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1 Executive Summary

This document contains the large-scale analysis of multiple train runs over the same two journeys carried out on CAF demonstrator.

The objective of this work is to understand the error repeatability patterns that may occur on a large-scale analysis in a positioning algorithm. The research carried out in this document has followed the same methodology as the one used in [5], where over 20 trips with more than 900km are analysed.

The results show that large-scale analysis can be beneficial for debugging and maintenance purposes where systematic errors could be encountered. In addition, the proposed algorithm by CAF presented a predictive behaviour as its dependencies on GNSS events are very limited.

In conclusion, a large-scale type analysis has been found to be a recommended analysis to be done in future projects.

2 Table of Contents

2.1 Table of Figures

2.2 Table of 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.
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	EGNOS Satellite Service Provider
ETCS-OB	European Train Control System - On-board
ETS	Euskotren Trenbide Sareak
FSTP	Fail Safe Train Positioning
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GT	Ground Truth
IGS	International GNSS Service
IMU	Inertial Measurement Unit
LRBG	Last Relevant Balise Group
LSE	Least Square Error method
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.
SFTP	Stand-Alone Fail-Safe Train Positioning System
SOM	Start Of Mission
spoke	edge (it refers to the 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 the first issue of WP7's Deliverable D7.4 "Results of a broader statistical evaluation on a dedicated commercial line for error repeatability analysis". 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 objective of this document is two-fold. On one hand, the speed analysis related to CAF's demonstrator on [5] is completed using radar-based speed information, although not crucial for pure positioning estimation comparison, it corroborates the proposed algorithm runs as expected. On the other hand, increasing the number of analysed trips, to determine by large statistical analysis if there is any performance issues to be reported back to the system requirement specification.

6 Introduction

This document is based on a CAF demonstrator whose description and main outcomes for the positioning algorithm can be found in [5]. CAF's algorithm is based on GNSS receivers, IMU sensors, digital maps, and wheel speed sensors to produce a safe algorithm based on an IMU and curvature map-matching methodology. This algorithm has proven to be successful over two journeys which are a combination of Urban Area, multiple tracks, trees, tunnels, and sections with single line tracks. In the analysis provided in [5], the positioning algorithm is analysed for several trips with the limitation of not having an independent wheel speed sensor from the algorithm and the ground truth generation. This limitation came from a sensor installation delay but as proven in this document, it does not have a major impact on the overall performance values. Furthermore, the authors believed that taking a larger quantity of trips and analysing them allows for identifying potential error sources of the performance degradation.

In this document, the analysis is based on the same principles and methodologies defined in [5]. The analysis is carried out over the line of Matiko-Bermeo where we have over 20 trips analysed, since the completion of [5].

6.1 Short Summary of CAF Demonstrator from D7.3

CAF demonstrator's train is running over commercial lines and the line of Matiko Bermeo is taken as an example for positioning algorithm performance evaluation due to the multiple interesting cases that could potentially occur to a GNSS based positioning system. In the following Figure 1, the train hosting the positioning algorithm real-time application is shown.

Figure 1 Euskotren Electric Series 950 unit

The train trips are divided into journeys where each journey is described in the following Table 6.1:

:

ID	Journey	Dist.	Environmental information
CAF_J1	Matiko-Bermeo	44.92	Combination of Urban areas with multiple tracks, trees, tunnels, sections with single tracks.
CAF_J2	Bermeo-Matiko	44.92	Combination of Urban areas with multiple tracks, trees, tunnels, and section with single tracks.

Table 6.1 – Journey types

For further details on the set-up, the reader is invited to read [5].

7 Analysis

7.1 Introduction

In the following analysis two subsections are considered. First, a single trip analysis which takes one set of examples of data from the demonstrator, including speed independent results, whereby the focus is on the performance values for travelled distance and speed values as well as in the methodology followed. Second, the overall statistical analysis is presented using the same principles shown in the single trip analysis but with a wider/broader statistical information. In this analysis, the GNSS or 3D position based analysis is not presented as it is a repetition of what is shown in [5] unless there is a relevant situation that may require to do so. What is further analysed though, is the performance on 1D position based on equal segment values between GT and AO data, similar to. Recall from [5] that whenever the Algorithm Output (AO) and Ground Truth (GT) are compared in 1D, they are compared using the segment identifier plus the travelled distance. Since the digital map has multiple segments, the difference between the AO and GT travelled distance has great spikes whenever there is a change on segment identifier which leads to an erroneous representation of the true distance error in 1D. For that reason in [5], the authors compared the travelled distance only when the segment identifiers of AO and GT are the same and analysed the track discrimination issue in a different subsection.

Since the closure of [5], in this analysis, 22 trips per journey are analysed, with over 968km run by the train generating both Ground Truth (GT) and Algorithm Output (AO) for each trip. This information is then analysed and presented hereafter. Recall from [5] that a journey is referred to a fixed geographical track section whereas a trip refers to the specific time and moment in which the train passed the journey. In other words, for each journey we may have one or several trips to be analysed.

7.2 Single trip Analysis

7.2.1 Trip Conditions

This journey covers the trip from Bermeo to Matiko. The following Figure 2 shows the weather conditions under which the trip is carried out, which refers to a cloudy day with no rain registered for the whole day.

Figure 2 Matiko Bermeo day image to show weather conditions.

The trip is summarised in the following two graphs. Figure 3, illustrates The first graph shows the overall trip trajectory as defined by the GT and Figure 4 and in displays the second, speed of the GT. This trip covered a distance of 44.81 kilometers within 81.61 minutes of recording.

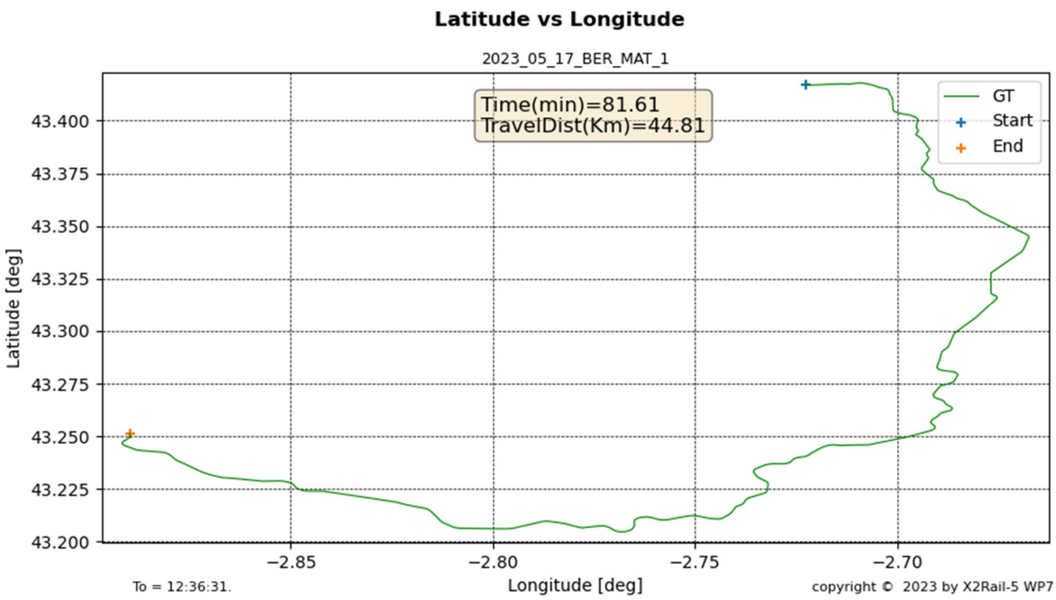

Figure 3 Journey trajectory plot based on Ground Truth information.

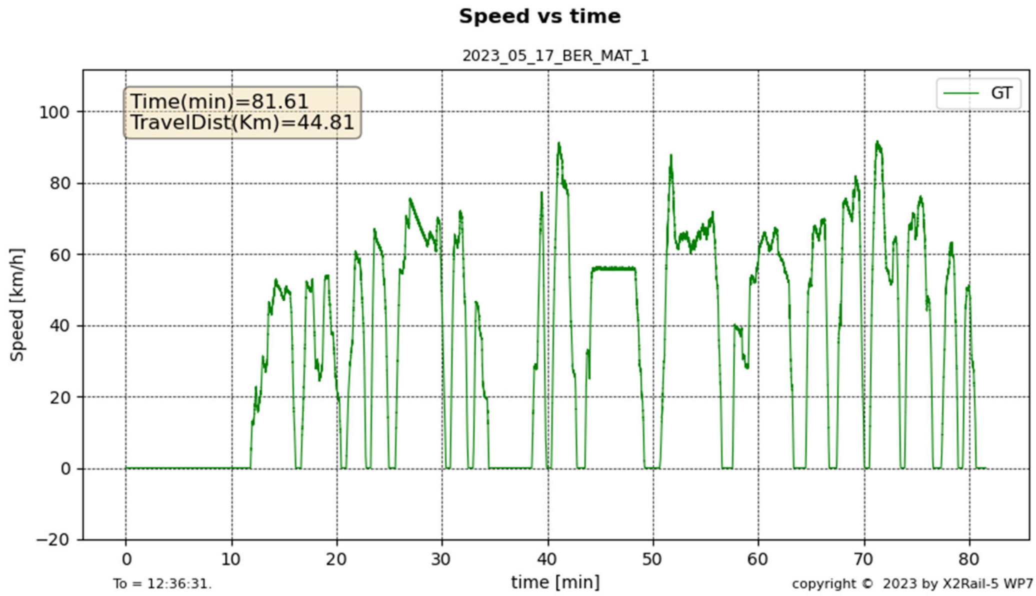

Figure 4 Journey Matiko Bermeo, id 1, trip 1 overall view on speed.

