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Stand Alone Fail-Safe Train Positioning Demonstrators: Prototypes, Developments, Analysis and Test Report

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1 Executive Summary

This document contains the overall positioning results of the demonstrators carried out in the frame of WP7 of X2RAIL-5. The document provides an overall analysis and data interpretation of each of the demonstrators whose detailed studies are part of the annexes of this document too.

The objective of this work is to demonstrate by different levels of dissemination the feasibility usage of GNSS based algorithms for safety applications. Each partner has led its demonstrator with the system requirement specification [1] in mind.

The WP7 has work on a methodology whereby standardised interface is defined to disclose the results for both Algorithm Output (AO) and Ground truth (GT). It has also developed common scripts to be able to present the work result in a harmonised manner. Finally, both speed and absolute position has been analysed in detail under different circumstances.

The document present preliminary results with promising performance from all demonstrators where Confidence Interval for 3σ values vary from 20 m to below 5 m whenever the conditions are appropriate. The interesting part though is the high diversity on sensors proposed by each partner which leave the room open for improvements and more cost/effective solutions.

In conclusion, WP7 has fulfilled all its objectives and contributes with its results to the railway community in the hunt of the system requirements definition of the future localisation system. However, despite the results presented here, some limitations on the number of analysed trips is considered and it is advisable to perform further research increasing the number of trips and scenarios.

2 Table of Contents

2.1 Table of Figures

2.2 Tables

3 Abbreviations and acronyms

Abbreviation / Acronyms	Description
Absolute Position	Absolute position refers to a position that defines the train location unambiguously. For instance, an absolute position can be given by WGS84 coordinates but it can also be given by a track identifier and the travelled distance from a reference point within a specific track.
AO	Algorithm Output
CMD	Cold Movement Detector
CI	Confidence Interval refers to a range of values so defined that there is a specified probability that the value of a parameter lies within it.
COTS	Commercial off-the-shelf
DFDC	Dual Frequency Dual Constellation
DFMC	Dual Frequency Multi Constellation
DOF	Degree Of Freedom
EDAS	EGNOS Data Access Service
EKF	Extended Kalman Filter
E_ODO_TS	Enhanced odometry Track Side.
E_ODO_OB	Enhanced ODOmetry On-board.
ESSP	European Satellite Services Provider
ETCS-OB	European Train Control System - On-board
FA	Fusion Algorithm (TD and SNCF term) as being a function of the Safe Fusion Algorithm
FSTP	Fail Safe Train Positioning
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GT	Ground Truth, as a definition of the absolute true position of the train
IGS	International GNSS Service
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LRBG	Last Relevant Balise Group
MEMS	Micro Electro Mechanical System
NA	Not Available
OPG	Odometer Pulse Generator (with wheel turning direction)
OSM	OpenStreetMap, the free wiki world map
POI	Point of Interest
RTK	Realtime Kinematic (with GNSS Carrier Phase Ambiguity Solution)
segment_id	For 1D-positioning segment identifier from digital map. In CLUG also referred as TrackEdgeId.
SBAS	Satellite Based Augmentation System
SFA	Safe Fusion Algorithm
SFTP	Stand-Alone Fail Safe Train Positioning System
SiS	Signal In Space
spoke	edge (representation of a track segment in digital map)
SRS	System Requirement Specification

Train Consist	a set of vehicles comprising cabs and other attached vehicles that define the complete train length.
WAS	Wheel Angular Speed
WIG	Wheel Impulse Generator

4 Background

The present document constitutes WP7's Deliverable D7.3 "Stand Alone Fail-Safe Train Positioning Demonstrators: Prototypes Developments, Analysis and Test Report". The Deliverable is part of the framework of the Project titled "Completion of activities for Adaptable Communication, Moving Block, Fail safe Train Localisation (including satellite), Zero on site Testing, Formal Methods and Cyber Security" (Project Acronym: X2Rail-5; Grant Agreement No 101014520).

5 Objective / Aim

The aim of this document is to report the data analysis and interpretation of the results obtained by the demonstrators in the framework of WP7. In this report three demonstrators with different dissemination levels are presented, where multiple track lines and scenarios have been covered by trains running in in France, Germany and Spain. The proposed algorithm in all three demonstrators are not the same but they all respect the architecture inputs defined in [13].

The detail data analysis and interpretation of the results of each demonstrator are documented as annexes to this document which also belong to this deliverable. This methodology has been used to allow parallel work of different partners whose evolution on the development phase has had different pace.

6 Introduction

6.1 Demonstrators Context

In this report the reader will find the data analysis and interpretation of the performance of different demonstrators from WP7. Recall from [1] that these demonstrators aim to estimate train's position and speed for safety critical applications using GNSS. In the following illustration from the architecture in [13], it is shown the Safe Fusion Algorithm (SFA) functional block which has been the aim of the demonstrators on this work-package. Not all demonstrators have achieved the full performance of the system but they all have algorithms running and a ground truth from which the algorithm performance can be analysed. Further details on demonstrators can be found in [16]

