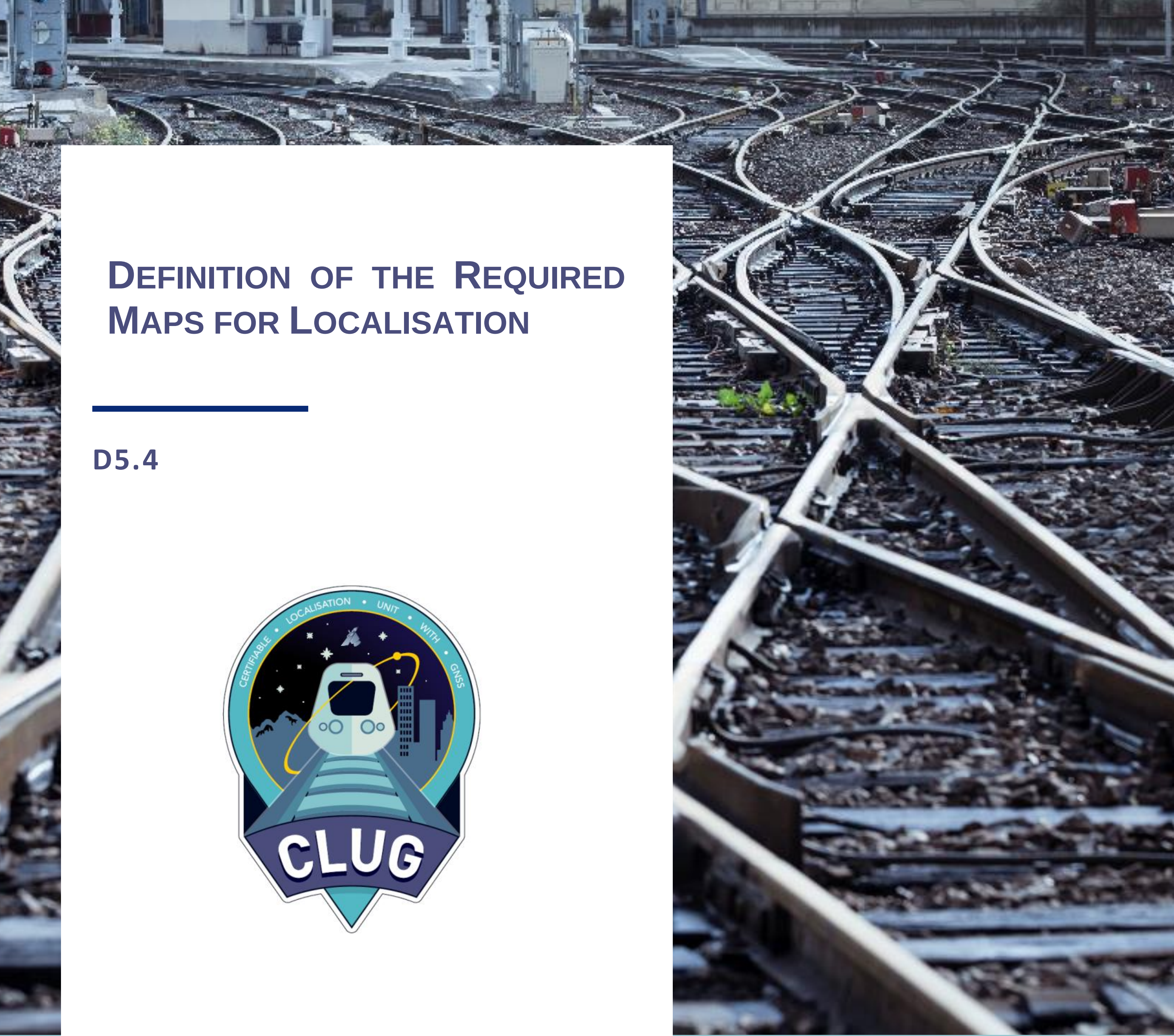

Definition of the Required Maps for Localisation

D5.4

JUNE 23, 2022

VERSION 1.3

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 870276

D5.4 – DEFINITION OF THE REQUIRED MAPS FOR LOCALISATION

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VERSIONS OF THE DOCUMENTS

Revision	Date	Description
0.1	10/06/2021	**First draft** - Agreement on document structure - First content transferred from WP3 document
0.2	2021-12-29	**Initial draft DB for review by CLUG contributors** - Introduction finished - In scope / out scope defined - Data model specified - Content
0.3	03/03/2022	**Initial draft with incorporated review comments from SNCF** - Data model adapted - Content definition revised
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1.0	2022-04-15	**Stable draft for review by WP5.4 contributors** • Executive summary revised • Figures adapted • Data model content revised • Editorial errors corrected
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1.2	2022-05-12	**Final version after review by CLUG Operational and Technical Management Team (OTMT)** • Minor changes including date of deliverable, formatting, and confidentiality of deliverable in the footer.
1.3	2022-06-23	**Final version** • Minor changes after review by Salvatore Bellomo

EXECUTIVE SUMMARY

This document is the deliverable *"D5.4 – Definition of the Required Maps for Localisation"* of the European project "Certifiable Localisation Unit with GNSS in the railway environment" (hereinafter also referred to as "CLUG").

The 5.4 is a public document about the provision of required and optional infrastructure data (hereafter also referred to as "Map Data" / "Track features") on the interface (airgap) between a trackside data management system and the onboard localisation unit.

The specifications in this document are based on the high level system requirement of the CLUG work package 2 "Mission Definition and System Requirements" and on results of several workshops performed with the contributors in the work packages 3 "Localisation System Design" and 5 "Application to the Train Localisation System".

This document is based on the terms and conditions established in the Grant Agreement (GA) and its Annexes, as well as in the Consortium Agreement (CA).

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APPLICABLE DOCUMENTS

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

- Grant Agreement N°870276: This is the contract with the European Commission which defines what must be done, how and the relevant efforts.
- Consortium Agreement CLUG_CA96_20001_V2.7_CO: This defines our obligations towards each other.

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

In the event of a conflict between this document and any of the contractual documents referenced above, the contractual document(s) shall take precedence.

REFERENCES

[CLUG_GA] Grant Agreement N°870276, 2019

[CLUG_CA] Consortium Agreement CLUG_CA96_20001_V2.7_CO, 2020

[1] CLUG: System Preliminary Definition, D5.7, v 0.8, 09/05/2022

[2] Reference CCS Architecture (RCA) - https://ertms.be/workgroups/ccs_architecture (Last access: 21/12/2021)

[3] RCA: MAP Concept – Overall Solution Concept (Preliminary Issue), RCA.Doc.54, v 0.1, 30/11/2021

[4] RCA: Digital Map – Evaluation Reference Model (Preliminary Issue), RCA.Doc.57, v 0.3, 30/11/2021

[5] RCA: Digital Map – Evaluation Publish Onboard Map Approaches (Preliminary Issue), RCA.Doc.56, v 1.1, 30/11/2021

[6] RCA: RCA Domain Knowledge (Preliminary Issue), RCA.Doc.18, v 0.3, 02/06/2021

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[8] Specification of interoperability relating to the "infrastructure" subsystem of the railway system in the European union (TSI-INF) - https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014R1299&from=DE, 12/12/2014

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[10] ATO over ETCS Engineering Rules, SUBSET-141, v 0.0.10, 17/05/2021

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1 INTRODUCTION

1.1 OBJECTIVES OF THE CLUG PROJECT

1.1.1 The H2020-project CLUG stands for Certifiable Localisation Unit using GNSS in the railway environment.

1.1.2 The CLUG project performed a mission analysis, needs identification and a preliminary feasibility study of an onboard localisation unit with the following characteristics:

- Failsafe onboard multi-sensor localisation system consisting of a navigation core brought in reference using GNSS, track map and a minimal number of reference points,
- On-board continuous localisation system that provides location, speed and other dynamics of the train,
- Localisation system that is operational and interoperable across the entire European rail network,
- Localisation system that is compatible with the current ERTMS TSI or with its future evolutions.

To achieve its objectives, the CLUG's management and the design and development of the localisation unit followed agile processes taking into account former projects results – especially STARS – as well as observations resulting from new test campaigns.

CLUG has been structured to maximise the knowledge earned from STARS. Most importantly, the process to setup a recording train, its ground truth and the tools to automatise the analysis of the recordings has been greatly reused and in cases improved by CLUG. In addition, the knowledge gained from STARS has been used to mitigate many of the encountered issues and to anticipate as much as possible the difficulties when commissioning trains. An example of such an optimisation is the reuse of the data recording platform and methodology specified in STARS by the CLUG project.