7.2.2 Data Analysis

7.2.2.1 Speed Data Analysis

7.2.2.1.1 Speed Performance

The following Figure 5 shows the speed value of the algorithm output AO over the analysed trajectory. As it can be spotted there are some differences that will be covered in the next sections.

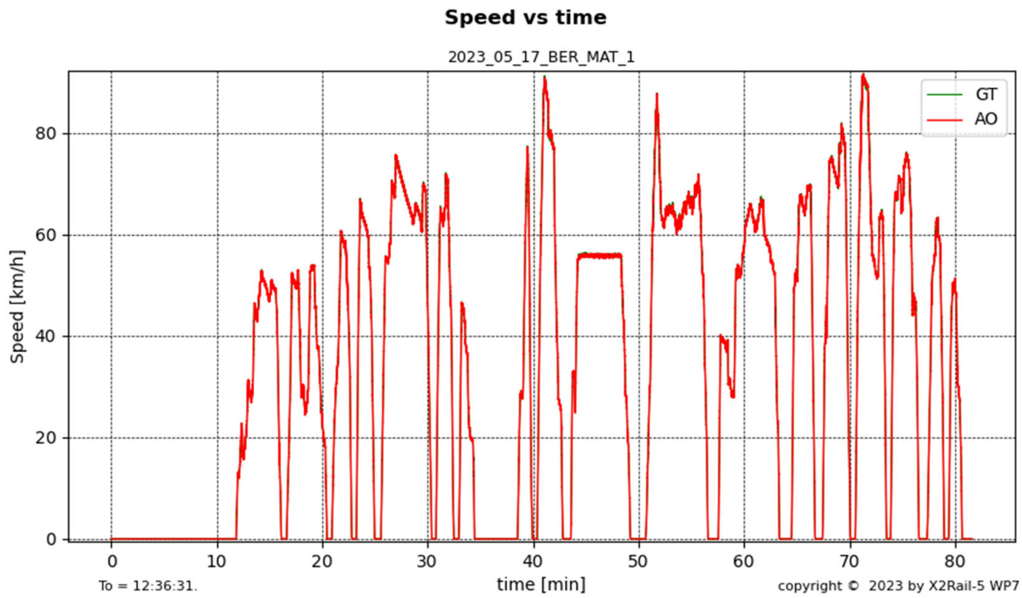

Figure 5 Speed Overall view for both GT and AO data.

7.2.2.1.2 Speed Error and CI value

The following Figure 6 illustrates the Confidence Interval (CI) value of the algorithm output with a 3 σ probability value. As it can be appreciated by a glance in almost all situations the error is well bounded by the confidence interval. The average and maximum values of speed error and CI values are summarised in Table 7.1. This table also shows 47 events in which the CI did not bound the speed error. These cases are then more deeply analysed in Table 7.2 where most of the exceedance cases are of 0.08 seconds long with a maximum error of 0.238km/h with respect to the CI.

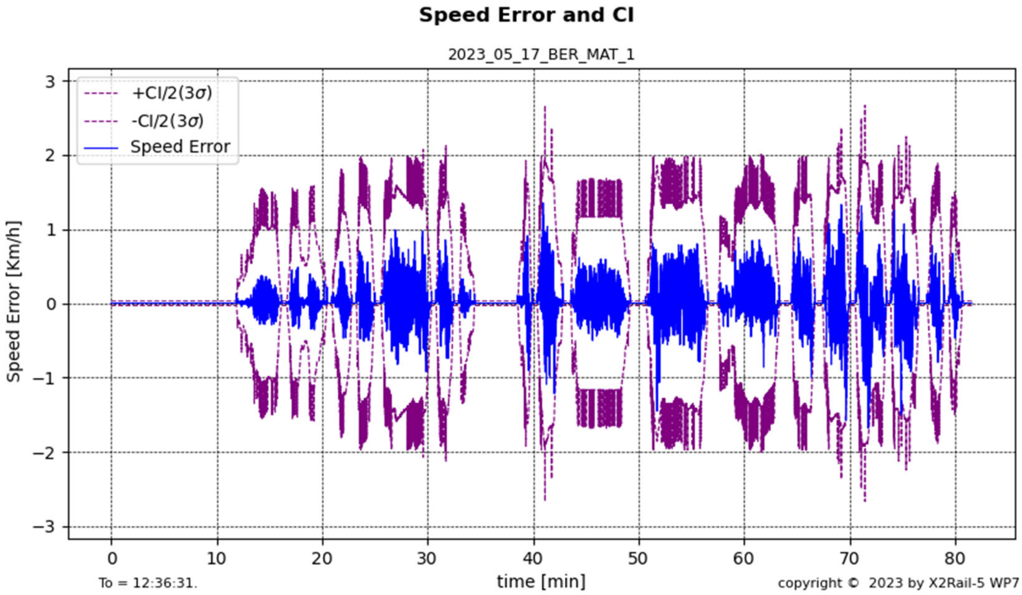

Figure 6 Speed Error figure with CI values.

Concept	Value
Speed Error Mean (km/h)	0.105
Speed Error Max Value (km/h)	1.681
CI (3 σ) Mean Value (km/h)	0.702
CI (3 σ) Max Value (km/h)	2.668
Number of times Speed Error exceeded CI value	47

Table 7.1 – Summary statistics of the trip performance for a speed

Exceedance ID	UTC Time (sec)	Time Range (sec)	Max Diff(Speed Err- CI (3 σ)) (km/h)	CI Mean Val. in Range (Km/h)	Travel Dist. on Range (m)
0	1684234103	0.032	0.101	0.032	0.01
1	1684234359	0.096	0.011	0.032	0.01
2	1684234360	0.096	0.086	0.032	0
3	1684234619	0.064	0.191	0.032	0
4	1684234647	0.128	0.065	0.032	0.04
5	1684234760	0.48	0.079	0.032	0
6	1684234786	0.128	0.115	0.032	0.05
7	1684234891	0.032	0.115	0.032	0
8	1684234927	0.032	0.068	0.032	0.01
9	1684234927	0.032	0.004	0.032	0.01
10	1684235214	0.032	0.13	0.032	0
11	1684235239	0.032	0.155	0.032	0.01
12	1684235239	0.032	0.004	0.032	0.02
13	1684235340	0.032	0.101	0.032	0
14	1684235369	0.128	0.09	0.032	0.03
15	1684235458	0.032	0.004	0.032	0
16	1684235458	0.48	0.097	0.032	0.01
17	1684235703	0.032	0.079	0.032	0
18	1684235703	0.032	0.004	0.032	0.01
19	1684235788	0.032	0.173	0.032	0
20	1684235814	0.032	0.104	0.032	0.01
21	1684235961	0.064	0.238	0.032	0
22	1684236006	0.096	0.148	0.032	0.04
23	1684236006	0.032	0.014	0.032	0.02
24	1684236346	0.096	0.09	0.032	0
25	1684236431	0.032	0.061	0.032	0
26	1684236786	0.032	0.13	0.032	0
27	1684236846	0.032	0.112	0.032	0.011
28	1684237192	0.48	0.209	0.032	0.01
29	1684237262	0.064	0.104	0.032	0.02
30	1684237262	0.032	0.007	0.032	0.01
31	1684237396	0.064	0.169	0.032	0
32	1684237438	0.192	0.065	0.032	0.05
33	1684237571	0.096	0.166	1.415	1.777
34	1684237597	0.096	0.115	0.032	0
35	1684237625	0.096	0.14	0.032	0.052

Exceedance ID	UTC Time (sec)	Time Range (sec)	Max Diff(Speed Err- CI (3 σ)) (km/h)	CI Mean Val. in Range (Km/h)	Travel Dist. on Range (m)
36	1684237803	0.16	0.144	0.032	0
37	1684237825	0.032	0.14	0.032	0.01
38	1684237884	0.032	0.029	1.469	0.6
39	1684237885	0.032	0.058	1.436	0.58
40	1684237986	0.032	0.022	0.032	0
41	1684237987	0.032	0.191	0.032	0
42	1684238033	0.032	0.097	0.032	0
43	1684238130	0.032	0.22	0.032	0
44	1684238155	0.032	0.061	0.032	0
45	1684238155	0.032	0.011	0.032	0
46	1684238232	0.096	0.14	0.032	0
AVERAGE	NA	0.0864681	0.0990851	0.1218723	0.072340426
MAX Value	NA	0.48	0.238	1.469	1.777

Table 7.2 – Summary statistics of the exceedance of CI cases for speed

The following Figure 7 represents the detail of the maximum error found in Table 7.2, which refers to index 21 with a maximum error of 0.238 km/h. The plot is a zoom of 12 seconds, and the error occurs just at second 6 (0.1 minutes) when the train is stopped with a minor impact on the overall performance. Many of the cases analysed in the table are some minor speed differences and as a prove is the maximum travelled distance of 1.777 meters from Table 7.2 which means that the train has barely moved when the speed value was exceeded by the CI.