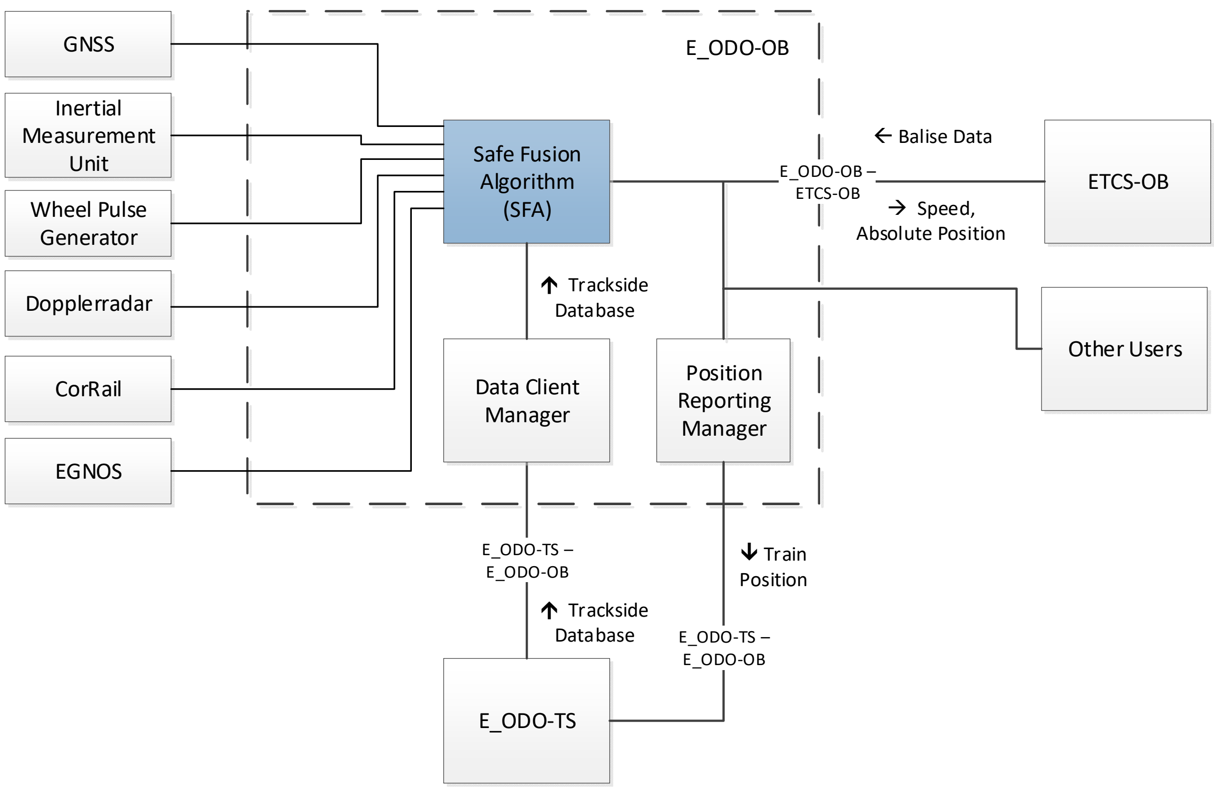

Figure 6-1 Architecture definition of Fail-Safe Train Positioning

6.2 Analysis methodology

All demonstrators have their algorithm output and ground truth information stored on a standardised file format as defined in [16]. The actual description of the Algorithm Output (AO) and the Ground Truth (GT) generation is explained case by case as seen in section 7. On one hand, the algorithm output from one company to others differ in their target. SNCF does not tackle the issue of track discrimination whereas TD and CAF have made algorithms which are able to detect switch points and even track discrimination. Similarly, the methodology to generate the GT is different as CAF has used balises, speed sensors and digital maps to perform the ground truth whereas TD has used RTK based systems to perform their ground truth. SNCF uses a high-grade IMU coupled with post-treated GNSS data and odometry, all feed an offline software to optimize Data Fusion (backward, forward and combination treatment).

In addition, for all demonstrator common scripts have been developed and shared with the partners. This has allowed performing cross checks, common understanding of the statistical values used to report performance and harmonisation on the result dissemination. These scripts also allow to detect points of interest on a trip where the performance of the algorithm may need to be looked in more detail. For example, whenever the Confidence interval does not bound the error value.

Each demonstrator has identified the journeys where the trains have been running. Then for each journey there could be one or more trips. For each trip three major sections have been identified, Trip Conditions, Speed Analysis and Position Analysis. In all cases, the algorithms are based on more or less on filter proposal where the uncertainty or confidence interval is expressed by a statistical value. In this report, it has been decided to use sigma multiplied by 3 as an standardised output for the Confidence Intevarl (CI) representation. This value is only for reference as it may differ on the final target of the application. In addition, SRS limits for both speed and travelled distance have also been added to the analysis in order to provide other work packages such as WP5 with valuable information when defining standardised requirements.

6.2.1 Trip Conditions

The trip conditions section is aimed to describe general conditions of the trip such as the weather conditions, trip duration, kilometres run or with a general plot from where the train has been running from. An example of the type of information that can be found is shown hereafter:

Length /km	Station / Terminal	Line Abbr.
0	**Weiden** (Oberpfalz)	NWDO
80,6	Martinlamitz	NMLZ
86,9	Oberkotzau	NOKP
92,5	**Hof** Hbf	NHO
175	Neumark (Sachsen)	DNM
181,3	Werdau Bogendreieck Neumarker Spitze	DWBN
181,9	Werdau Bogendreieck Zwickauer Spitze	DWBZ
182,6	Steinpleis	DSPH
184,8	Lichtentanne (Sachsen)	DLI
186,8	**Zwickau** (Sachsen) Hbf Stw B13	DZW C

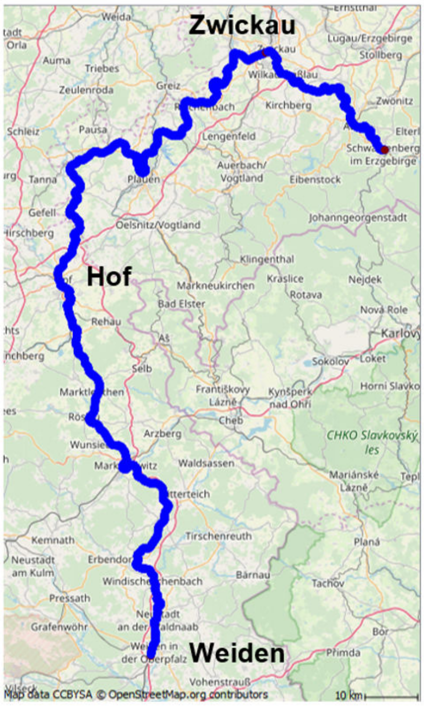

Figure 6-2 Trip description example figure

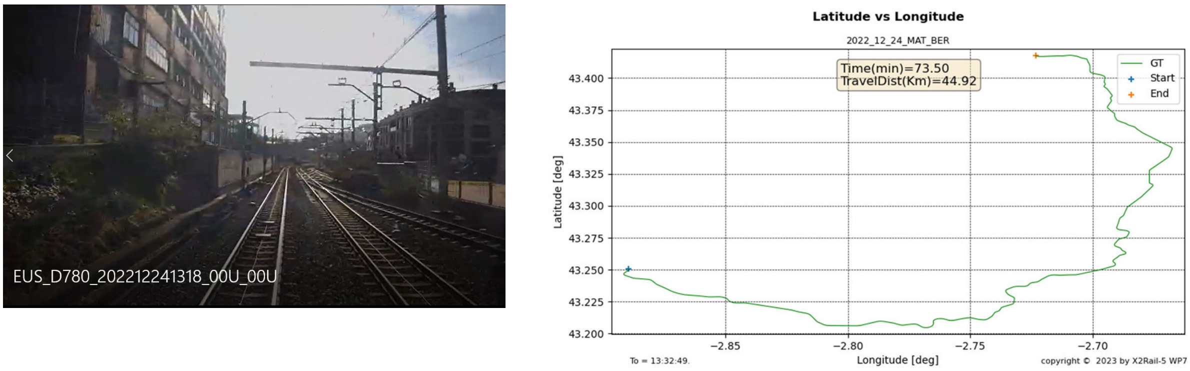

Figure 6-3 Trip weather conditions evidence and overall trajectory representation example

