorithm design and could enhance overall performance. In particular, short-duration errors in the OPG data may be detected more easily and with greater accuracy. If this approach does not yield sufficient improvement, it is recommended to use an additional speed sensor to provide more accurate and reliable speed information.

Finally, it could also be explored if the availability of a certain time window buffer could lead to advantage of the System FDE, adding on GNSS and Tacho measurements.

- Improve CI strategy

This point is related to the CI fault-free limitation already identified in chapter 3.1.

The CI delivered by the LOC-OB prototype are covering only the fault-free scenarios. Any impact of the misdetections (on Tacho or GNSS) on the delivered output is therefore not bounded in the current version.

The CI computation algorithm designed in D4.7 [R4] envision a strategy to also include GNSS and tacho fault scenarios, but an over-pessimistic behaviour has been observed in the preliminary assessment of the algorithm.

It is recommended to perform additional work to find the root cause of the overestimation of the CI and fix it. This should happen both at design and prototype level.

- Improve speed CI

If the TSI [2 12] km/h half-MCI speed requirement remains confirmed at these values, performances can be improved by enforcing the speed and IMU sensors (redundancies, stronger FDE, and/or IMU higher grade).

- Track selectivity should be tested more in details

The Track selectivity has been successfully tested Trip 45. However, given the critical role of this function, further extensive testing is needed. It is well known that in the railway network many different topological scenarios can be encountered, with very diverse switching patterns.

It is therefore recommended to further test this function, by exposing it to the largest possible number of real-world examples.

- Implement initialization phase as defined in task 4.9

In the tested version of the LOC-OB, a simplified initialization strategy has been performed.

The initialization of the LOC-OB has always occurred at standstill, with the initial position and initial clock errors computed through GNSS-only Least Square algorithm and track edge id provided by the ground truth routing file. All the other LOC-OB parameters (IMU biases, tacho scale factors, misalignment angles) are initialized with zero values.

The implementation of the initialization function following the roadmap identified in WP4.9 would be an interesting evolution of the current prototype.

- Extension of sensor fusion by processing of balise data

The design of the along-track localization function performed in WP4.6 has envisaged also the use of the balise positioning information inside the EKF.

It could be interesting to test this feature that has not been included in the LOC-OB prototype.

5.8.3 Input data

The open points and recommendations described in this section are intended for railway infrastructure managers.

Map validity

One of the major open issues anticipated in CLUG 2.0 Deliverable 4.10 [R9], concerning map topics, which was confirmed during testing activities, is the validity of the map. The developed localisation algorithm strongly relies on the geometrical information of railway tracks. As the testing activity was done under real conditions in a daily-operated network, construction and maintenance works were undertaken during this period. Consequently, the infrastructure manager had to maintain the track database. And with this, different perspectives of actuality and validity of the representation materialized. An effect in the testing activities and especially in the live demonstration was that the

train drove on a track that the map data was not aware of. The issues have been addressed in D4.10 [R9], and recommendations provided.

Provision of route information

Route information, such as the provision of the expected single connected series of track edges ahead of a journey, would heavily simplify the complexity of a localisation algorithm. The functionality of track selectivity is then obsolete and safely solved by the trackside. The information is available in the interlocking, which is responsible for setting the switches. The open issue is an open interface from the interlocking through the radio block center (RBC) to the train. The technical challenge is seen as much simpler to provide this information to the train instead of a SIL4 track-selectivity module as part of the on-board localisation. This request needs to be placed towards the EU-Rail System Pillar.

5.8.4 LOC-OB System requirements

The recommendations described in this section are intended for railway operators aiming at defining system requirements for a localisation on-board system.

Size of speed CI

The requirement SpecSysReq[009] of CLUG 2.0 [R1] regarding the speed CI has been formulated more restrictively compared to the TSI requirement [R5] without clear rationale. The outcome of the analysis activities documented herein has shown that this hardened requirement was difficult to fulfil. Therefore, the recommendation is to rely on the TSI definition of the speed CI in follow-up activities. This recommendation is already considered in D21.2 R2DATO System requirements of ASTP System [R14].

Accuracy and CI of the distance around the operational surrounding stop

The requirements defining the distance accuracy (1.25 m) SpecSysReq[005] and maximum acceptable CI (10 m) SpecSysReq[003] for specific surroundings were difficult to fulfil by the LOC-OB algorithm, and testing was limited due to the undefined areas of applicability of the requirement. It is therefore recommended to formulate the requirements in the simplest and most unambiguous manner possible. Note, that the corresponding requirement FP2-ASTP-SRS-038 in D21.2 R2DATO System requirements of ASTP System [R14] has been relaxed to +/- 5m.