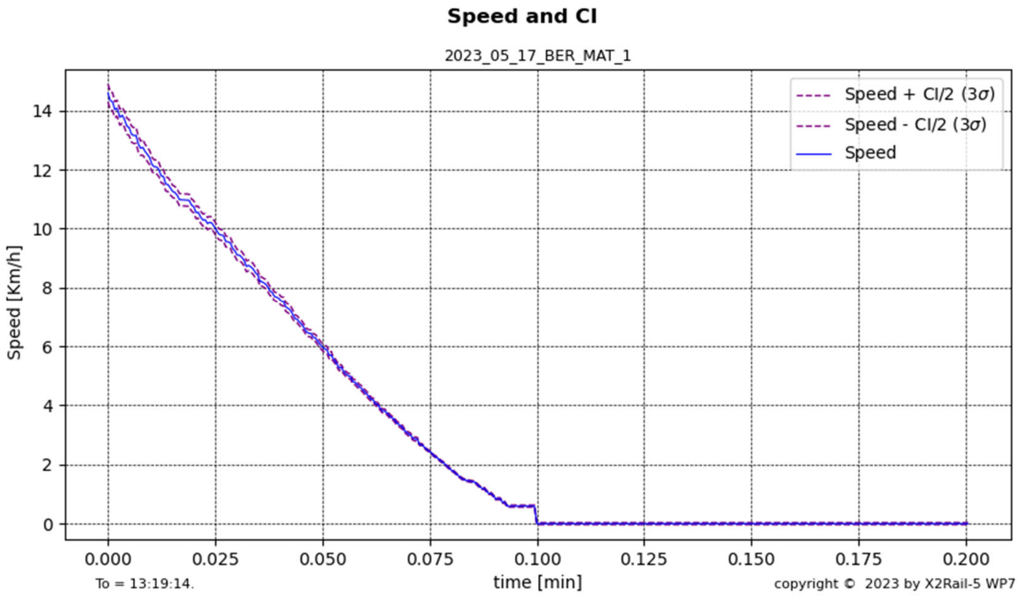

Figure 7 Speed Error CI exceedance detail.

In addition to the CI versus speed error analysis, speed values are also compared to System Required Specification (SRS) values in the following Figure 8. Recall the System Requirements Specification (SRS) values for speed are defined in [1]. In this case the yellow line represents the SRS, and it is never exceeded by the algorithm performance.

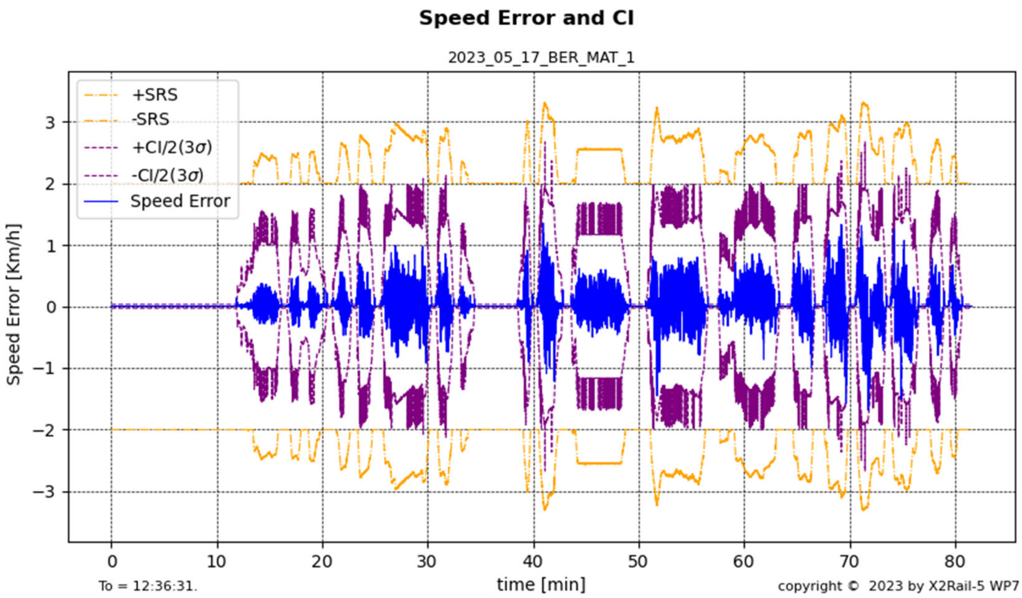

Figure 8 Speed Error performance with CI and SRS values.

7.2.2.2 Position Data Analysis

In the next plot the overall performance of the algorithm can be seen for Bermeo to Matiko journey. In this plot it is presented the GT position in terms of latitude and longitude against the algorithm output latitude and longitude values. As it can be seen from a first glance the algorithm is not able to obtain a valid position until the gyroscope information corroborates the initial fix point, which explains the red line coming from a 0.0 value of not positioned case to first position fix. This is a limitation on the plotting scripts as the status of the AO is defined as not valid, but it is not considered at plotting phase. Once the train is positioned, then the position of the train is never lost again. The reader is invited to read [5] to better understand the behaviour of the algorithm to understand the self the track discrimination algorithm performance as well as the details behind the performance over switch points.

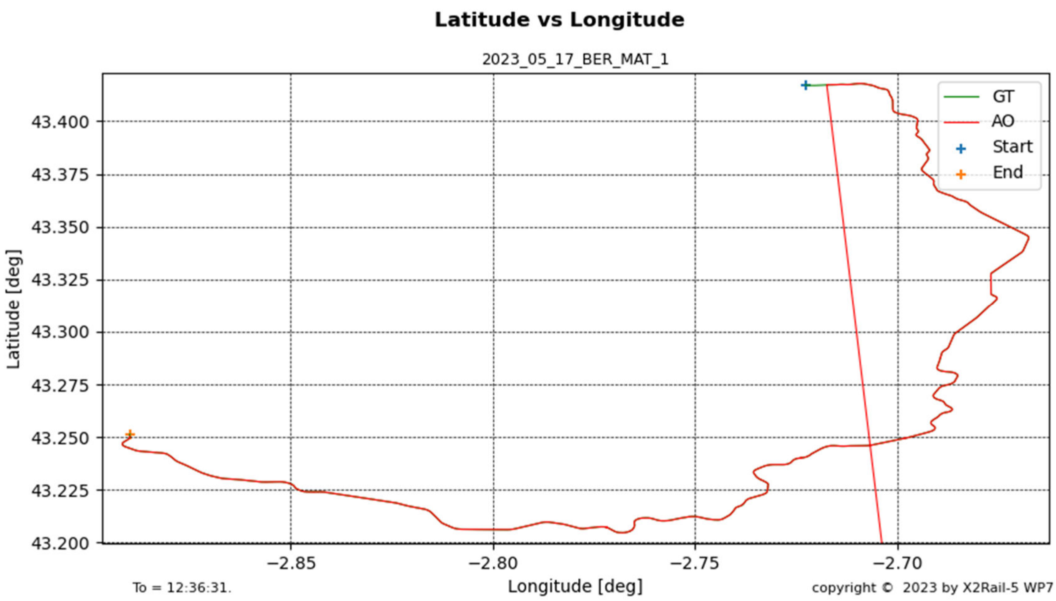

Figure 9 Overall Positioning performance of the AO vs GT.

7.2.2.2.1 1D Position Analysis

As explained in [5], the 1D position results are more meaningful when the AO and the GT are at the same segment identifier (segment id). It is therefore in the interest of this study to focus the details related to this case, as other cases are more related to track discrimination and switch points and those are well covered in [5].

In the following Figure 10 it can be seen the overall performance of the segment travelled distance whenever the segment id is equal to the ground truth segment id. The plot shows that most of the time the segment distance error is well bounded by the CI. In fact, only 3 time the CI is exceeded as summarised in Table 7.3. In addition, this table also shows the mean and the max error of the travelled distance which are in line to what it was already shown in [5], which corroborates that the speed independence does not influence much in the overall performance. Recall that in [5] GT speed and AO speed where both the same but in this analysis the speed information from the GT is based on radars whereas the speed estimation from the AO is based on the fusion algorithm considering tachometers and IMU data mainly.