6.2.2 Speed Analysis

Speed estimation and confidence intervals from the AO are compared against the GT. Depending on the required detail sometimes the error difference and the CI are shown. Some examples are shown hereafter. On one hand, Figure 6-4 illustrates the overall absolute speed performance over the trip. On the other hand, Figure 6-5 represent the speed error value calculated. The figure also includes the CI values as well as the SRS expected values. Notice that Figure 6-5 is shown only as example as zero speed error is not realistic. Whenever the speed error exceeds its CI the common developed tools provides a CSV file with details of each of the times the exceedance occurred. Similarly, each time the SRS is not met by the CI value then another CSV file is generated. An example table for CI exceedance is shown in Table 6-1, where the time range refers to the duration of the exceedance persisted, max speed error is the maximum speed error encountered at this time range, the mean value of the CI and the travelled distance within the time range.

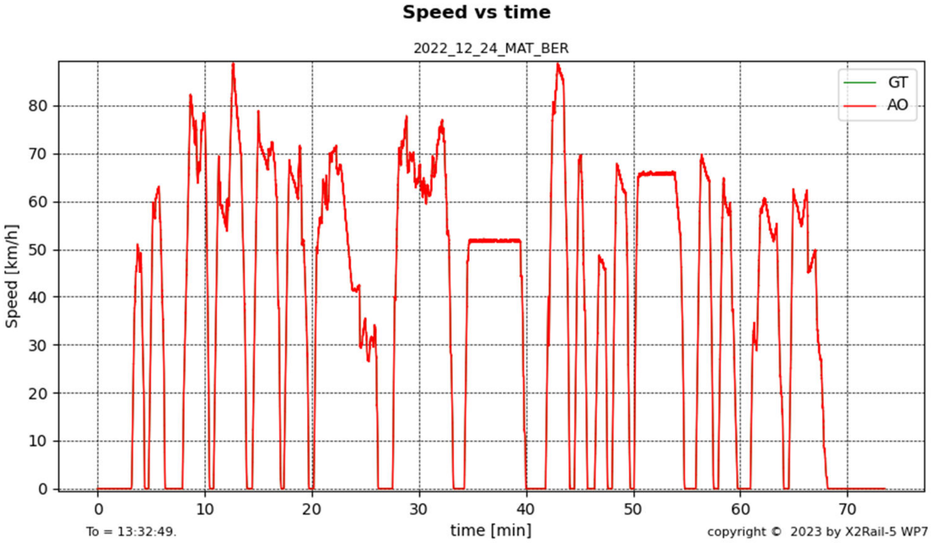

Figure 6-4 Speed representation example

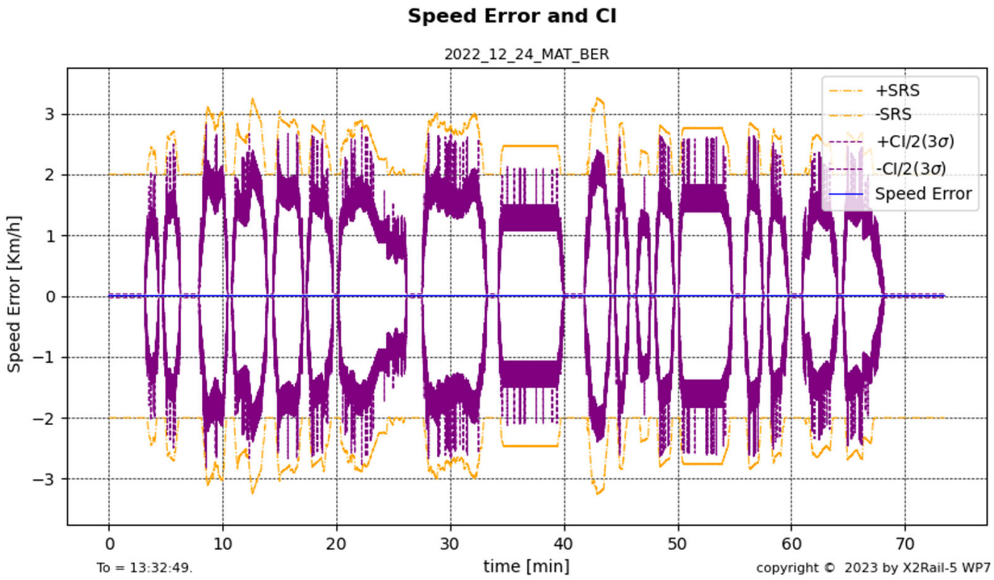

Figure 6-5 Speed Error representation example

Time / UTC	Time Range / sec	Max Speed Error exceeding CI/ km/h	CI Mean in Range / km/h	Traveled Dist in Range / m
09:50:01	35	0,03	0,00	-0,02
09:50:38	52	0,03	0,00	-0,04
09:51:32	555	7,96	0,00	-29,43
10:00:49	311	9,85	0,00	81,58
10:06:02	45	0,03	0,00	0,00
10:06:49	115	0,03	0,00	-0,07
10:08:46	74	0,04	0,00	-0,19
10:10:02	27	0,02	0,00	0,20
10:26:21	8	29,94	0,00	66,83
10:49:21	1	0,04	5,37	5,55
10:50:27	1	0,18	6,28	4,41
10:52:15	1	14,56	5,44	6,02
10:59:14	1	1,96	5,51	5,99
11:00:06	1	1,51	8,05	3,39
11:04:52	1	13,38	7,00	5,64
11:08:29	1	12,66	5,29	6,23
11:12:34	1	2,40	5,82	4,26
11:12:39	1	0,53	6,05	7,60

Table 6-1 CI of 3σ exceedance example by the speed error.

6.2.3 Position Analysis

The position estimation is based on the travelled distance from the start of the segment of the AO against the GT. A segment is defined as the minimum track section entity which is limited at least by switch points or track end point. There are two cases here to consider. The analysis based on a single-track demonstration as carried out by SNCF or segment based travelled distance as done by CAF and TD. The former creates a unique segment out of the whole route of the train avoiding any calculations for track discrimination or switch points, whereas the latter uses track segments as defined by the operator. This distinction makes the analysis for each case a bit different as the jumps occurred from segment to segment need to be considered in the latter case.