1.1.3 The actual development of the Localisation System as a certified device is not in the scope of CLUG. The CLUG localisation solution is a software demonstrator. Data evaluation and testing is performed by the acquisition of real sensor data and reference position on test trains and the offline data processing.

1.1.4 The CLUG project is subdivided into five work packages:

- WP1 “Project Management and Coordination”
- WP2 “Mission Definition and System Requirements”
- WP3 “Localisation System Design”
- WP4 “Testing and Evaluation”
- WP5 “Application to the Train Localisation System”

1.1.5 The main objective of WP5 is to ensure the successful exploitation and dissemination of the CLUG outcomes (e.g. architecture, sensor definition, data collection, feasibility and assessed performances), aiming to achieve a high level of public awareness by managing external communication with recognised forums and communities targeted mainly to railway sector, regulators, authorities, E-GNSS experts, manufacturers and European space stakeholder.

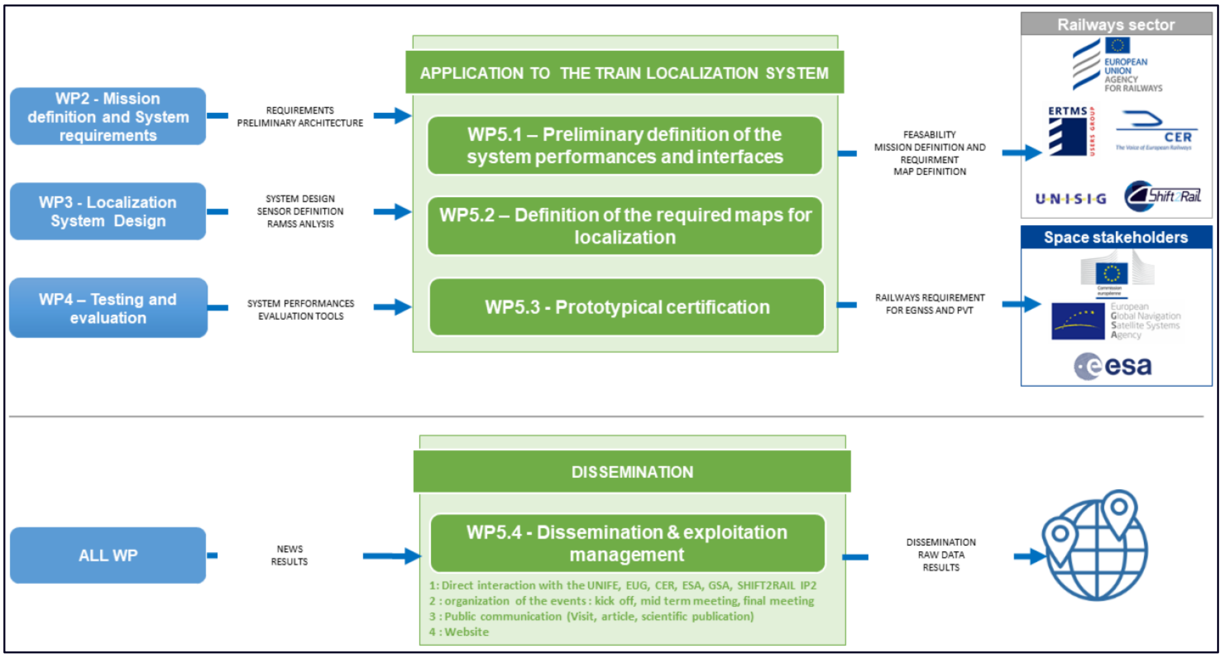


Figure 1: WP5 global logic

1.1.6 CLUG capitalises on the achievements of European Commission and GSA funded projects such as NGTC and STARS.

NGTC provided some preliminary safety analysis that sheds light on the use of GNSS under many assumptions that needed to be corroborated by field testing. The results of NGTC led to a massive field testing campaign run throughout Europe under the STARS project. STARS used three train sets on three completely different environments. On one side the best-case scenario for GNSS was recorded in Sardinia. On the other side where the train recordings from Czech Republic and Switzerland. The former showed a challenging environment full of trees offering some interesting multipath recordings, whereas the latter full of high mountains corroborated the lack of sky visibility and availability of the GNSS signal in the railway domain with some challenging spiral tunnels.

In CLUG, the work done in STARS especially with regard to the data collection methodology and platform has been adopted. NGTC safety analysis and the data collection scenarios in STARS have been used as a preliminary input for the mission and system specification.

1.1.7 The functional scope of the Localisation System specified by CLUG is to locate a given reference point on a railway vehicle. This will typically be the point where the GNSS antenna is installed but can be also any other defined point. The location of the reference point includes confidence intervals and motional information.

1.1.8 In operational use, the Localisation System will be embedded in a localisation system that provides an application layer which derives from the location of the reference point, as provided by the Localisation System, the location of the front and rear ends of the Train Unit or of an individual consists within the Train Unit which are the information needed for operation. The application layer is outside the scope of CLUG.

1.2 Scope of the Document

1.2.1 As defined in D2.1 'High-level Mission Requirements Definition', one of the key characteristics of the proposed onboard localisation unit is a multi-sensor fusion engine that utilizes track map (e.g. digital maps).

1.2.2 The purpose of this document is to define a comprehensive definition of the digital map needed by the train localisation system on the air gap between trackside and the train.

1.2.3 The primary objective of the comprehensive definition of the digital map for train localisation system are as follows:

- To define the relevant and necessary map data (e.g. track centerline points, Eurobalise positions, etc) needed by the TLOBU.
- To provide the required map data on the air gap between trackside and train in a future-proof, structured, simple and extendable way.
- To define and propose a common data model for the track information.

1.2.4 This document is written in alignment with the system requirements defined in WP2, the recommendations provided by sensor fusion experts in WP3 and the analysis done in WP4. And in case of any deviations, D5.4 'Definition of Required Maps for Localisation' is to be considered as the final document that defines the digital map specification for the CLUG project.

2 REQUIRED DIGITAL MAP FOR LOCALISATION

2.1 BACKGROUND

2.1.1 In the CLUG project, digital maps are a key input to the navigation engine and the integrity engine that forms the core of the onboard localisation system.

2.1.1.1 For this purpose, the air gap between trackside and the train was identified as an input and listed on the interface definition for the onboard localisation system in D5.7 'System Preliminary Definition' [1].

2.1.1.2 The failsafe onboard localisation system can utilize map data / track features for a range of needs, e.g. as an input for:

- Map-matching the 3D position output by CLUG localisation system to a linear movement along the current track edge (when the current track edge ID is known).
- For the track selectivity algorithm to determine the current ID of the track edge on which the train is located (pre-requisite for 2.1.3.1)
- Bounding the errors of the inertial sensors using map data / track features (e.g. azimuth / direction angle, curvature radius, cants, gradients)
- Determining the train direction using the base topology model / node-edge-model
- Proofing the integrity of the system by checking measured track features against map data / track feature

2.1.1.3 Not in the scope of the CLUG project: In addition to the use cases/needs mentioned above, in the future, after proper safety analysis / TSI gap analysis and change request processes / qualification or certification, digital maps can also be used for the following:

- As a digital alternative to the physical infrastructure, e.g. Eurobalise, used today as the reference point for distance measurement ('Last Relevant Balise Group (LRBG)') and localisation information transmitted as part of the train position report
- To provide real-time information regarding infrastructure elements and their status (e.g., switches, level crossings, etc) to the onboard localisation system for track selectivity/determination of the current track edge ID.

2.1.2 Beside the CLUG context the CLUG D5.4 was in a continuous alignment process with all RCA [1] activities especially from the Digital Map Cluster until April 2022.

2.1.2.1 The RCA is an initiative of the ERTMS User Group (EUG) and EULYNX Consortium. With RCA, European infrastructure managers define an internationally standardized signalling system, focusing on modular architecture and standardized interfaces with the objective to enable the European infrastructure manager to optimize cost, reliability, safety, capacity and fast migration.

2.1.2.2 Like the CLUG approach one of the main tasks of the Digital Map Cluster within RCA is the specification of the Map Data interface on the air gap between trackside and train, e.g. for localization use cases.

2.1.2.3 Following RCA document are taken into consideration for the CLUG map approach:

- Concept: MAP – Overall Solution Concept [3]
- Digital Map – Evaluation Reference Model [4]
- Digital Map – Evaluation Publish Onboard Map Approaches [5]
- RCA Domain Knowledge [6]

2.2 General Assumptions

2.2.1 In scope / out of scope

2.2.1.1 What is in the scope of this digital map specification?

This specification of the digital map is written at the point of the airgap, which is the interface between trackside and onboard as shown in Figure 2. The map is being specified with focus on the use for localization purposes.