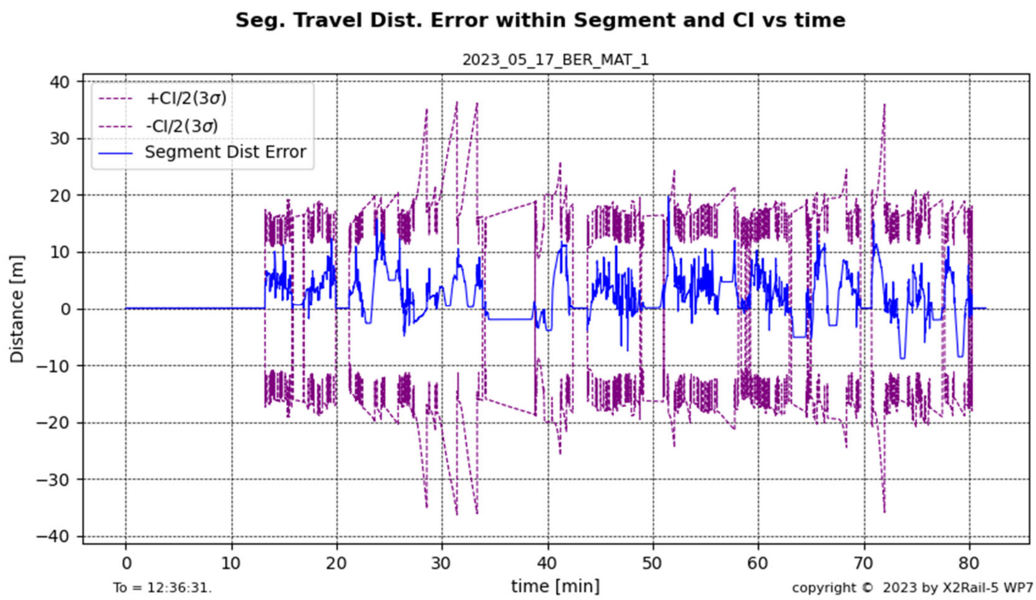

Figure 10 1D Position analysis of the whole run using only equal segment ID values.

Concept	Value
Segment Travel Distance Error Mean (m)	2.806
Segment Travel Distance Error Max Value (m)	19.694
CI (3 σ) Mean Value (m)	13.770
CI (3 σ) Max Value (m)	36.300
Number of times Segment Travel Distance Error exceeded CI value	3

Table 7.3 – Summary statistics of the trip performance for a 1D analysis

Exceedance ID	UTC Time (sec)	Time Range (sec)	Max Diff (Speed Err- CI (3 σ)) (km/h)	CI Mean Val. in Range (Km/h)	Travel Dist. on Range (m)
0	1684234821	0.128	2.136	13.32	2.281
1	1684236480	0.512	6.27	15.456	10.142
2	1684237647	0.16	2.422	12.036	2.883
AVERAGE	NA	0.2666667	3.6093333	13.604	5.102
MAX Value	NA	0.512	6.27	15.456	10.142

Table 7.4 – Summary statistics of the exceedance of CI cases for a 1D analysis

In the following Figure 11, it is depicted the detail of the maximum error found in Table 7.4. The plot shows the moment the segment error exceeds the CI value which occurs in a resetting point due to a curve repositioning. This could be either because the map is not well defined, a mismatch between the AO and GT synchronisation or an error in the algorithm. In the next section 7.3 with further recordings this type of errors is analysed from a broader perspective.

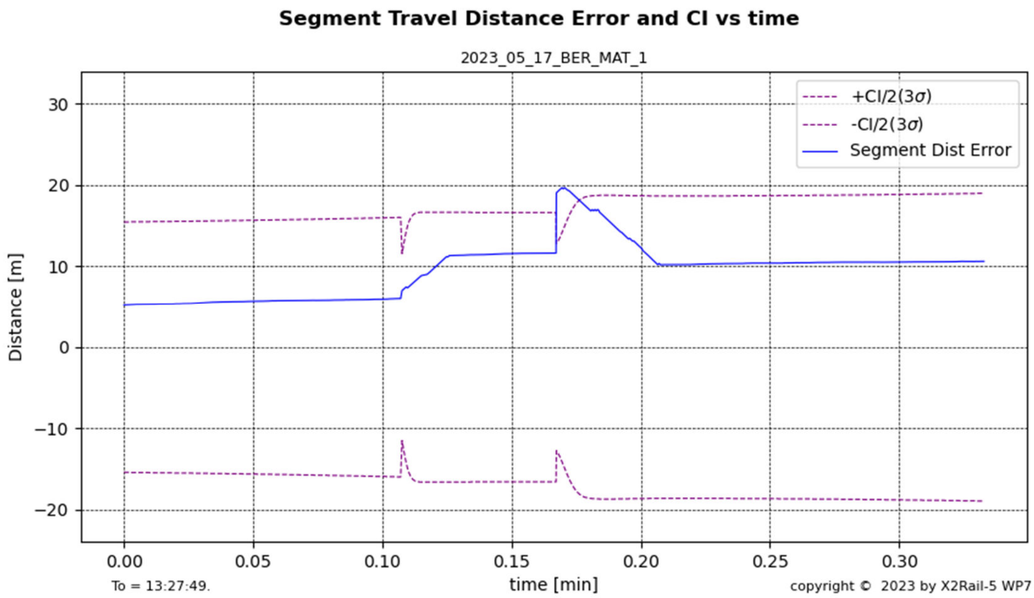

Figure 11 1D Position CI exceedance detail

Like the CI exceedance, the SRS exceedance is also analysed. Recall the System Requirements Specification (SRS) values for distance are defined in [1], which basically follows the formula of 10 meters plus 2% of the travelled distance from the segment ID. Notice that the exceedance of SRS itself is not a safety related issued but rather performance related issue. In Figure 12 it can be seen SRS line with a dash-dotted representation. For a more concise analysis, Table 7.5, summarises all the SRS exceedance cases, where time range, the maximum difference between the CI and SRS travel distance exceedance (see column MaxDiff(CI(3σ)-SRS)), the mean value around the exceedance of the SRS and the travelled distance within this time range are shown. The results are in line to what it is suggested in the conclusion of [5] where there is a maximum exceedance of 10.479m of the SRS and the values proposed as 10m + 2% may need to be revised.

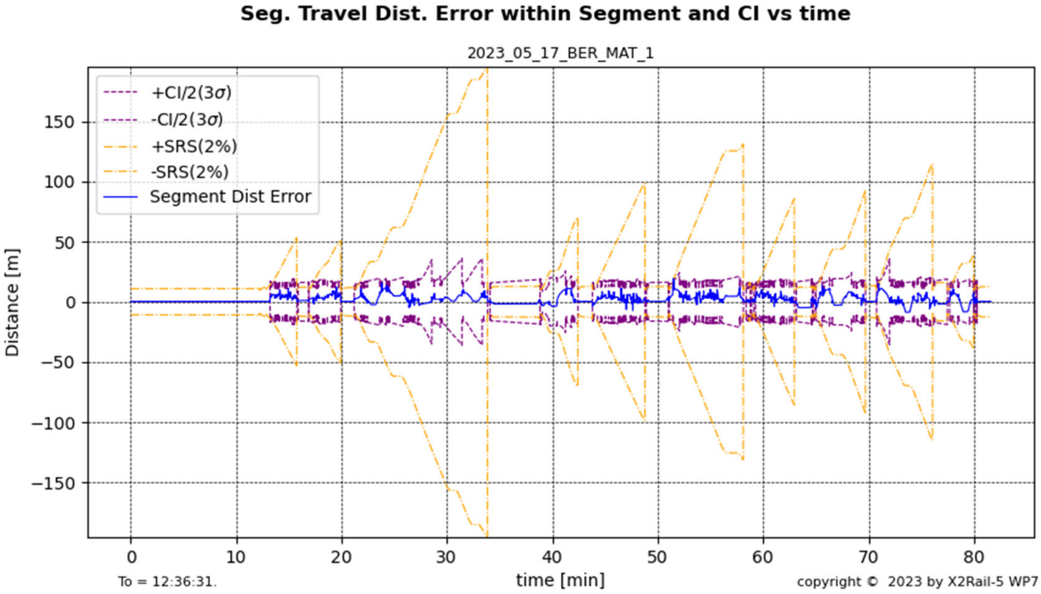

Figure 12 1D Position analysis of the whole run using only equal segment ID values including SRS values.