Whenever multiple segment analysis is carried out the reader may encounter the following type of illustration, see Figure 6-6. The illustration shows the travelled distance from the beginning of the segment ID for both GT and the AO. In addition, the vertical lines represent the segment changes for both the GT and AO. Each vertical line has a different dotted line to distinguish then. In Figure 6-6 it can be seen how the GT vertical lines comes in first because they define the moment where the train has changed segment ID whereas the AO vertical lines comes always after the GT's vertical line as it is a representation of the same segment ID change but from the AO point of view.. In this example the first part of the graph there is AO available and therefore AO is set to zero whereas the GT shows some valid data. Then, the algorithm provides a solution that is often simillar to the GT value and therefore the figures overlaps both values but only AO value can be seen. this type of figures lead to a problem when representing the error analysis of the travelled distance because whenever there is not a AO valida value or the moment the segment changes, high errors may be encountered in the analysis, but they do not represent the reality. For instance, Figure 6-7 is the illustration of the travelled distance error, where the values are as high as 4000 at the point of segment changes because GT information describes its positions as new segment Id and zero travelled distance whereas the AO is still represented the position with the old segment id and a large travelled distance.

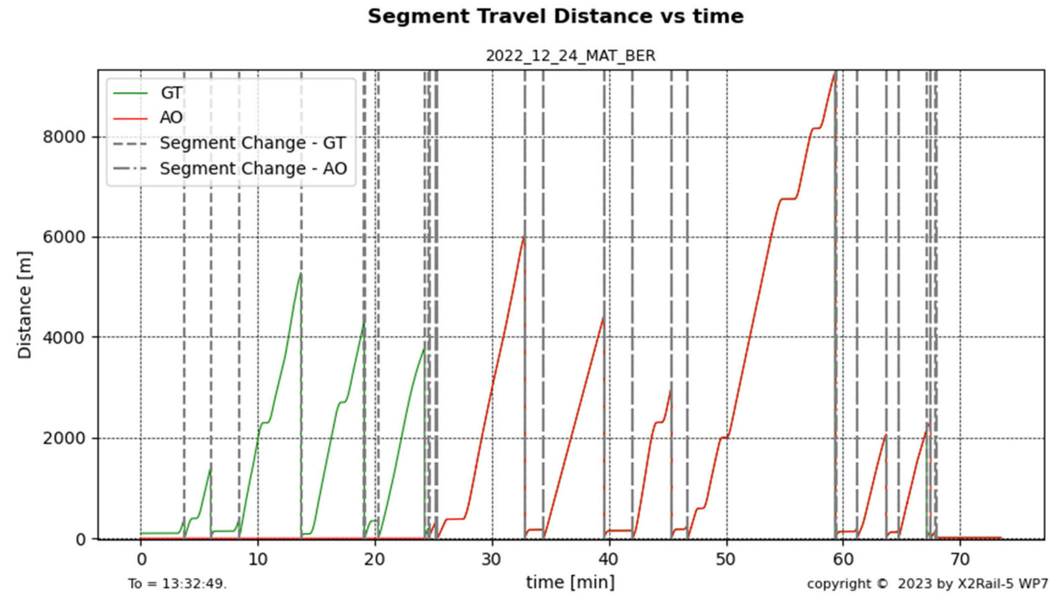

Figure 6-6 Segment travel distance crossing segments example

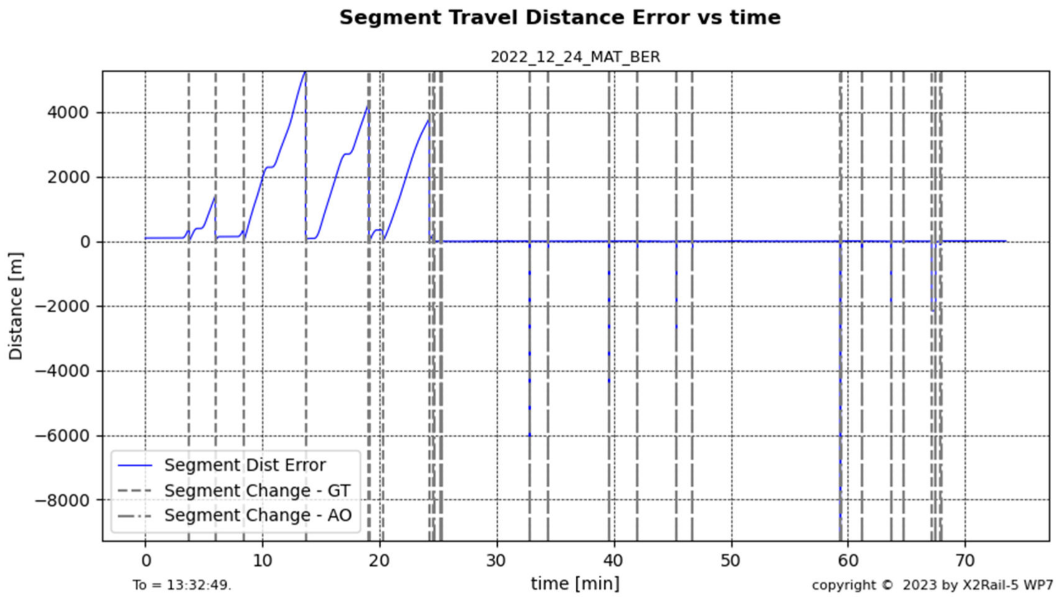

Figure 6-7 Segment travel distance error crossing segments example

To avoid misleading information, in WP7 it has been decided to analyse also the cases where the segment id values are equal for both GT and AO. The other intermediate points are left to the switch point or start of mission analysis. This type analysis allows us to focus on the performance of CI and SRS values within the segment leading to some interesting results. In Figure 6-8, it is shown a segment travelled distance error whenever both segments of the GT and AO are the same. The illustration also shows the CI and SRS expected values, which facilitates on a visual look to understand the performance of the trip. Furthermore, the analysis tool also provides CSV type table to identify the cases in which the CI has been exceed by the segment distance error and whenever the CI exceeds the SRS values. It is important to understand that in these figures the segment ID change is considered as a reset point for the SRS which is not a direct comparison of the performance against ETCS type value as they are not based on the distance from balise group. Nevertheless, WP7 has decided to use this methodology because not all partners based their GT information on balises and therefore this comparison cannot be carried out. Still, considering that the segment ID's is the minimum entity that defines a track section it ensures that there will be a new segment ID at least at every switch point which essentially a resetting point for the ETCS to know continuously where the train is.