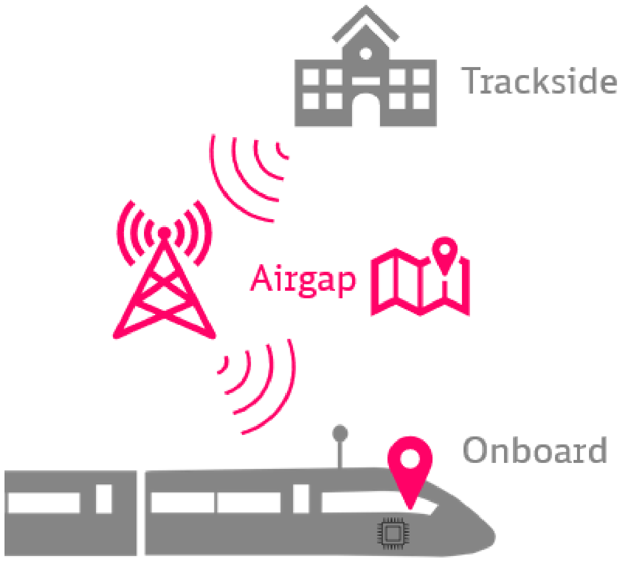


Figure 2: Airgap between trackside data management and onboard localisation

This specification will define the minimum map content required by the localisation algorithm and optional information which could also be used for localisation use cases as shown in chapter 2.1.1.2.

This specification will define a data model (see chapter 2.3.2) and a map structure (see chapter 2.4) that fulfil the following criteria:

- Be usable for a long term
- Structured as simple as possible
- Universally extendable
- Without redundancies

In addition, different data elements and user applications shouldn't affect each other. A possible approach for such a data model is to define a base layer and to add attribute layers on top for different data, which are independent from each other as shown in Figure 3. The definition of these layers containing the data for the localization algorithm is in scope of this specification, other layers might be specified by other applications. Using this approach each application can easily extract the data it requires from the digital map.

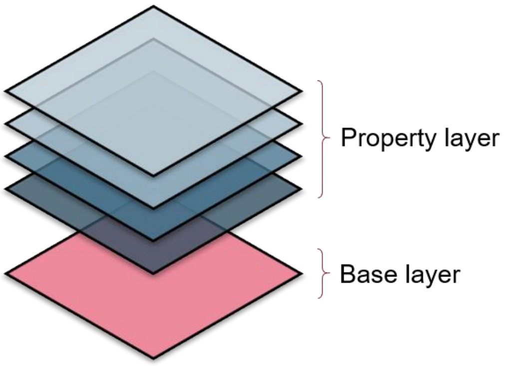


Figure 3: Layer approach

2.2.1.2 What is out of scope of this digital map specification?

Use cases and requirements of other onboard and trackside applications besides onboard train localisation such as ATO, Planning System, Plan Execution, Safety Logic (Systems taken from RCA), etc. can be specified by different organisations and/or in different projects and are not in the scope of the CLUG project digital map specification.

Digital map segmentation approaches, potential data formats for the exchange of the map data and concepts for the update of the onboard map data are not part of this document. These topics are addressed in the RCA Digital Map Cluster.

The measurement specifications for the acquisition of the track centerline points as well as the curvatures, cants and gradients currently depend on the regulations and guidelines of the various European infrastructure managers within Deutsche Bahn, Schweizerische Bundesbahnen, Société nationale des chemins de fer français and others. In future there will be the need of a standardisation to guarantee interoperable digital maps for localisation use cases.

Note: By the time of the publication of this document, the RCA Digital Map Cluster has started activities to create a sufficient base for "optimal" (in the meaning of finding the balance between feasibility and efficiency) requirements to generate Map Data, which also involve the measurement / acquisition specifications.

2.2.2 Minimum digital map content

2.2.2.1 For the localisation algorithm the following map data is required (mandatory):

- Logical relationship of infrastructure objects to each other within the railroad network (node-edge-model)
- Absolute positions (longitude, latitude, altitude) of track centerlines, e.g. points determined by dedicated measurement systems / procedures

2.2.2.2 For the localisation algorithm the following information could be considered (optional):

- Balises represented by their distance from the start point of the current TrackEdge, IDs and country codes
- Curve radius as points where the value changes for the upcoming TrackEdge segment including the azimuth / direction angle for the upcoming element
- Cants as points where the value changes for the upcoming TrackEdge segment
- Gradients as points where the value changes for the upcoming TrackEdge segment

Note: Curvature and gradient could be calculated from the track centerline points. As a further optional input for better calculations of the train heading it could be also possible to provide the positions of the left and right rail at every track centerline point.

2.2.3 Geodetic datum

To fulfil the High Level System Requirement all absolute coordinates in the digital map are referenced to WGS84 reference system.

The WGS84 (World Geodetic System 1984) is an earth-centred, earth-fixed terrestrial reference system. The WGS84 is the geodetic basis of the Global Positioning System (GPS). The horizontal coordinates LONGITUDE and LATITUDE are normally given in degree (°), minutes (‘) and seconds (‘’) and the vertical position ALTITUDE is normally given in metres (m).

The WGS84 is based on the ITRF (International Terrestrial Reference Frame). The ITRF is realised by over 400 fixed survey points worldwide. Due to this reference point distribution WGS84 coordinates are changing all the time because of the plate tectonics.

Note: The more feasible solution from the digital map perspective would be using the ETRS89. It is also an earth-centred and earth-fixed reference system, in which the Eurasian Plate is static. This results in the advantage over WGS84 that the coordinates and maps in Europe based on ETRS89 are not subject to change due to the continental drift. This solution is also envisioned by the RCA Digital Map Cluster.

2.2.4 Units and resolutions for coding the data

Table 1: Overview about units and resolutions

Description	Unit	Resolution
Length – Real length of a track section between two TrackNodes (see chapter 2.3.2.2)	Metre [m]	0,01 m
Offset – Distance of an object on a track section related to the Side_A TrackNode of a TrackEdge (see chapter 0) based on the length	Metre [m]	0,01 m
Longitude / Latitude – 2D coordinates of WGS84 system	Degree [deg / °]	0,000001 deg
Altitude – Height of WGS84 system	Metre [m]	0,001 m
Curve radius – Half diameter of a circle, reciprocal value of the curvature	Metre [m]	0,01 m
Curvature – reciprocal value of the curve radius	*Without unit*	0,000000001
Azimuth – Direction angle between North and the upcoming track section	Radian [rad]	0,0001 rad

Gradient (ascent / descent) - Elevation along the track axis	Per Mille [‰]	0,001 ‰
Cant – Height difference between left and right rail	Millimetre [mm]	1 mm

2.3 Data Model

2.3.1 Underlying data model

The CLUG map data model (see chapter 2.3.2) defined for the localization use cases is a node-edge model derived from the Reference CCS Architecture (RCA [2]) Topology considerations.