Exceedance ID	UTC Time (sec)	Time Range (sec)	MaxDiff(CI(3 σ)-SRS) (m)	CI Mean Val. in Range (m)	Travel Dist. on Range (m)
0	1684234185	3.232	3.276	17.37	24.8
1	1684234188	5.92	1.553	16.179	45.779
2	1684234194	6.112	1.038	16.595	52.701
3	1684234345	60.544	4.734	16.266	96.05
4	1684234406	26.432	6.472	16.952	320.21
5	1684234432	1.632	0.364	16.933	23.079
6	1684234663	4.288	4.33	14.407	31.744
7	1684234668	2.784	2.45	13.157	22.525
8	1684234671	1.824	3.896	14.96	15.423
9	1684234673	18.688	3.388	15.061	194.444
10	1684234691	0.032	0.001	15.42	0.439
11	1684235436	2.784	4.38	15.21	15.471
12	1684235439	282.017	5.733	17.329	170.647
13	1684235721	9.536	8.809	17.796	48.233
14	1684236020	7.072	6.301	15.836	64.405

Exceedance ID	UTC Time (sec)	Time Range (sec)	MaxDiff(CI(3 σ)-SRS) (m)	CI Mean Val. in Range (m)	Travel Dist. on Range (m)
15	1684236048	2.496	0.64	17.015	38.671
16	1684236327	2.688	3.95	15.27	16.18
17	1684236330	5.632	3.429	15.083	30.087
18	1684236335	116.064	3.909	16.325	88.588
19	1684236452	2.176	1.421	15.471	16.66
20	1684236454	21.888	5.398	15.33	295.332
21	1684236477	1.248	0.424	16.632	23.597
22	1684236480	2.56	0.931	18.64	51.95
23	1684236894	5.664	3.198	15.426	59.427
24	1684236900	11.296	2.281	15.949	96.664
25	1684236912	3.424	0.521	15.973	29.272
26	1684236926	2.464	4.936	15.715	19.835
27	1684236929	2.336	3.923	15.038	18.467
28	1684236931	8.64	3.864	15.448	75.754
29	1684236947	3.104	3.73	15.883	44.816
30	1684236950	5.056	3.808	16.825	74.088
31	1684236955	9.344	2.492	17.132	138.638
32	1684237180	89.056	6.718	17.508	80.409
33	1684237269	4.128	3.563	16.43	39.28
34	1684237274	5.92	6.429	16.567	76.803
35	1684237280	8.32	4.154	15.843	121.362
36	1684237292	21.088	5.32	17.309	364.269
37	1684237314	5.504	1.605	19.828	104.045
38	1684237637	9.952	10.479	17.406	150.495
39	1684237647	12.16	4.599	18.036	253.909
40	1684237955	11.488	10.219	18.762	155.922
41	1684237967	72.32	4.038	18.248	154.271
42	1684238052	7.616	4.504	15.959	92.003
43	1684238060	11.264	3.242	16.561	164.56
44	1684238072	0.384	0.092	16.818	5.81
45	1684238190	16.384	7.319	17.319	201.711
46	1684238206	2.016	7.703	17.04	17.16
AVERAGE	**NA**	**19.501638**	**3.9481702**	**16.431064**	**89.914574**
MAX Value	**NA**	**282.017**	**10.479**	**19.828**	**364.269**

Table 7.5 – Summary statistics of the exceedance of SRS cases for a 1D analysis

In the following illustration it is shown an example of the maximum exceedance of the previous table. In this illustration, index 38 from Table 7.5 has been taken. As it can be observed, the situation represents a segment change where the SRS value drops down to around 10 meters whereas the algorithm typically offers 20m CI value. Notice that the CI value at the moment the segment is changed is set to zero as part of the travelled distance analysis within a segment.

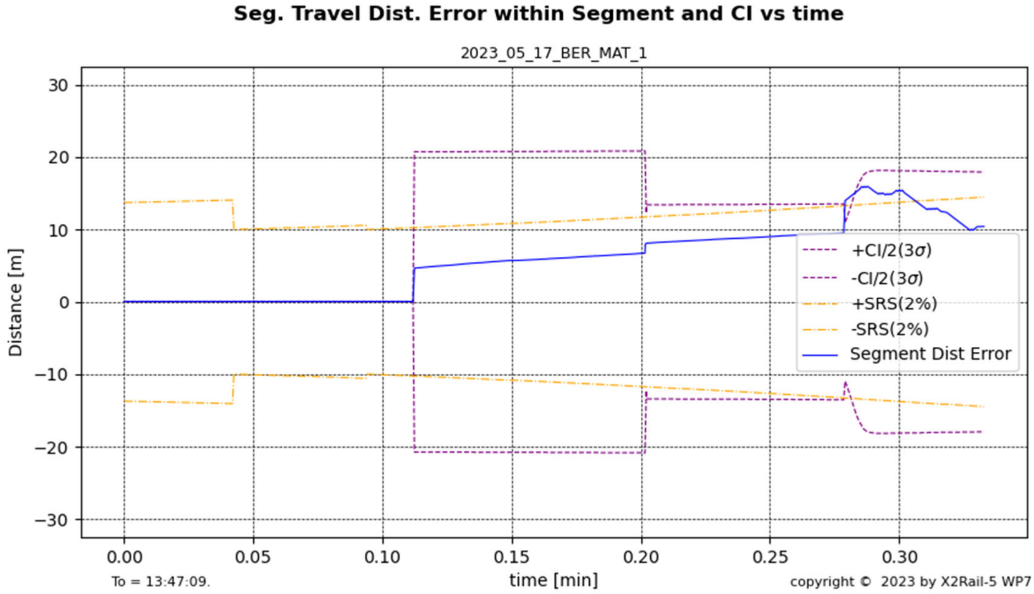

Figure 13 1D Position analysis, SRS exceedance of Index 8.

7.2.2.3 Observations/Discussion

In this trip, it has been shown a focused analysis on speed and travelled distance whenever the segment id from GT and AO are the same. Firstly, speed analysis shows the fluctuation of the speed confidence interval which is always within the SRS values and that the speed errors exceedances do not go beyond 0.238km/h for a time spam of 64ms. Secondly, the 1D position error have shown 3 times CI exceedance and 47 time of exceedance of SRS. These results are in line to what it is concluded in [5] where the average expected value of error with respect to the SRS proposal in travelled distance may need to be increased up 20 meters or so if this type of algorithm is put in place.

7.3 Multiple trip analysis

In the scope of multiple trip analysis, first each of the trips needs to be assessed individually. Once the analysis per trip is carried with the same methodology as shown in section 7.2, then an overall perspective can be tackled.

7.3.1 Overall Speed Analysis

For each of the trips the core statistical values are gathered in Table 7.6. The table presents the same data as presented for each individual trip as for example Table 7.1. Consequently for each trip it is defined the trip reference, as described in section 6.1, the Mean Speed Error, Maximum speed error, the CI value mean value, the Maximum CI value and then number of the CI value is exceeded by the speed error and the number of times the CI value exceeded the SRS values. The results from the table first show an average error of 1.541km/h for all trips and maximum CI value of 2.46km/h. In addition, the number of times the speed error exceeded the CI value has some outliers that need further analysed. Recall from section 7.2.2.1 that the exceeded values around 47 have shown little impact on the overall performance as they are errors that last around 64ms for a very little distance run. Finally, for all cases, the number of SRS values exceeded is zero, which means that the performance is as good as expected.

Trip Reference	Speed Error Mean (km/h)	Speed Error Max Value (km/h)	CI (3 σ) Mean Value (km/h)	CI (3 σ) Max Value (km/h)	Number of times Speed Error exceeded CI value	Number of times CI exceeded SRS value
CAF_J2_BM_05_17_1	0.105	1.681	0.702	2.668	47	0
CAF_J2_BM_05_17_2	0.106	1.21	0.696	2.095	1148	0
CAF_J2_BM_05_17_3	0.109	1.336	0.71	2.009	1189	0
CAF_J1_MB_05_17_1	0.109	1.584	0.779	2.398	863	0
CAF_J1_MB_05_17_2	0.078	1.04	0.786	2.225	45	0
CAF_J1_MB_05_17_3	0.14	2.128	0.755	2.549	890	0
CAF_J2_BM_05_30_1	0.126	1.994	0.805	2.7	1032	0
CAF_J2_BM_05_30_2	0.108	2.146	0.708	2.516	48	0
CAF_J2_BM_05_30_3	0.081	1.44	0.712	2.7	50	0
CAF_J2_BM_05_30_4	0.099	1.494	0.802	2.43	41	0
CAF_J1_MB_05_30_1	0.089	1.541	0.713	2.279	56	0
CAF_J1_MB_05_30_2	0.079	1.206	0.79	2.279	44	0

CAF_J1_MB_05_30_3	0.096	1.3	0.762	2.668	45	0
CAF_J1_MB_05_30_4	0.102	1.685	0.674	2.365	42	0
CAF_J2_BM_05_31_1	0.096	1.238	0.719	2.398	47	0
CAF_J2_BM_05_31_2	0.131	1.753	0.798	2.635	1123	0
CAF_J2_BM_05_31_3	0.116	1.429	0.792	2.635	49	0
CAF_J2_BM_05_31_4	0.076	1.472	0.695	2.398	53	0
CAF_J1_MB_05_31_1	0.1	1.89	0.692	2.668	39	0
CAF_J1_MB_05_31_2	0.072	1.494	0.677	2.549	45	0
CAF_J1_MB_05_31_3	0.115	1.526	0.792	2.581	46	0
CAF_J1_MB_05_31_4	0.088	1.307	0.791	2.549	45	0
AVERAGE	**0.10095455**	**1.541**	**0.74318**	**2.46791**	**317.59091**	**0**
MAX	**0.14**	**2.146**	**0.805**	**2.7**	**1189**	**0**

Table 7.6 – Speed Summary for the 22 trips analysed

With regards to the larger number of CI exceedance values deeper analysis is carried out. In this case for each of these outliers, namely those trips whose value in column “Number of times Speed Error exceeded CI value” exceed for more than a hundred times, their maximum values have been analysed as it is done in Table 7.2. However due to the large values the table is not printed here but rather the maximum values are gathered and presented. The summary of such analysis is shown in Table 7.7. In this table it can be observed that the maximum time range of the speed error is below 1.5 seconds and that the maximum travelled distance while this error occurs is of 4.124 meters. Consequently, these errors do not introduce much uncertainty to the overall performance and they are considered minor events to be revised by future evolution of the algorithm and/or synchronisation methods between GT and AO. In fact, synchronisation offset, or delays introduces a value discrepancy of short times which could be related to the situation faced here. However, since the errors are limited and well identified no further investigation is carried out at this phase.