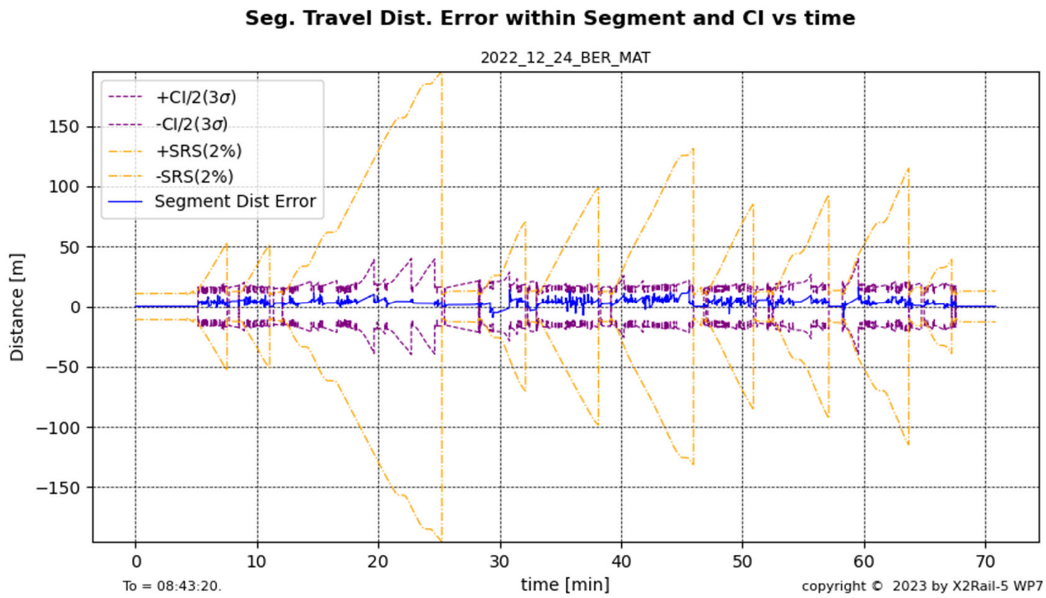

Figure 6-8 Segment travel distance error within a segment example

The following two tables, Table 6-2 and Table 6-3, represent the summary table examples extracted from one of the trips. On one hand, Table 6-2 shows the time at which the Segment distance error is greater than the CI, the time range or time duration for which this exceedance has occurred, the maximum difference under the window of exceedance that has been recorded, the mean value of the AO CI within the exceedance window and the travelled distance within the exceedance window. On the other hand, Table 6-3, shows the time at which the CI is greater than the SRS value as defined in [1], the time range or time duration for which this exceedance has occurred, the maximum difference under the window of exceedance that has been recorded, the mean value of the AO CI within the exceedance window and the travelled distance within the exceedance window.

ExcedenaceIdx	**UtcTime(sec)**	**TimeRange (sec)**	**MaxDiff(CI (3σ)-SegErr)(m)**	**CIMeanValInRange(m)**	**TravelDistOnRange(m)**
0	1671887028	0.064	1.307	13.59	1.099
1	1671887755	0.064	1.469	13.815	1.559
2	1671888405	0.032	0.984	11.67	0.583
3	1671889220	0.064	3.139	11.715	0.48
AVERAGE	n/a	0.056	1.72475	12.6975	0.93025
MAX	n/a	0.064	3.139	13.815	1.559

Table 6-2 CI exceedance by the Segment Error example table

ExcedenaceIdx	UtcTime(sec)	TimeRange(sec)	MaxDiff(CI(sigma3)-SRS)(m)	CIMeanValInRange(m)	TravelDistOnRange(m)
0	1671886650	11.968	4.818	15.657	105.398
1	1671886662	10.272	3.16	16.156	97.982
2	1671886673	7.744	1.237	16.28	66.991
3	1671886685	7.424	5.3	15.303	56.661

4	1671886692	12.544	5.441	15.662	108.714
5	1671886705	2.24	2.789	14.944	19.294
6	1671886707	16.224	4.939	17.615	138.822
7	1671886724	4.128	2.701	18.144	37.299
8	1671887141	94.72	17.298	25.687	197.568
9	1671887236	27.808	8.816	18.236	371.083
10	1671887547	145.184	21.607	27.682	193.273
11	1671887693	24.832	25.563	31.331	352.501
12	1671887894	81.568	31.01	37.925	273.954
13	1671887975	3.744	36.976	25.087	46.717
14	1671887979	13.12	5.142	16.251	173.163
15	1671887993	4.704	1.191	15.78	62.534
16	1671888734	108.288	22.056	27.663	173.284
17	1671888842	14.912	4.975	13.979	141.057

18	1671888857	14.016	4.447	17.58	132.825
19	1671888872	3.328	1.019	16.537	40.764
20	1671888992	61.376	13.33	22.783	145.903
21	1671889054	15.104	16.544	17.07	201.295
22	1671889069	2.688	1.402	15.527	46.296
23	1671889072	1.472	0.422	15.531	25.103
24	1671889076	4.224	1.818	18.615	70.936
25	1671889081	0.704	0.144	18.473	11.767
26	1671889220	21.632	5.868	15.328	111.925
27	1671889247	332.577	6.698	16.108	9.07
AVERAGE	n/a	37.44803571	9.16825	19.3905	121.863536
MAX	n/a	332.577	36.976	37.925	371.083

Table 6-3 SRS exceedance by the CI example table

In addition, in the position analysis is common to find dedicated tools plots for GNSS or IMU or INS data analysis to understand and explain the outliers or error reasoning. Figure 6-9 shows an example of GNSS satellite information whereas Figure 6-10 shows an example of IMU performance where the raw yaw rate values from IMU reading are illustrated against the theoretical yaw rate values obtained from the multiplication of digital map curvature values and speed values.