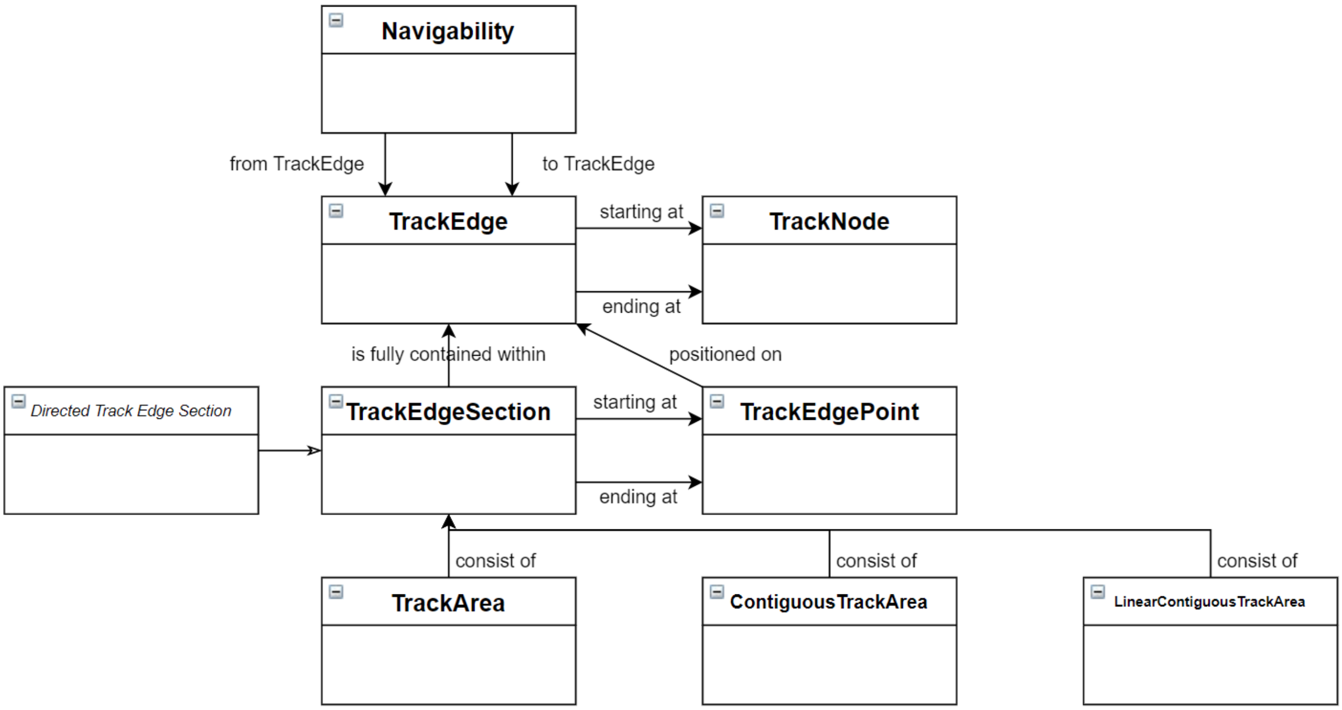


Figure 4: RCA Domain Knowledge: Topology

"This diagram represents the relationships between the main topology objects: TrackEdges and TrackNodes. These two objects build the fundamental topology which only changes when the infrastructure is physically changed. Navigability, TrackEdge, TrackNode, TrackEdgeSection and TrackEdgePoint provide a set of domain objects for representing the network topology." (Description taken from [6]).

2.3.2 CLUG map data model specification

2.3.2.1 Class diagram of the data model

The CLUG map data model is a direct derivation from the RCA Topology domain and is reduced to a minimum required set of elements / objects for the localization use cases in CLUG: TrackNodes, information like in the RCA model, the CLUG data model follows the approach to place AttributePoint everywhere on the TrackEdge where the linear information value significantly changes to describe the upcoming part of the TrackEdge in the direction from Side A to Side B.

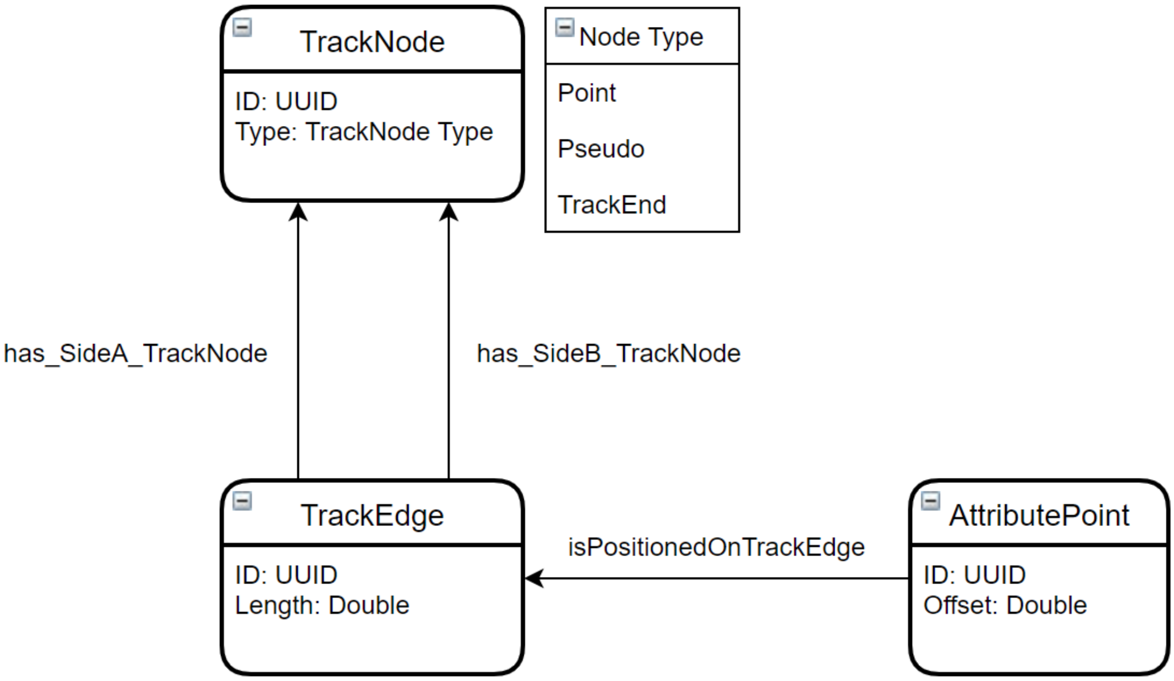


Figure 5: Base topology element classes

2.3.2.2 Object: TrackNode

Table 2: Definition of TrackNode object

TrackNode	A TrackNode is a position on the topological model of the track network. It defines the beginnings and endings of TrackEdges. There are three different situations which are modelled with a TrackNode: *Note: Color coding only for distinguishing the TrackNode types in the figures.* **Point TrackNodes** connected to exactly three TrackEdges and are used for marking points.  *Figure 6: Point TrackNode* *Note: A point (or railroad switch) is a track element which enables trains to be guided from one track to another without a stop. The Point TrackNode is placed at the geometric beginning of the point. The geometric beginning is the tangent point of the main and the diverging track. The tangent point also corresponds to the tip of tongue blades of a point with little deviations. The deviations depend on the radius of the diverging track and correspondingly the tip can be located 0.5m - 2m away from the tangent point.* **Pseudo TrackNodes** connect to exactly two TrackEdges and can be used for data management purposes, e.g. at - Station boundaries - RBC boundaries

- Digital map segment boundaries

Figure 7: Pseudo TrackNode

TrackEnd TrackNodes connect to exactly one TrackEdge and are used for marking the endings of tracks, e.g. at buffer stop.

Figure 8: TrackEnd TrackNode

Attribute	Data type / unit	Description
TrackNode_ID	UUID	Unique (over the European countries) identifier
TrackNode_Type	Point / Pseudo / TrackEnd	Type of TrackNode

2.3.2.3 Object: TrackEdge

Table 3: Definition of Track Edge object

TrackEdge	A TrackEdge represents one piece of one track (e.g. not a double track line) which really exists (“pseudo” TrackEdges are not allowed), including its real length. A TrackEdge always connects exactly two TrackNodes. TrackEdges is described using the direction TrackNode A (Side A) to TrackNode B (Side B).

Attribute	Data type / unit	Description
TrackEdge_ID	UUID	Unique identifier
Side_A	TrackNode_ID	Unique (over the European countries) identifier of TrackNode
Side_B	TrackNode_ID	Unique (over the European countries) identifier of TrackNode
TrackEdge_Length	Unsigned Integer with 32 bit / [cm]	True length in unit metre

2.3.2.4 *Figure 7* shows an example of a simple track topology representation using the CLUG map data model main objects TrackNodes and TrackEdges.