	MAX Values			
Reference	**Time Range (sec)**	**MaxDiff(SpeedErr-CI(3 σ)) (km/h)**	**CI Mean Val. in Range (Km/h)**	**Travel Dist. on Range (m)**
CAF_J2_BM_05_17_2	0.96	0.716	0.691	0.748
CAF_J2_BM_05_17_3	1.088	0.666	0.745	0.746
CAF_J1_MB_05_17_1	1.152	0.587	1.501	0.832
CAF_J1_MB_05_17_3	1.312	0.641	1.706	4.124
CAF_J2_BM_05_30_1	1.12	0.846	1.825	1.818
CAF_J2_BM_05_31_2	1.312	0.572	1.685	1.22

Table 7.7 – Speed Error Outliers Summary of the maximum errors

To conclude on the speed analysis all trips per journey are plotted in the following Figure 14 and Figure 15. On one hand the speed data for all trips for journey one is plotted and on the other hand the speed data for journey two is plotted. In general, for both cases, it can be observed that the speed value is very similar from trip to trip.

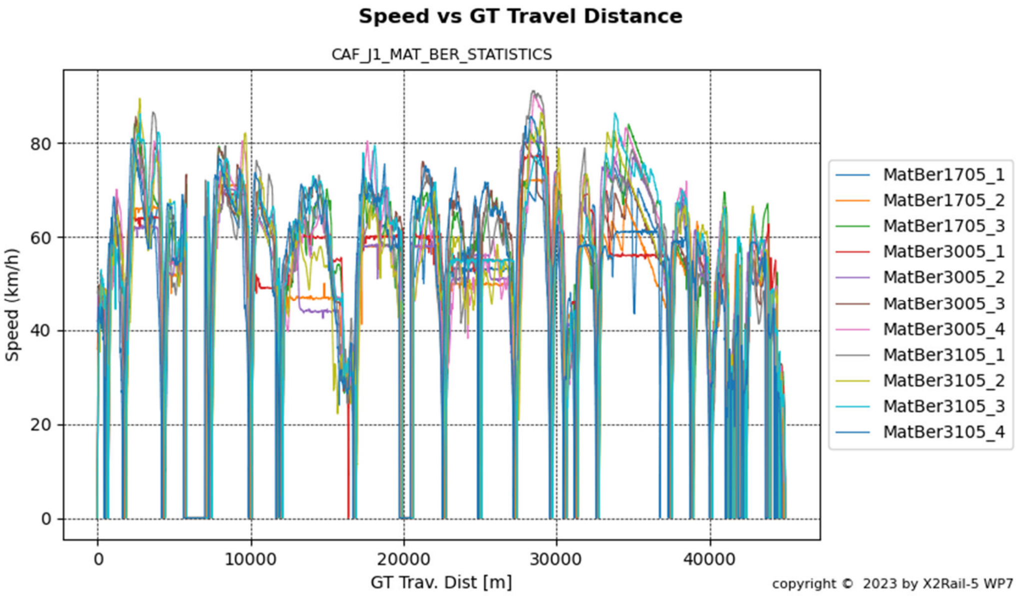

Figure 14 Overall Speed illustration for Journey 1.

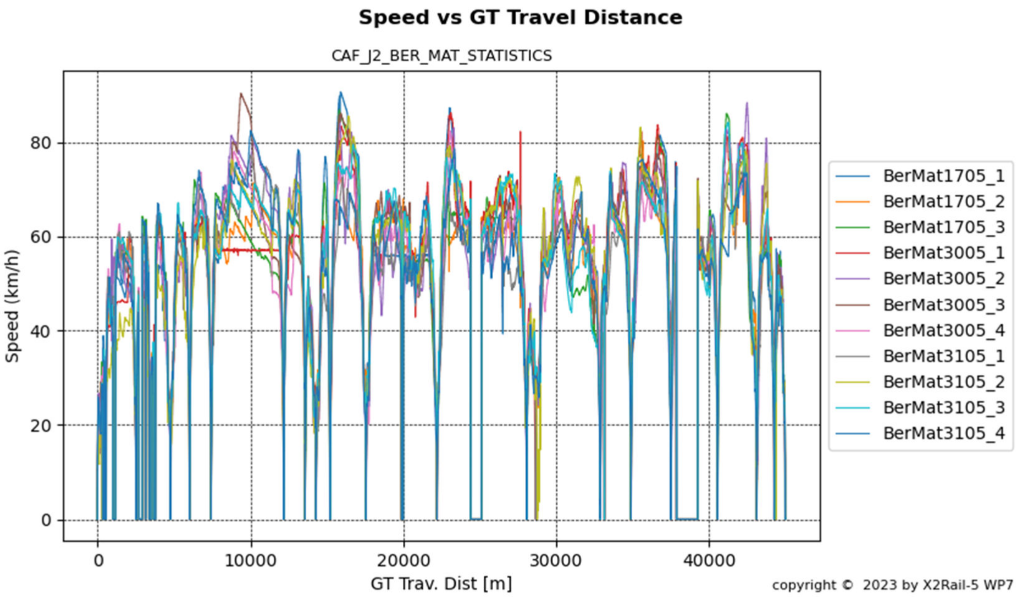

Figure 15 Overall Speed illustration for Journey 2.

7.3.1 Overall Distance Analysis

For each of the trips the core statistical values are gathered in Table 7.8. The table presents the same data as presented for each individual trip as for example Table 7.3. Consequently for each trip it is defined the following is defined:

- Trip reference, as described in section 6.1
- Travel Distance Error Mean value
- Maximum Travel Distance Error value
- Mean CI value for the travelled distance
- Maximum CI value for the travelled distance
- Number of times the CI value is exceeded by the travel distance error
- Number of timeshe CI value exceeded the SRS values

The results from the table first show a maximum travel distance error of 28.206m for all trips and maximum CI value of 67.08m. In addition, the number of times the travel distance error exceeded the CI has an average value of 10 with a maximum value of 42. In this case, the number of exceedance value is low if compared to the speed analysis. Finally, for all cases the number of SRS value exceeded is with an average value of 37.8 times with a maximum value of 52 times. Notice that these values are all very similar to the ones analysed in [5] and in section 7.2.2.2.1 whereby the time span for the errors is small, for instance in section 7.2.2.2.1 for about 0.512 seconds. In conclusion, the overall performance in terms of travel distance seems to be similar for most cases.