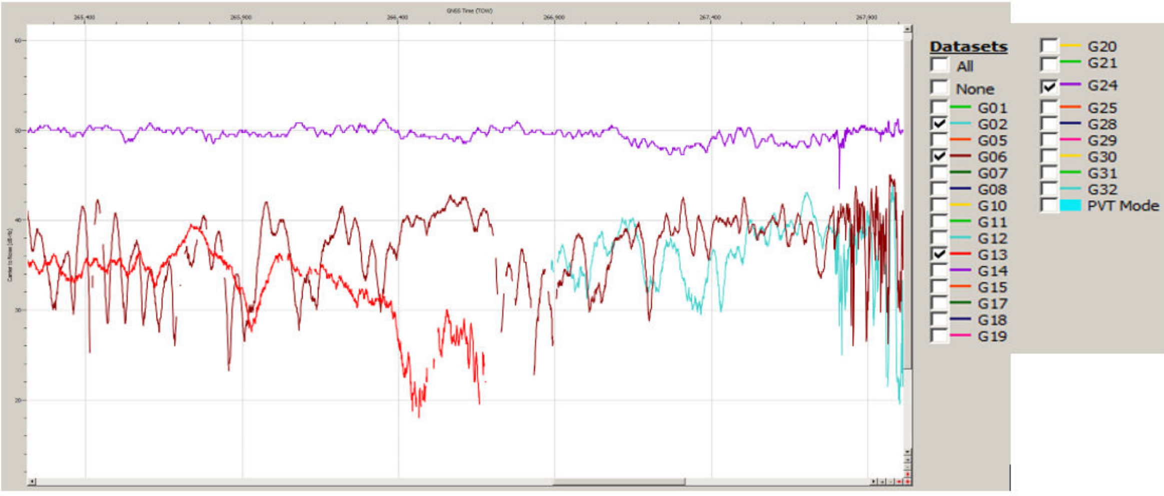

Figure 6-9 Signal To Noise ratio for GNSS example

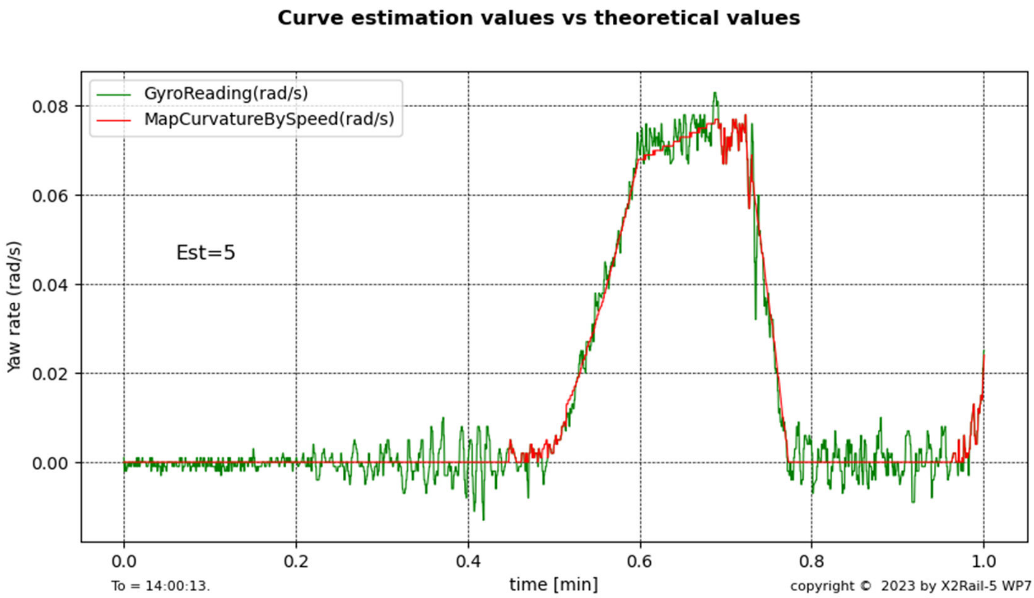

Figure 6-10 IMU values against theoretical curvature example

Finally, whenever a trip is analysed the operational test scenarios defined in [16] have been considered as points of interests. Although not all cases have been covered, many of them has been encountered by each demonstrator.

7 Analysis

In the following subsections the reference to each demonstrator detail analysis can be found.

7.1 CAF Analysis Report

The reader is invited to read [17] to learn from the analysis from CAF.

7.2 SNCF Analysis Report

The reader is invited to read [18] to learn from the analysis from SNCF.

7.3 TD's Analysis Report

The reader is invited to read [19] to learn from the analysis from TD.

8 Discussion of the results

In section 7 the reader has been redirected to the detailed analysis of each of the demonstrators. In summary, WP7 has analysed 8 journeys as shown in Table 8-1. For each journey one or more trips are analysed, and this table shows the overall distance and environmental conditions for each of them.

Journey	Dist/Km	Environmental information
Matiko-Bermeo	45	Combination of Urban Aera with multiple track, trees, tunnels, section with single tracks.
Bermeo-Matiko	45	Combination of Urban Aera with multiple track, trees, tunnels, section with single tracks.
Weid-Anabg18	186	3°C, cloudy, light rain GNSS GT, FA with IMU, Radar
KKB-NS220302	21	10°C, dry, sun Dual Chain, Switch Resolution Tunnel passing
KKB-NS220706	60	22°C, dry, slightly cloudy Dual Chain, Switch Resolution enhanced
KKB221117	13	10°C, light rain & heavy rain
Toulouse - Foix	93	Open environment, mainly in the countryside with few tunnels. Weather : sunny day, clear sky, mild temperatures
Foix - Latour de Carol	80	Open environment, mainly in the countryside with some tunnels. Weather : sunny day, clear sky, mild temperatures

Table 8-1 Journey table summary

Due to the different budgets and company interests, each demonstrator has had a different focus within the Fail-Safe Train Positioning algorithm to demonstrate different parts of the whole system. It is therefore unfair and dangerous to compare conclusions from all of them.

CAF and TD has targeted for real time applications whereas SNCF has provided post-processing performance. SNCF has used EGNOS v3 information whereas CAF and TD has used EGNOS v2 as it is from the SiS. TD has shown a redundant architecture whereas CAF uses an approach to match curves to a map. All these differences have been collected on Table 8-2.

	CAF	SNCF	TD
Type Solution	Real-Time	Post-Processing	Real-Time
GNSS receiver	DFDC	DFDC	DFDC
EGNOS	Via SiS (integrity bit only)	V3 (post processing)	Vía Sis (full v2 corrections)
IMU	6DoF (low grade)	6DoF(high grade)	2x6DoF(medium grade)
Speed Sensor	Impulse based Sensor(1 Driving axle and 1 Trailing Axle)	Impulse based Sensor (1 Trailing Axle)	Radar
Digital Map	Yes, with curvature information (vector based)	Yes, discretised every 10 m (point based)	Yes, HD map, discretised every 1 meter
Cost	Low Cost	High Cost	Medium Cost
Analysed Kilometres	~292	~180	~60
Track discrimination	Yes	No	Yes

Table 8-2 Differences from all demonstrators

Finally, not all demonstrators have run on the same train nor use the same set-up and therefore the conclusions of each of the demonstrators shall be interpreted individually.

The variety of solutions within the same technology with their different performance is indeed a desirable option for the industry to ensure that there is room for the future safe train positioning as a black box where its supplier has the freedom to choose from as long as the minimum performance values are guaranteed.