6 CONCLUSION & DISCUSSION

This analysis report presents the key findings from the analysis and testing of the LOC-OB performance based on the requirements defined in CLUG2.0 [R1].

The analysis is performed on the LOC-OB output created in post-processing based on real sensor data gathered on the Domino test train over a number of 10 trips (see chapter 4) which were chosen by the test team. These trips feature different environmental conditions, from favourable (no tunnels, no dense urban area) to very challenging (Gotthard lines, Zurich city centre). While all 10 trips were processed using the standard configuration featuring EGNOS DFMC, 3 of those 10 trips have been processed using different configurations featuring Track selectivity and EGNOS DFMC+PR+PV, allowing a performance comparison between these configurations (see chapters 5.1.3, 5.2).

The conducted analysis shows that the LOC-OB performs adequately for its intended purpose, with most of the key requirements either fulfilled or nearing fulfillment (see chapter 5.7).

The CLUG2.0 requirements [R1] defining the distance accuracy and confidence interval at operational surrounding «Stop» remain demanding. It could be observed that the distance accuracy is not correlated to the vehicle speed, therefore, the distance accuracy does not systematically increase when the vehicle speed decreases.

Although the requirement defining confidence interval for speed in [R1] is not met, the corresponding requirement defined in SUBSET-041 [R5] relevant for ETCS application is fulfilled for almost 94% of the samples (see chapter 0).

Even in challenging environmental conditions such as on the Gotthard lines (Trip 73 and 77) and through the city center of Zurich (Trip 79), the LOC-OB still performs according to today's railway operational needs, as shown by the cumulated distribution of distance and speed error (see chapter 5.5.3):

- 95% of the samples present an error of around 5 m for the surrounding «Stop» and 7.5 m for the surrounding «Open».
- More than 95% of the samples have a speed error below 0.25 m/s.

Rare isolated events were identified in which the distance or the speed error were not bounded by the confidence interval (0.252 % of the samples for the distance, 0.175 % for the speed, refer to chapter 0), however the deviations were always very small and lasted few seconds. Associated root cause(s) could not be clearly identified in all cases; it could come from LOC-OB sensor data FDE not excluding properly invalid data or undetected cumulative errors on both LOC-OB 1D estimates and computed Ground Truth.

By implementing the recommendations outlined in chapter 5.8, it is expected that the LOC-OB performance can achieve the level specified in the CLUG2.0 requirements [R1].

7 REFERENCES

Ref ID	Document ID	Title / Source	Version	Date
[R1]	CLUG2.0 D2.4	D2.4 LOC-OB System Requirements	2.0	05/03/2024
[R2]	-	Test and Analysis list (internal CLUG2.0)	latest	latest
[R3]	CLUG2.0 D5.2	CLUG2.0 Raw Data (internal CLUG2.0)	1.0	28/07/2025
[R4]	CLUG2.0 D4.7	Confidence intervals computation & integrity algorithm design document (internal CLUG2.0)	2.0	12/09/2024
[R5]	SUBSET-041	ERTMS/ETCS Performance Requirements for Interoperability	4.0.0	05/07/2023
[R6]	CLUG2.0 Test Plan	D5.2.2 TEST PLAN (internal CLUG2.0)	1.3	27/06/2025
[R7]	CLUG2.0 D3.7	CLUG LOC-OB System Evaluation Report	2.0	04/06/2025
[R8]	DOC130724827	iNAT-RQT-4001 / -4002 / -4003 Datasheet https://www.imar-navigation.de/downloads/NAT_RQT_400x_en.pdf	Rev 2.39	15.02.2024
[R9]	CLUG2.0 D4.10	On-board Digital Map Definition and Interfaces	2.0	28/02/2024
[R10]	RINEX	IGS Formats and Standards, available at https://igs.org/formats-and-standards	-	-
[R11]	-	Artykbaev, A. T. (2025). An Optimal Method of Determining the Railway Track Plan. Sustainable Development of Transport. Springer. https://link.springer.com/chapter/10.1007/978-3-031-88846-5_2	-	2025
[R12]	-	General requirements for the competence of testing and calibration laboratories. (03 2018). DIN EN ISO/IEC 17025:2018-03. Springer.	-	03 2018
[R13]	-	Han, Z. N. (2025). Overview of the Application of Optimal Location Technology in the Field of Railway Construction. AIAT 2024. Springer. Von Springer:	-	2024



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		https://link.springer.com/content/pdf/10.1007/978-981-96-3977-9_21.pdf		
[R14]	D21.2	Rail to Digital automated up to autonomous train operation D21.2 – System requirements of ASTP system	08	15/11/2024



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