Trip Reference	Trav. Dist. Error Mean (m)	Trav. Dist. Error Max Value (m)	CI (3 σ) Mean Value (m)	CI (3 σ) Max Value (m)	Number of times Trav. Dist. Error exceeded CI value	Number of times CI exceeded SRS value
CAF_J2_BM_05_17_1	0.105	1.681	0.702	2.668	3	47
CAF_J2_BM_05_17_2	2.972	18.763	14.082	35.52	8	49
CAF_J2_BM_05_17_3	2.799	16.828	14.568	35.73	4	50
CAF_J1_MB_05_17_1	3.139	21.243	11.888	56.76	9	29
CAF_J1_MB_05_17_2	3.184	21.528	14.53	62.1	16	29
CAF_J1_MB_05_17_3	4.07	24.295	14.548	61.71	27	30
CAF_J2_BM_05_30_1	2.808	16.137	15.35	36	3	47

CAF_J2_BM_05_30_2	2.784	20.164	14.054	40.35	5	47
CAF_J2_BM_05_30_3	2.519	13.294	14.173	36.39	2	47
CAF_J2_BM_05_30_4	3.9	18.946	16.345	37.71	6	52
CAF_J1_MB_05_30_1	3.193	20.038	15.356	65.34	8	29
CAF_J1_MB_05_30_2	3.677	23.171	15.527	67.08	15	28
CAF_J1_MB_05_30_3	3.051	18.099	14.719	62.46	7	26
CAF_J1_MB_05_30_4	4.537	28.206	14.286	62.19	42	28
CAF_J2_BM_05_31_1	3.233	18.099	14.691	37.8	11	47
CAF_J2_BM_05_31_2	3.673	16.242	15.675	35.61	1	45
CAF_J2_BM_05_31_3	3.627	18.915	16.122	40.38	7	47
CAF_J2_BM_05_31_4	2.835	16.779	13.859	42.57	1	43
CAF_J1_MB_05_31_1	3.94	23.626	15.038	65.46	17	29
CAF_J1_MB_05_31_2	3.979	23.319	14.133	63.21	16	27
CAF_J1_MB_05_31_3	3.154	21.276	14.965	62.49	17	27
CAF_J1_MB_05_31_4	3.152	22.815	12.444	58.53	14	29
AVERGE	**3.196863636**	**19.24836**	**13.95705**	**48.54809**	**10.863636**	**37.818182**
MAX	**4.537**	**28.206**	**16.345**	**67.08**	**42**	**52**

Table 7.8 – Travel Distance Summary for the 22 trips analysed

Focusing on each of the journeys, the following Figure 16 and Figure 17 illustrate the travel distance error and the confidence interval performance values. In general, the travel distance error shows a noisier behaviour than the CI, but both show very similar results from one trip to another. The noisy part of the travel distance can be considered as normal as the train does not always travel at the same speed and its individual trip may have its own particularities. However, the Confidence Interval results are clearer. This behaviour is expected as the safety of the algorithm comes mainly from the digital map footprint. Consequently, the CI peaks between GT travel distance 10000 and 15000 are strongly related to the digital map definition at these points where the curvature value calculated from the algorithm brings higher uncertainty. This indeed cancould be because there is either a very low speed values or because of a mismatch between the reality and the digital map. If the reader investigates Figure 15 it can be observed that between 10000 and 15000 GT travelled distance the train stops several times which makes it harder for the algorithm to determine the position of the train.

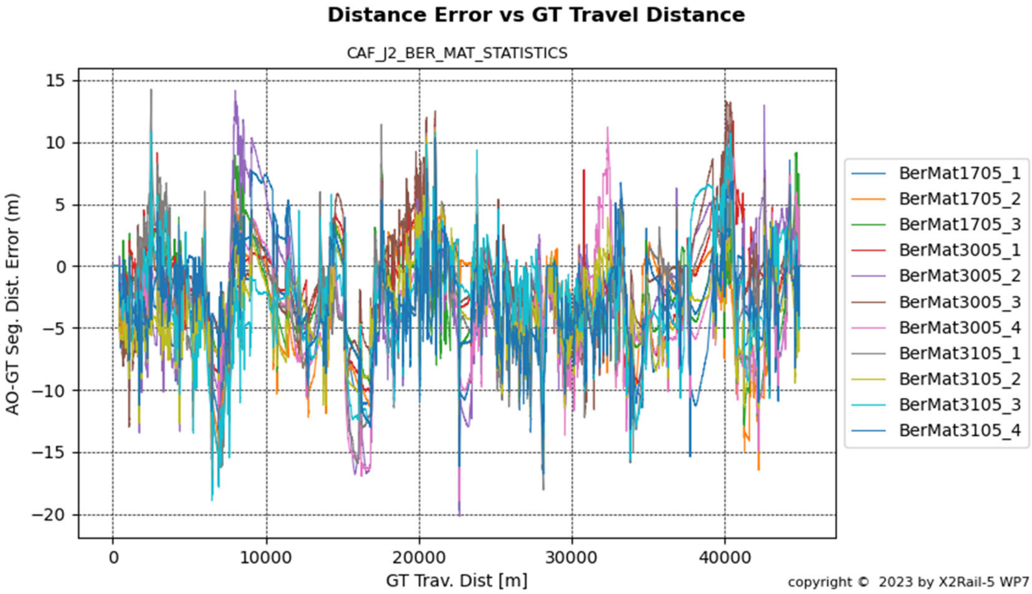

Figure 16 Overall Travel distance Error for Journey 2.

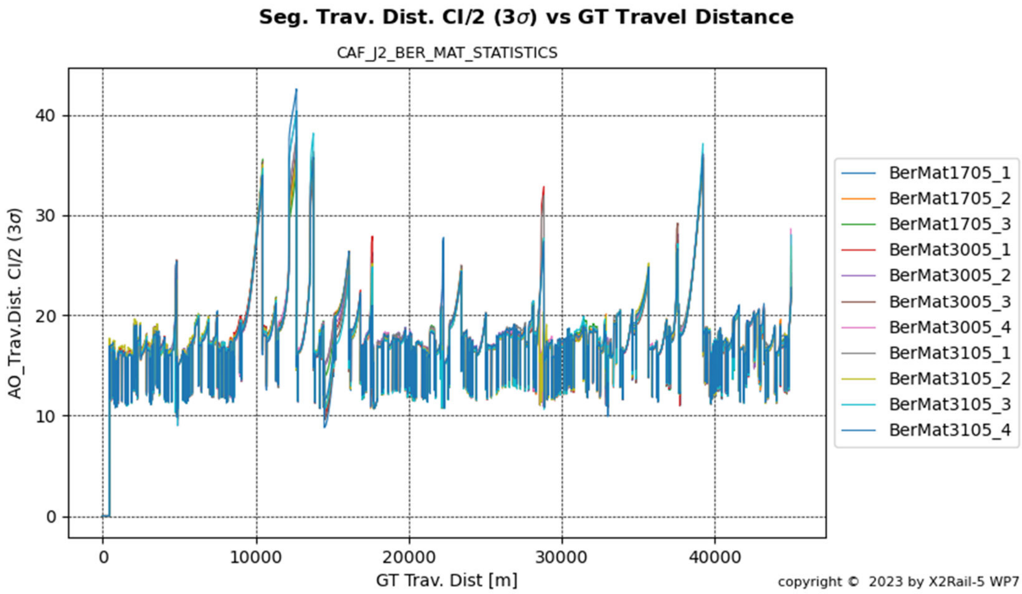

Figure 17 Overall CI/2 (3 σ) for Journey 2.

Mirroring the analysis carried out for Journey 2 the following Figure 18 and Figure 19 show the results for Journey 1. Notice that in journey 1 the algorithm requires a distance before it can guarantee track discrimination and up until the point the illustrated information is set to zero. In this journey the travel distance performance can be considered very similar to the journey two, meaning that the results are noisier than the CI, but all trips present the same shape of errors. For the CI, though values are very similar with a particular peak at around 30000m of the GT travelled distance. This case is further analysed.

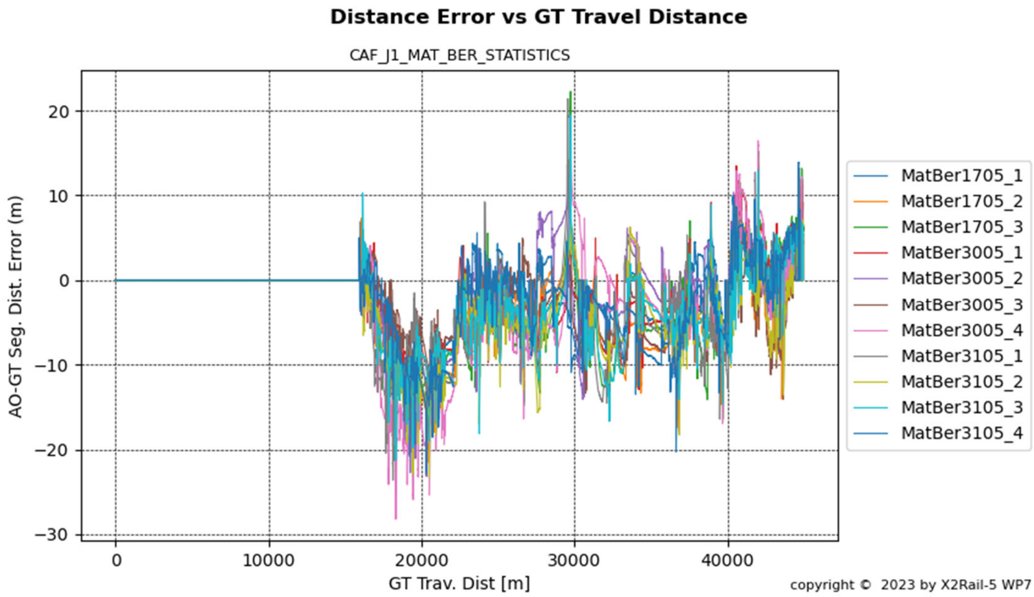

Figure 18 Overall Travel distance Error for Journey 1.