8.1 Highlights from the demonstrators

As a consequence of the experience gained from this project the following highlights have been identified out of the demonstrator's analysis:

1. Different types of fusion algorithm structures have been presented for absolute and along the track positioning.
2. Start of mission without the usage of balises has been analysed by CAF solution with different performance values depending on the track geometry.
3. Both CAF and TD have provided an analysis on track discrimination with different performance results.
4. Safety apportionment is differently handled by each demonstrator.
    a. TD: provides a dual chain FA architecture solution
    b. SNCF: provides a solution based on EGNOS V3 with prototyped integrity algorithms.
    c. CAF: provides a solution where the yaw rate from IMU is used to match with the digital map information to provide integrity of the algorithm.
5. GNSS disturbances have been analysed for static cases, dynamic situations with and without large disturbance areas. Static analysis has been carried out in more detail by TD whereas SNCF have shown detailed plotting of the satellite receiver signals. In the case of CAF, a more qualitative analysis is carried out for comparison between a conservative GNSS algorithm solution against COTS solution.
6. SBAS has been used in all solutions, where CAF and TD has used EGNOS v2 from the SiS and SNCF has introduced an emulator for EGNOS v3 whose corrections have been used in the fusion filter as well as integrity filter to compute the CI.
7. Speed analysis has been carried out with the exception from CAF demonstrator whose speed analysis has been limited.
8. IMU has been used as a navigation sensor in both SNCF and TD solution whereas CAF solution focuses on the yaw rate information. In any case, the IMU has become a key sensor in all solutions whose performance enhances the overall FSTP solution.
9. All SFA solutions have used Digital Map information, but its contents and usage has been different. SNCF has based on discretised map with GNSS information for every 10 m and a map matching technique to find the most likely position estimation. TD defines a High Definition (HD) map discretised every 4 m which the algorithm can interpolate using splines to get the best position estimation. Finally, CAF uses a continuous map with a maximum error of 5 m in curvature which can be interpolated to obtain the match between the yaw rate and the map information to define the best position estimation. Overall, any map matching based solution precision depends upon the precision on the map itself and therefore any assumption and requirement to the map will need to be agreed on between the partners.

9 Conclusions

All demonstrators have reached their goals within WP7, presenting their developments and analysis for the Stand-alone Safe Train Positioning solution. The demonstrators have shown results on speed and position analysis including along track position, track discrimination and switch point cases. The results include the calculation of the confidence interval which already provides a hint on the capabilities on performance of the algorithm. Furthermore, some preliminary analysis of the proposed solutions against the SRS performance requirements are disclosed too, which may be of use for the future common FSTP solution under discussion on X2RAIL5 - WP5.

WP7 has also developed a methodology to commonly analyse the performance of multiple solutions by defining common scripts. This tool allows a common view on the different demonstrator analyses to the reader. It also helps to ensure, that all partners have the same understanding of each concept.

It is worth to highlight that all three demonstrators have chosen a common technology set up based on GNSS receiver, IMU sensor, speed sensors and digital map. EGNOS has also been used by all three demonstrators with two major differences. On one hand CAF and TD have used EGNOS as information from signal in space and on the other hand SNCF has introduced an emulator for EGNOS version 3 and the use of these corrections for the CI computation in the integrity filter.

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9.1 Conclusions of each demonstrator.

In the following subsection the conclusions from each demonstrator is copied here to facilitate the readers overview of WP7. As stated before, not all demonstrators have run on the same train nor use the same set-up and therefore the conclusions of each of the demonstrators shall be interpreted individually.

9.1.1 CAF analysis conclusion taken from [17]

In this report, CAF's algorithm performance is shown for X2RAIL-5 WP7 demonstrator. The report has extensively analysed four trips out of two different journey types. The analysis has been **focused on** positioning where the **start of mission**, **along track precision**, **passing switch points** and **sensor disturbances** at a place such as tunnels, bridges and bad line of sight effects have been considered. Position information is analysed in both manners, either by using segment identifier plus travelled distance within a segment or by 3D position based on WGS84 ellipsoid. In this report an issue with independent speed sensor for Ground Truth has been reported and therefore speed analysis is not complete.

The algorithm presented by CAF **does not use any supporting information from trackside** except the digital map, to prove its performance: there is no dynamic route information and no augmentation information received from trackside.

In this report, **GNSS**, the **vertical gyroscope**, **speed information** for the relative travelled distance and the **digital map** have been used to perform a map matching technique **to ensure a safe train positioning**. The positioning challenge can be divided into two main problems, the start of mission for the first position fix and the retention of track discrimination once the train is positioned for the first time even if it has crossed multiple switch points. For each of the trips both cases have been analysed

Despite the limited number of trips shown in this report some meaningful conclusions can be extracted from the algorithm analysis:

1. The **mean of the CI** along the track position has reached to **+/- 20 m for a 3 σ** probability.
2. **Track discrimination is guaranteed** on a real time application using GNSS.
3. Once the train is positioned, **Switch Points are detected and handled** so that the position on track is retained.
4. Start of Mission procedure reaches to a first position fix although **the time for this first position** fix is **dependent on the geography** as known by design.
5. All cases where the error has exceeded the CI last not more than a few seconds.
6. **SRS performance limits exceedance** are followed by an average **pattern** whereby the **average error of the exceedance is set to 20 m** instead of the 10 m suggested in [1].
7. The algorithm has shown **great resilience against any GNSS disturbances**, including multipath and loss of line of sight due to tunnels or any other environmental condition.
8. The **digital map has played a key role** in achieving a resilient algorithm, and it has proven that the curvature information of the track is indeed a source for positioning. However, the precision of the curve profile in the digital map can limit the performance of the overall result. In this demonstrator it is assumed an SRS value of +/-5 m which has a direct impact on the +/-20 m of the CI obtained.
9. The statistical data of the trips have shown that the algorithm performance is good, but the detailed exceedance may need to be looked at in detail to understand what caused the error and potentially improve the algorithms or ground truth calculations.
10. The proposed solution is based on low-cost sensors such as tachometer, low cost IMUs and COTS GNSS receiver and low precision digital map, leaving room for improvement should any of these sensors/inputs be changed to a higher-grade.

9.1.2 SNCF analysis conclusion taken from [18]

The overall performance observed through the two journeys presented in SNCF report can be considered as very good. However, this algorithm is only a prototype so far, and therefore conclusions from this evidence may be limited. As a fact, computed errors should be backed up with the corresponding confidence interval whose values presented here are only preliminary. Nevertheless, the introduction of EGNOS V3 even in post-processing is already an achievement for the results which clearly needs improvements to make a more robust solution and correct some of the observed behaviors.