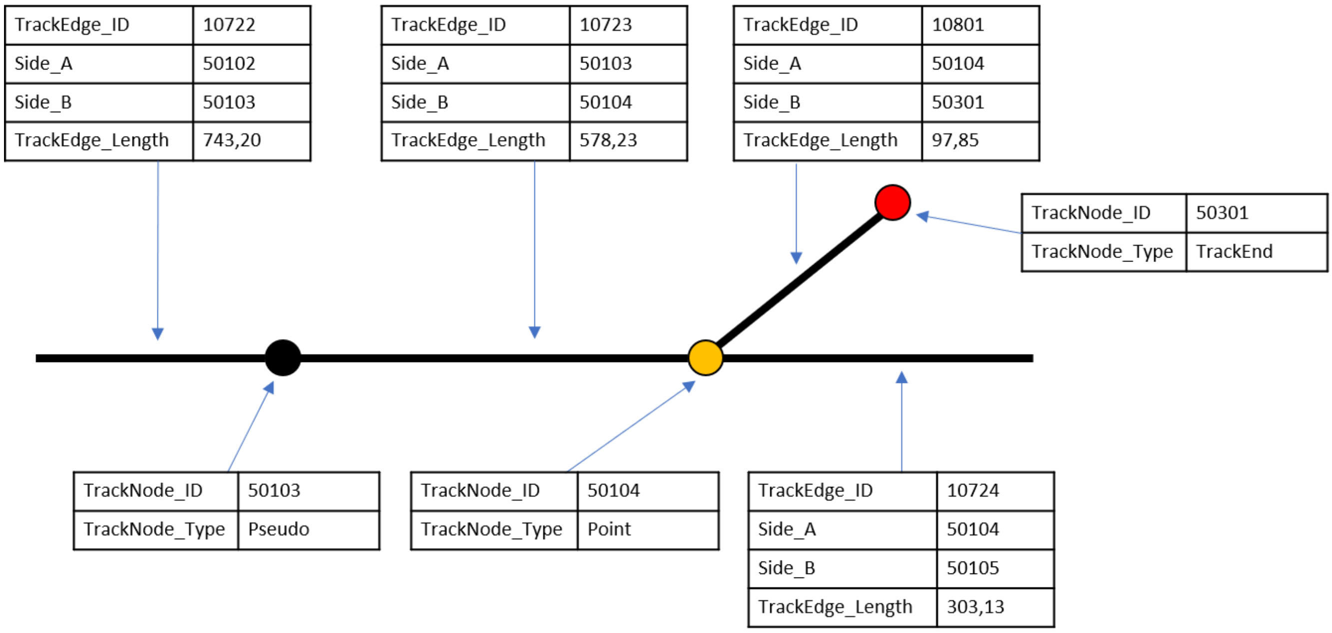


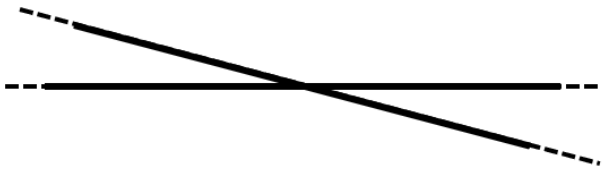
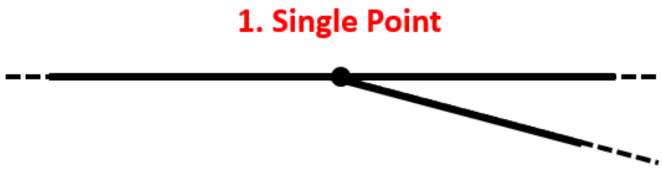
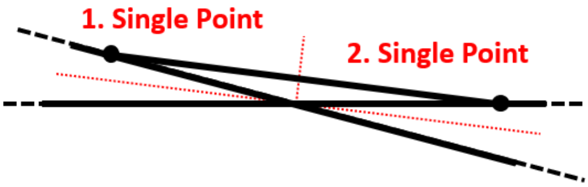
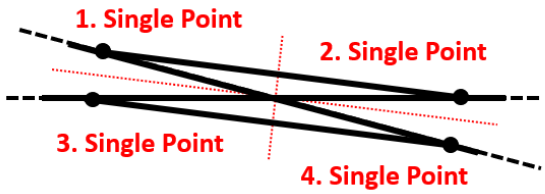
Figure 9: Topology example including attributes

Note: All UUID identifier could be replaced by more practicable coding according to the ETCS principles for the identification of balises (country code, balise ID, …).

2.3.2.5 Specific Usage Notes

Table 4 shows how to describe different kind of points and crossings which are representative for a railway network using TrackNodes and TrackEdges. Turntables, especially used in shunting areas, are deliberately not considered here.

Table 4: Points representations with CLUG data model

Diamond Crossing (Crossings of two TrackEdges without a height difference)	**Single Point**
 *Figure 10: Crossing of two tracks*	 *Figure 11: Single point (1 TrackNode, 3 TrackEdges)*
Single slip point	**Double slip point**
 *Figure 12: Single slip point (2 TrackNodes, 5 TrackEdges)*	 *Figure 13: Double slip point (4 TrackNodes, 8 TrackEdges)*

2.3.2.6 Object: AttributePoint

Table 5: Definition of AttributePoint object

AttributePoint	An AttributePoint represents • Reference points with absolute coordinate to map the track axis • Track elements, e.g. balises • Main points of the track geometry, e.g. curvature radius changes An AttributePoint is always defined by its *AttributePoint_Type*, the UUID of the connected *TrackEdge*, the *Iteration* number of its type within the TrackEdge, the *Offset* along the TrackEdge based on its real length and value(s) corresponding to the type. Following types of AttributePoints are defined for the CLUG localisation system: • Track centerline points (chapter 2.4.2.2) • Balise points (chapter 2.4.2.3) • Curvature points (chapter 2.4.2.4) • Cant points (chapter 2.4.2.5) • Gradient points (chapter 2.4.2.6)	
Attribute	**Data type / unit**	**Description**
AttributePoint_Type	TrackCenterline, Balises, …	Type of property layer
TrackEdge_ID	UUID	Unique (over the European countries) identifier of TrackEdge

Iterations	Integer	Number of AttributePoints
AttributePoint_Offset(n)	Unsigned Integer with 32 bit / [cm]	Relative position along the TrackEdge