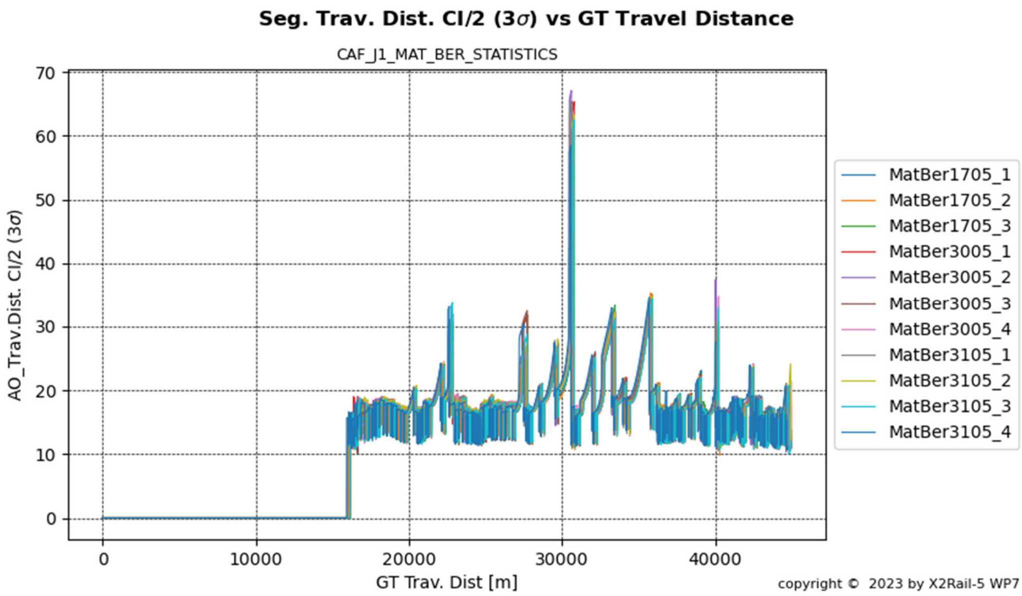

Figure 19 Overall Travel distance Error for Journey 1.

In order to understand the peak of the CI value the following Figure 20, Figure 21and Figure 22 provide further details. In Figure 20 the moment where the CI increases is illustrated. In Figure 21, it can be seen for the same time span the speed value which corroborates that at the moment travel distance CI increases the speed is around 15km/h. Finally, a deeper look into an aerial view of the situation in Figure 22 shows that the uncertainty is triggered by the curvature defined in the digital map, which is a large radius curve run at low speed where the curvature of the radius in the map may not be aligned with the reality.

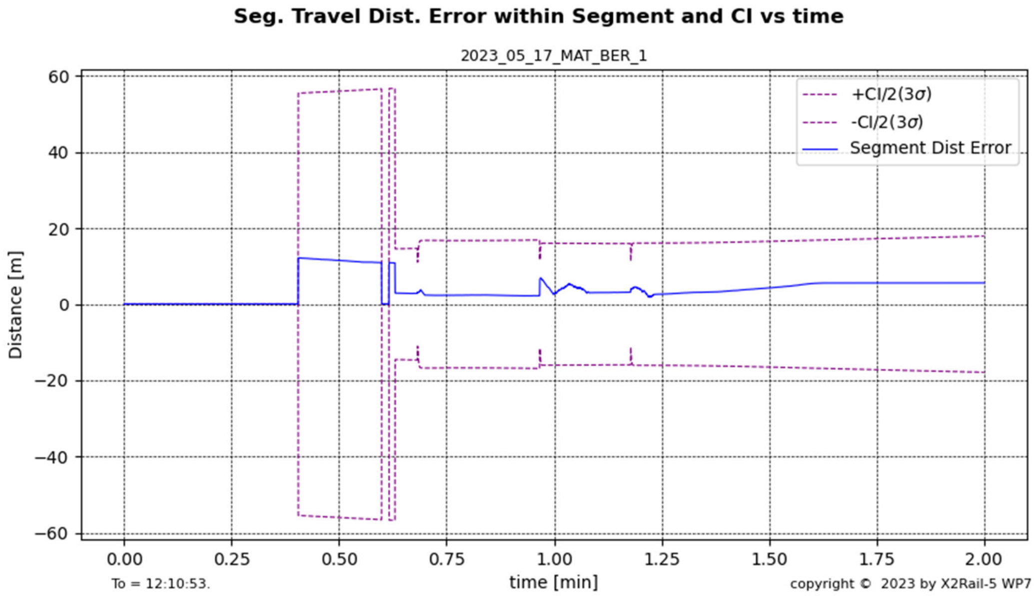

Figure 20 Zoomed result for Segment Travel distance error for MatBer1705_1 at the exact place where the CI increases considerably.

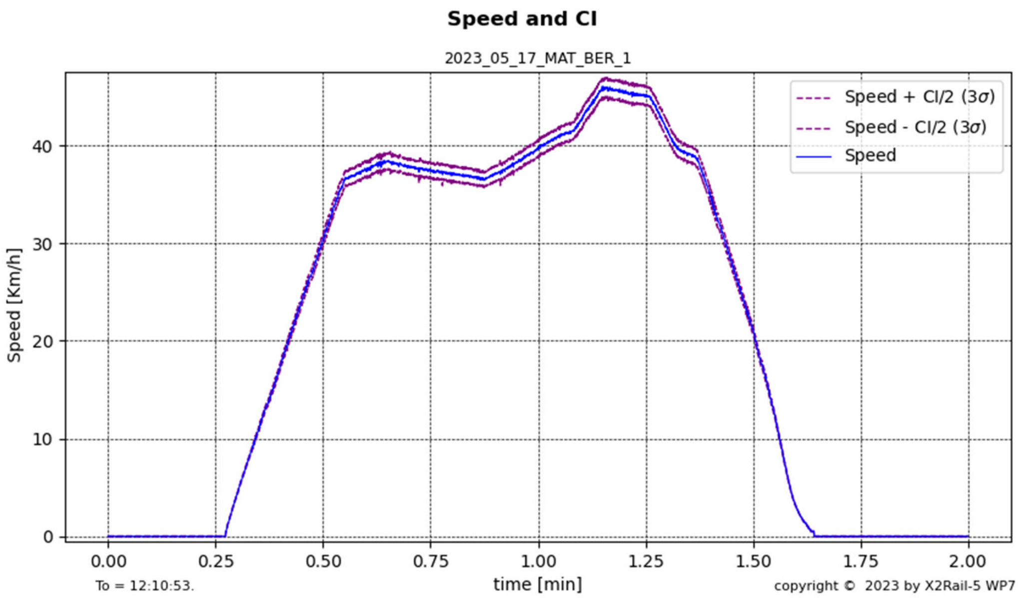

Figure 21 Zoomed result for Speed for MatBer1705_1 at the exact place where the CI increases considerably.

Figure 22 Overall Google earth view of the Zoomed section where CI increases considerably. The red circle is where the CI is increased.

To conclude, the overall travel distance error can highlight issues on both the algorithm and the digital map which could be used for maintenance and debugging purposes.

8 Conclusions

In this report, CAF's algorithm performance has been analysed in a large scale. The document shows 22 trips with over 900km analysed where the objective is to analyse the travel distance error performance repeatability over multiple trips. The analysis first shows the individual case study per trip where the insides of the travel distance and speed errors are explained. This methodology is already applied in [5] but in this case an independent speed sensor is available.

From the individual analysis the research has been focused in analysing the errors at large scale showing multiple performance indicators such as the maximum confidence interval values for both speed and travel distance values in section 7.2.2.1 and section 7.2.2.2 respectively.

The results show that the outcomes presented in [5] are still valid which means that the algorithm performance follows the expected behaviour, the performance values slightly exceed the suggested SRS values for travelled distance and that the usage of map matching techniques with the gyroscope information is a well valid solution. In addition, the performance of the algorithm has shown a strong pattern of repeatability in terms where the errors encountered, both the average and max values are very similar in most of the cases (see Table 7.8). This is mainly due to the speed repeatability behaviour of the train through the analysed trips and the algorithm design where the CI values is very much tight tied to the speed and radius definition accuracy in the digital map. This leads to similar Confidence interval values across multiples trips if the speed is similar too (see Figure 17).

Finally, a case where a potential error on the digital map that triggers a spike on the CI value for Journey 1 has shown that it is possible to use large scale analysis for both algorithm performance debugging as well as potential maintenance tool.

9 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] X2R2 D3.10 Technical solutions for Fail Safe train positioning, advantages and disadvantages V 05

[4] R.Grover Brown, Gerald Y. Chin, GPS RAIM: Calculation of Threshold and Protection Radius Using Chi-Square Methods-A Geometric Approach, in. Global Positioning System: Inst. Navigat., vol. V, pp. 155–179, 1997

[5] X2R5 D7.3 Stand Alone Fail-Safe Train Positioning Demonstrators: Prototypes Developments, Analysis and Test Report V0.3. Note the CAF demonstrator description is part of ANNEX submitted as X2R5-T7_5-T-CAF-010-09_-_D7_3_DemonstratorsAnalysisCAF.