The filter behavior during the initial static phase has to be improved to allow a quick convergence of the filter once the train starts moving.

For attitude, the Fusion Algorithm can achieve good performances but:

- The Yaw error drifts during static phase, immediately followed by transitions to converge,
- Roll and pitch errors are sometimes biased. The identified root cause for the pitch is the misalignment estimation which would need to be optimized. Other underlying root causes will have to be identified.
- The attitude error variation can be reduced by improving the GNSS error noise model and the GNSS FDE's.

For the speed along track error, both scenarios first and second, provided good results:

- means are close to zero (-0.0113 m/s for first scenario against -0.0016 m/s for second scenario)
- RMS are small (0.0529 m./s for the first scenario, 0.0611 m/s for the second scenario).

To conclude, positioning performance along track are good:

- The precision for first scenario is 1.62 m at 99.7%,
- The precision for second scenario is 2.8 m at 99.7%, including the period where the train is in a tunnel.

However, on some occasions, the position error exceeds these statistics. Urban environment (rail station or tunnels) can be identified as reasons, but the next points need to be clarified:

- Position management if the train is stand still is not always efficient (the error can go up to 7 m without any movements),
- Algorithm tuning for position error to prevent the error to surpass the CI (3σ).

Several areas for future improvements have been identified:

- Improve the initialisation, notably when it is made during a static phase (before filter's convergence),
- Improve the filter behavior (position, velocity and attitude) during any static phase after filter's convergence,
- Improve measurement error modelling and the associated FDE's to make the filter more robust to avoid local divergence,
- Improve the pitch and yaw misalignment estimation to avoid the small observed attitude offsets.

Besides, some areas were identified as complicated sections for the navigation solution. An identified root cause (not the only one) is the GNSS reception quality and the environments that signals must go through. To provide a deeper analysis of the filter behavior, the rail environment would need to be better characterised (multipath, SNR, etc). Moreover, the behavior of the WIG sensor should also be studied with respect to the train dynamics as well as environmental conditions.

9.1.3 Thales analysis conclusion taken from [19]

1. SFA dead-reckoning performance using IMU, radar and digital map for track constraint (but without GNSS) provides already robust positioning after getting an initial position.
2. Results of the tests in **adverse GNSS reception** environment with high mask angles (shaded sky), reflective obstacles and wet wood are clearly discriminated compared to benign test line environment like a deep horizon (open sky) and fields with flat vegetation.
3. **Ground Truth** generation **by a pure GNSS Receiver**, (even with RTK) is not sufficient in GNSS reception critical environment - as TD's test track on KKB Line.
4. For 1D positioning the CI better covers the true error than the CI for speed.
5. Errors exceeding CI (**feared events**) is trapped and mostly occurs only within small intervals (up to 15s).
6. The Speed **CI often exceeds** the new SRS Limit of 2km/h **for low speed** (like on KKB Line at 25km/h).
7. Due to **visualization of the measurements** several abnormalities have been detected. Their cause analysis will give the chance for algorithm enhancements.
8. Sophisticated Fault Detection and Exclusion (FDE) on the sensor data streams to the SFA and on Algorithm Output provide the chance for enhancing safe outputs of position and velocity in adverse environment.
9. Introducing **post processing of GT** with fusion of RTK GNSS Rx and high grade IMU helps to clearly identify the Algorithm Output errors. This will enhance proofing the achieved AO performance.

9.2 Lesson learnt from the project:

- Larger number of kilometres and on different railway lines may provide a better statistical basis for defining more reliable performance limits.
- The three solutions have been running on different trains and different railway lines. Therefore, the solutions cannot be compared in equal conditions. Future

research projects should consider to either use common data sharing of the sensor data to do post processing analysis or the same train for all systems should be used to be able to perform a fair comparison.

- The procurement of the demonstrator on a train may take up to a year from the beginning of the process which means that an early start with the train set-up is crucial to avoid possible delays on the test campaigns.

- If the digital map is not given by the operator, the responsibility is of the demonstrator to generate it. The generation of this information is complex, and the effort should not be underestimated. Also, errors due to incorrect, missing or obsolete data during running the demonstrator should be expected.

- For the process of demonstrating the performance, the Ground Truth generation by a pure GNSS receiver, is not sufficient if the coverage of GNSS is poor.

- Standardised interfaces from the beginning of the project is important to avoid unexpected missing or incorrect data from the demonstrator information.

10 References

[1] X2R2 D3.8 Stand Alone System Requirements Specification for Fail-Safe Train Positioning V 06

[2] X2R2 D3.9 System Architecture Specification and System Functional Hazard Analysis for Stand Alone Fail-Safe Train Positioning V 05

[3] X2R5-JWG-I-HRI-008-01_-_ESSP-TN-26038_01 - 00_SBAS_L1_Guidelines_Rx_Rail_trackside.pdf

[4] X2R5-JWG-I-HRI-010-01_-_ESSP-TN-26137_01 - 00_SBAS_DFMC_Guidelines_Rx_Railway_Trackside_Unit.pdf

[5] CLUG D2.2_operational_scenarios_v2.4

[6] X2R5-T7_3-M-SNR-009-01_-_Operational_Scenarios_X2RAIL5.xlsx

[7] X2R5-T7_3-T-SNR-004-03_-_SNCF_Demonstrator_Description.docx

[8] X2R5-WP07-I-DBA-001-01_-_X2R5_Demonstrator_SMO_ADS_DB_2022013.docx

[9] X2R5-T7_3-T-THD-003-01_-_DemonstratorDescription_TD_v5.docx

[10] X2R5-T7_3-T-CAF-002-02_-_CAF_Demonstrator_description.docx

[11] ERA, Report ERTMS Longer Term Perspective, 18/12/2015.

[12] STARS project. D5.1 - State of the art of EGNSS projects for the rail application, STR-WP5-D-IFS-033 (IFSTTAR - 21/03/17)

[13] X2R2-TSK3.10-D-CAI-001-02 - Architecture Specification for Stand-Alone Fail-Safe Train Positioning, Version 03

[14] X2R5-T7_3-T-CAF-006-03 GT file format

[15] X2R5-T7_3-T-CAF-007-02 Algorithm Output Format

[16] X2R5-T7_3-D-CAF-008-03_-_D7_2_DemonstratorsDesc_and_TestScenarios

[17] X2R5-T7_5-T-CAF-010 – CAF's demonstrator technical analysis attached to this document.

[18] X2R5-T7_5-T-SNR-021 – SNCF's demonstrator technical analysis attached to this document.

[19] X2R5-T7_5-T-THD-009 – TD's demonstrator technical analysis attached to this document.