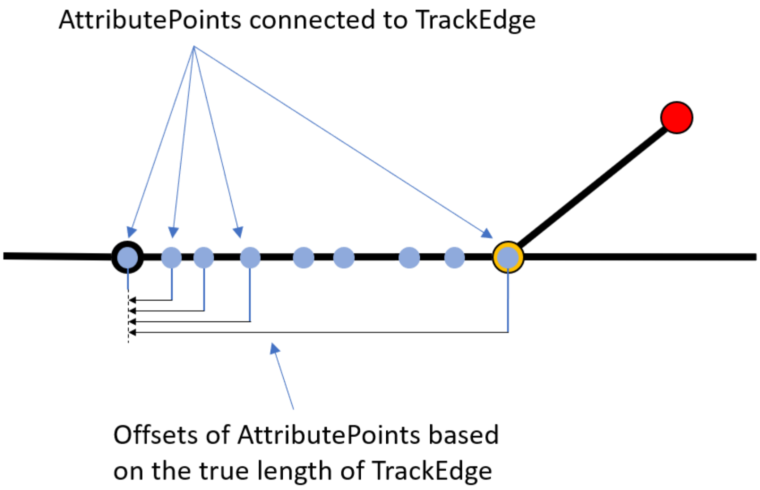


Figure 14: AttributePoint layer design principles

2.4 Specified Digital Map for CLUG

2.4.1 CLUG digital map overview

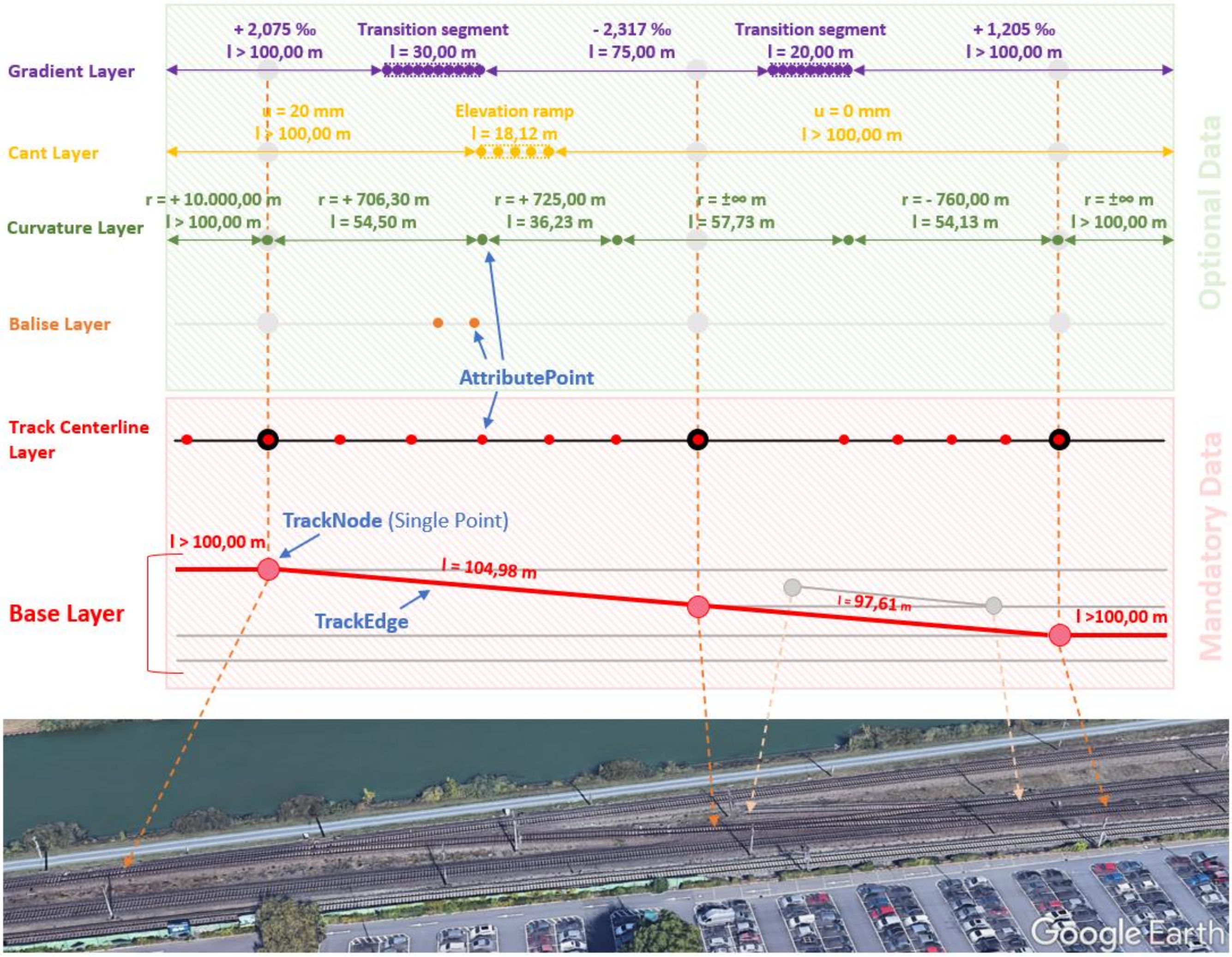


Figure 15: Overview of the specified map for CLUG

The digital map for CLUG is divided into an underlaying base layer which is mandatory and represents the real existing railway network as a node-edge-model / topology model using TrackNodes (chapter 2.3.2.2) and TrackEdges (chapter 0) with logical connections. Based on this base layer the digital map provides additional mandatory and optional track information in the attribute layers using AttributePoints (chapter 0) with cross-references to the TrackEdges.

2.4.2 Detailed layer overview

2.4.2.1 Base layer (mandatory)

Defining the network topology as set of TrackNodes and TrackEdges creates a consistent data model that is well-suited to processing in an automated manner. It must be ensured though that all track objects (points, crossings, etc.) are represented in a standardised way.

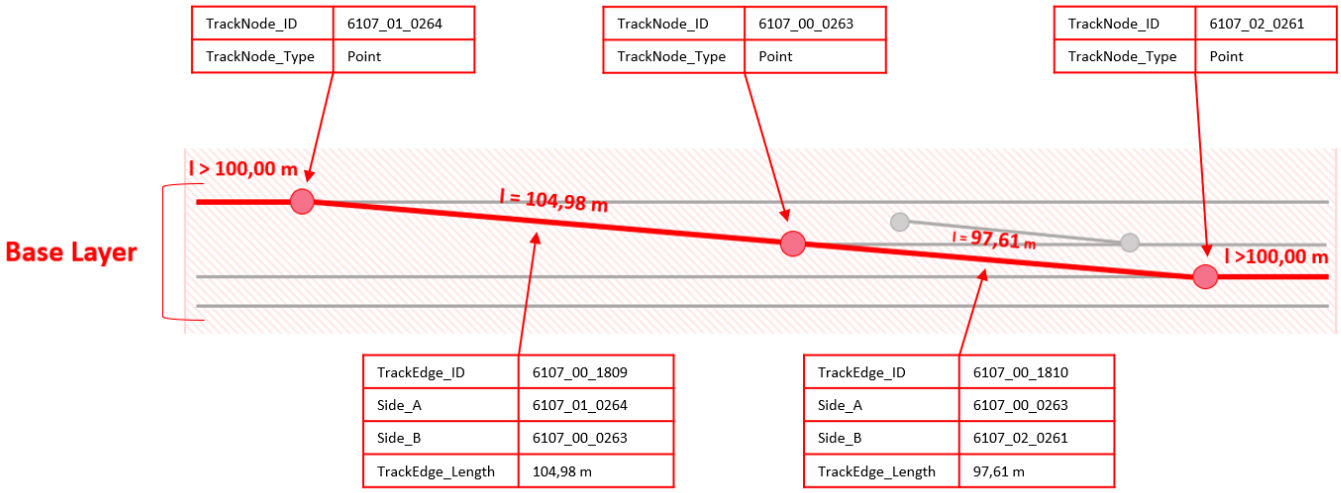


Figure 16: Base layer details

2.4.2.2 Track centerline layer (mandatory)

The track centerline layer consists of spot-based information and represents the centerline of the track with absolute coordinates in 3D (chapter 2.2.3). The absolute positions of track centerline points are determined by different standard measurements systems / methods, e.g. GNSS measurement, terrestrial tachymetry or extraction out of existing track geometry / engineering data. The relative position of a track centerline point between the rails is described in Figure 17.

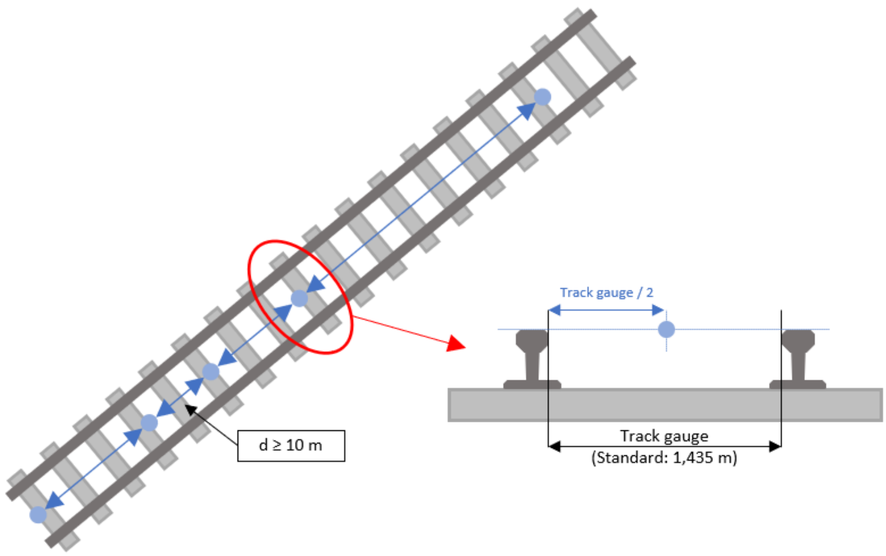
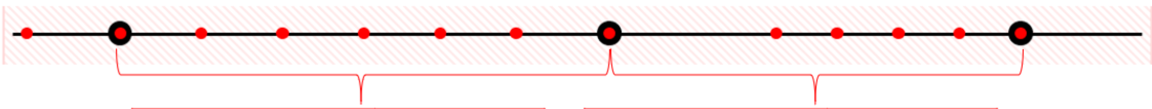


Figure 17: Relative position of TrackCenterline points

A dedicated track centerline point is always placed at both sides (Side_A and Side_B) of a TrackEdge. In other words, the offset of the first track centerline point will always be zero while the offset associated to the last one will always be equal to the length of the TrackEdge. To ensure the data consistency at the TrackNodes the referring track centerline points at the same location shall have identical values.



TrackEdgeAttribute_Type	TrackCenterline
TrackEdge_ID	6107_00_1809
Iterations	7
AttributePoint_Offset (1)	0,00 m
AttributePoint_Long (1)	10.775582 deg
AttributePoint_Lat (1)	52.428804 deg
AttributePoint_Alt (1)	37,881 m
AttributePoint_Offset (2)	18,13 m
AttributePoint_Long (2)	10.775780 deg
AttributePoint_Lat (2)	52.428813 deg
AttributePoint_Alt (2)	37,905 m
...	...
AttributePoint_Offset (7)	104,98 m
AttributePoint_Long (7)	10.777143 deg
AttributePoint_Lat (7)	52.428869 deg
AttributePoint_Alt (7)	37,820 m

TrackEdgeAttribute_Type	TrackCenterline
TrackEdge_ID	6107_00_1810
Iterations	6
AttributePoint_Offset (1)	0,00 m
AttributePoint_Long (1)	10.777143 deg
AttributePoint_Lat (1)	52.428869 deg
AttributePoint_Alt (1)	37,820 m
AttributePoint_Offset (2)	43,35 m
AttributePoint_Long (2)	10.777422 deg
AttributePoint_Lat (2)	52.428872 deg
AttributePoint_Alt (2)	37,794 m
...	...
AttributePoint_Offset (6)	97,61 m
AttributePoint_Long (6)	10.778800 deg
AttributePoint_Lat (6)	52.428892 deg
AttributePoint_Alt (6)	37,878 m

Figure 18: TrackEdgeAttribute_TrackCenterline details

To enable the localisation algorithm to fulfil the High Level Mission Requirements [6] there is the need of a derivation of a maximum distance between the track centerline points in dependence of the minimum curve radius.

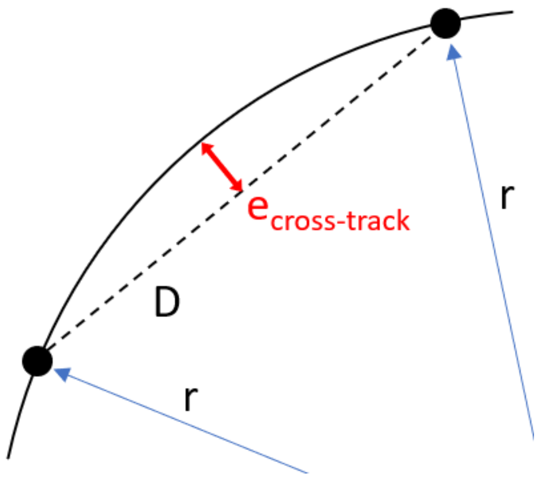


Figure 19: Cross-track error due to interpolation and curvature

Figure 19 shows how interpolating between two given track centerline points leads to a cross-track error / lateral error [$e_{cross\text{-}track}$] relative to the real track axis position if the curvature radius *r* is not infinite. D is the distance between two track centerline points.

$$e_{cross-track} = r * \left(1 - \cos\frac{D}{2 * r}\right)$$

Equation 1: Cross-track error

The cross-track error directly affects the accuracy of the extended Kalman filter (EKF) of the localization algorithm used within the CLUG project by Airbus and is dependent on r and D.

As a result of an accuracy analysis made by Airbus based on a total error budget of 10 m for the localization algorithm an upper bound of 0.1 m can be used for the cross-track error.

To reach the requirement of $e_{cross\text{-}track} \leq 0.1$ m a limitation of the maximum allowed distance between two track centerline points depending on the radius in the digital map is required.

Example: Considering that the minimum radius of horizontal curves is limited at r = 150,00 m by the Technical Specifications of Interoperability relating to the Infrastructure (TSI INF [7]), the maximum allowed distance between tow track centerline points is $D_{(r=150\ m)}$ = 10 m.

More required distances of track centerline points in different curve radius up to r = 10.000,00 m can be found in the following Table 6:

Table 6: Required distances of track centerline points for several curve radius

D [m] / radius [m]	10	11	12	13	14	15	20	30	40	50	60	70	80
150	0,083	0,101	0,120	0,141	0,163	0,187	0,333	0,749	1,331	2,079	2,990	4,065	5,302
160	0,078	0,095	0,112	0,132	0,153	0,176	0,312	0,703	1,248	1,949	2,804	3,813	4,974
170	0,074	0,089	0,106	0,124	0,144	0,165	0,294	0,661	1,175	1,835	2,640	3,590	4,684
180	0,069	0,084	0,100	0,117	0,136	0,156	0,278	0,625	1,110	1,733	2,494	3,392	4,426
190	0,066	0,080	0,095	0,111	0,129	0,148	0,263	0,592	1,052	1,642	2,364	3,215	4,195
300	0,042	0,050	0,060	0,070	0,082	0,094	0,167	0,375	0,666	1,041	1,499	2,039	2,663
500	0,025	0,030	0,036	0,042	0,049	0,056	0,100	0,225	0,400	0,625	0,900	1,224	1,599
760	0,016	0,020	0,024	0,028	0,032	0,037	0,066	0,148	0,263	0,411	0,592	0,806	1,052
1000	0,012	0,015	0,018	0,021	0,024	0,028	0,050	0,112	0,200	0,312	0,450	0,612	0,800
2000	0,006	0,008	0,009	0,011	0,012	0,014	0,025	0,056	0,100	0,156	0,225	0,306	0,400
3200	0,004	0,005	0,006	0,007	0,008	0,009	0,016	0,035	0,062	0,098	0,141	0,191	0,250
5000	0,002	0,003	0,004	0,004	0,005	0,006	0,010	0,022	0,040	0,062	0,090	0,122	0,160
10000	0,001	0,002	0,002	0,002	0,002	0,003	0,005	0,011	0,020	0,031	0,045	0,061	0,080

Note: The error budget / the accuracy for the single track centerline point is not considered.

2.4.2.3 Balise layer (optional)

The balise layer consists of spot-based information and represents the relative positions of physical Eurobalises on the TrackEdge. Every balise point has a reference to the TrackEdge_ID, a country code ID, a Balise group ID, a position in group ID (all according to the ETCS specifications) and a location accuracy (see SUBSET-026-3 [8]).

Note: To avoid redundancies the absolute positions of the Eurobalises are not part of this layer. They can be calculated out of the track centerline layer.

TrackEdgeAttribute_Type	Balise
TrackEdge_ID	6107_00_1809
Iterations	2
AttributePoint_Offset (1)	43,25 m
Balise_CountryID (1) [10-bit]	01 1100 0110 (dec:454)
BaliseGroup_ID (1) [14-bit]	00 0100 0010 1100 (dec: 1068)
PositionInGroup (1) [3-bit]	001 (dec: 1)
Location_accuracy (1) [m]	5
AttributePoint_Offset (1)	54,32 m
Balise_CountryID (1) [10-bit]	01 1100 0110 (dec:454)
BaliseGroup_ID (1) [14-bit]	00 0100 0010 1100 (dec: 1068)
PositionInGroup (1) [3-bit]	001 (dec: 1)
Location_accuracy (1) [m]	5

Figure 20: TrackEdgeAttribute_Balise details

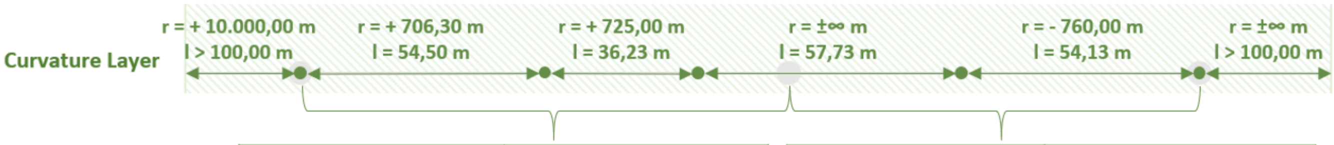
2.4.2.4 Curvature layer (optional)

The curve radius layer consists of along track information and represents the two-dimensional track course with points where the curve radius changes. Every curve radius point has a reference to the TrackEdge_ID, a curvature value, the azimuth and an offset to the TrackNode on Side A of the TrackEdge based on the real length of the TrackEdge.

The value of the curvature will be given with a “+” in front for a right curve and a “-” for a left curve depending on the direction of the TrackEdge.

Note: To avoid redundancies the absolute positions of the curvature points are not part of this layer. They can be calculated out of the track centerline layer.

Note: In a transition curve the curvature changes permanently. Therefore curvature points shall be evenly distributed over the length of the transition curve with a dynamic distance depending on the two connected curves - always under the condition to fulfil the $e_{cross\text{-}track}$ *requirement.*



TrackEdgeProperty_Type	Curve_Radius
TrackEdge_ID	6107_00_1809
Iterations	3
AttributePoint_Offset (1)	0,00 m
Curvature (1)	0,001415829 (1/+706,30 m)
AttributePoint_Azymuth (1)	1,4357 rad
AttributePoint_Offset (2)	54,50 m
Curvature (2)	0,001379310 (1/+725,00 m)
AttributePoint_Azymuth (2)	1,5414 rad
AttributePoint_Offset (3)	90,73 m
Curvature (3)	0,00000 (1/∞ m)
AttributePoint_Azymuth (3)	1,5928 rad

TrackEdgeProperty_Type	Curve_Radius
TrackEdge_ID	6107_00_1810
Iterations	2
AttributePoint_Offset (1)	43,48 m
Curvature (1)	-0,001315789 (1/-760,00 m)
AttributePoint_Azymuth (1)	1,5200 rad
AttributePoint_Offset (2)	97,61 m
Curvature (2)	0,00000 (1/∞ m)
AttributePoint_Azymuth (2)	1,4957 rad

Figure 21: TrackEdgeAttribute_Curvature details

2.4.2.5 Cant layer (optional)

The cant layer consists of along track information and represents the cross-track height differences between the two rail surfaces (see Figure 22: Definition of the cantFigure 22) with points where the cant changes (approach: significant change of the value = Δ 5 mm).

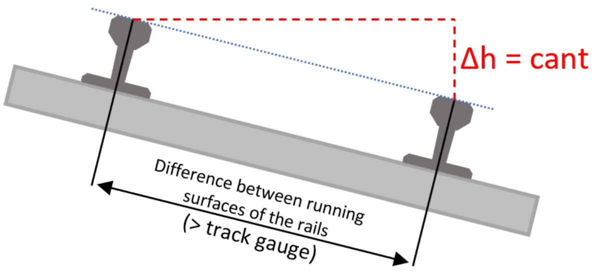
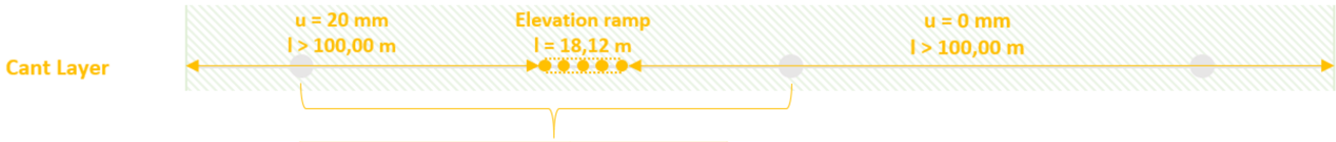


Figure 22: Definition of the cant

Every cant point has a reference to the TrackEdge_ID, a cant value and an offset to the TrackNode on Side A of the TrackEdge based on the real length of the TrackEdge.

The value of the cant will be given with a "+" in front when the left rail is higher than the right one and a "-" when the right rail is higher than the left one depending on the direction the TrackEdge.

Note: To avoid redundancies the absolute positions of the cant points are not part of this layer. They can be calculated out of the track centerline layer.



TrackEdgeProperty_Type	Cant
TrackEdge_ID	6107_00_1809
Iterations	5
AttributePoint_Offset (1)	54,50 cm
Cant (1)	+15 mm
AttributePoint_Offset (2)	59,03 cm
Cant (2)	+10 mm
...	...
AttributePoint_Direction (5)	Nominal
AttributePoint_Offset (5)	72,62 m
Cant (5)	0 mm

Figure 23: TrackEdgeAttribute_Cant example

2.4.2.6 Gradient layer (optional)

2.4.2.6.1 The height courses of real tracks are described by altitudes *h* and segments with a constant as well as variable (typically in transition segments) gradients *grd*.

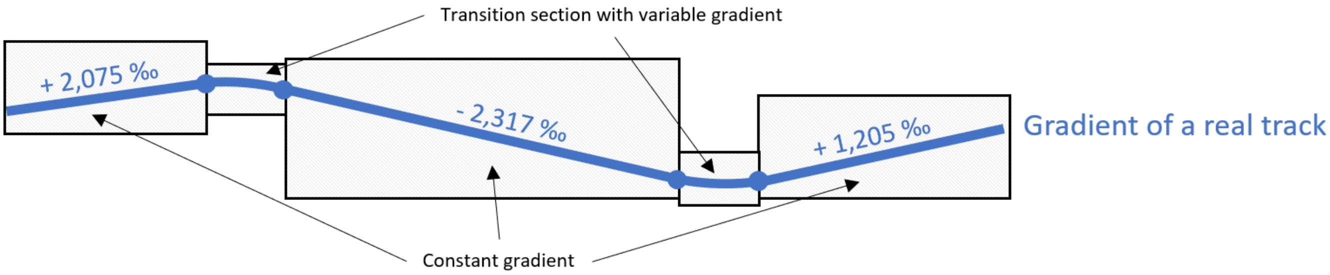
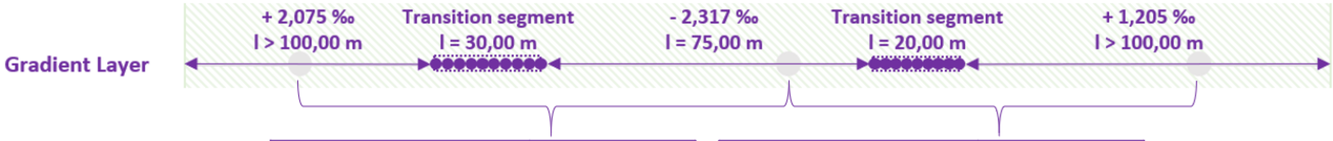


Figure 24: Gradient of a real track

To be able to represent every segment of the gradient in a digital map, a modelling based on the curve radius layer approach is sufficient:

The gradient layer consists of along track information and represents the elevation (ascent and descent) of the track course with points where the gradient significantly changes (approach: significant change of the value = Δ 0,1 ‰). Every gradient point has a reference to the TrackEdge_ID, a gradient value and an offset to the TrackNode on Side A of the TrackEdge based on the real length of the TrackEdge.

Note: To avoid redundancies the absolute positions of the gradient points are not part of this layer. They can be calculated out of the track centerline layer.



TrackEdgeProperty_Type	Gradient
TrackEdge_ID	6107_00_1809
Iterations	10
AttributePoint_Offset (1)	30,88 m
Gradient (1)	+1,978 ‰
AttributePoint_Offset (2)	34,21 m
Gradient (2)	+1,813 ‰
...	...
AttributePoint_Offset (10)	60,88
Gradient (10)	-2,317 ‰

TrackEdgeProperty_Type	Gradient
TrackEdge_ID	6107_00_1810
Iterations	9
AttributePoint_Offset (1)	24,70 m
Gradient (1)	-2,198 ‰
AttributePoint_Offset (2)	27.20 m
Gradient (2)	-2,087 ‰
...	...
AttributePoint_Offset (9)	44,70
Gradient (9)	+1,205 ‰

Figure 25: TrackEdgeAttribute_Gradient example

2.4.2.6.2 Alternative approach inspired by the ATO over ETCS Engineering Rules (see SUBSET-141 [9])

To be able to represent every segment of the gradient in a digital map and to reduce the amount of data points a translation of the transition section into sections with constant gradients could be feasible as described in the following:

The altitude h is a function of the along TrackEdge location s (offset): $[h(s)] = m$

The gradient grd is a function of the along TrackEdge location s (offset) as well segments and the derivation of the altitude function for s: $grd(s) = \frac{\mathrm{d}h(s)}{\mathrm{d}s}$; $[grd(s)] = ‰$

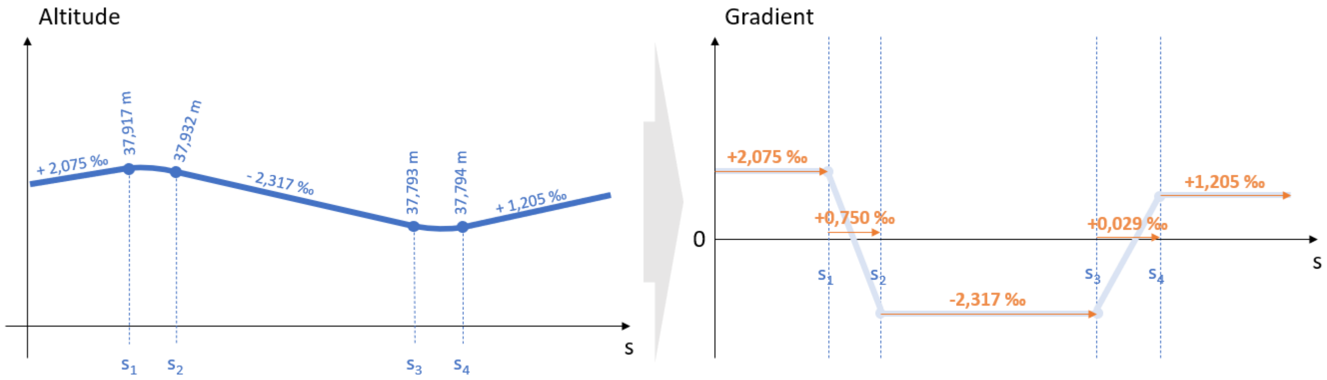


Figure 26: Gradient model

For the segment $s_{a,b}$ between s_a and s_b ($s_a < s_b$) with a constant gradient the function is defined as $grd(s) = const.$

e.g. **grd(s) = - 2,317 ‰** for $s_{2,3}$

For the segment $s_{a,b}$ between s_a and s_b ($s_a < s_b$) with variable gradient the function is defined as $grd(s) = \frac{h(s_b)-h(s_a)}{s_b-s_a}$

e.g. **grd(s) = (37,932 m – 37,917 m) / 20,000 m = + 0,750 ‰** for $s_{1,2}$

3 CONCLUSION

The contributors of DBN, SBB, SNCF, SMO, ADS, CAF and NAVE developed a very usable approach of a digital map for localisation purposes in the CLUG project and beyond. The defined mandatory content of the digital map fulfils the need of the localisation algorithms on the train and the optional content could be useful for validation functionalities and other future systems. The structure of the digital map with the layer approach is universally extendable to provide data not only to the localisation unit but also to other trackside and onboard systems in future stages of the development. The developed topology model is a simple as possible solution to represent the required data, it is derived from existing approaches and could be usable for a long term because of its conformity to existing RCA topology approach which is aligned on European level.

End of document.