D1.1 - Report concerning line and use-case based requirements

WP 1 – Generic FC Train Requirement Specifications and Concept

Task 1.1 – Use-cases and derivation of related requirements for generic train development

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Contributions Table

Partner	Contribution
DLR	Author, line analysis, use-cases preparation, analysis of use-cases, mechanical energy simulation, market potential.
RENFE	Provision of rolling stock data, services and timetables, contribution to workshops to select representative use-cases, support and review, quality check.
CAF	Provision of vehicle specifics, assistance in simulations, contribution to workshops to select representative use-cases, support and review.
ADIF	Provision of rolling stock data, services and timetables, contribution to workshops to select representative use-cases, support and review.
IP	Provision of rolling stock data, services and timetables, contribution to workshops to select representative use-cases, support and review.
ZSSK	Provision of data for line analysis Slovakia.

Executive Summary

The project 'Fuel Cell Hybrid Power Pack for Rail Applications' was an innovation action in Horizon 2020, the most significant research programme in the European Union. Aimed at reducing the production costs of fuel cell systems in transport applications while increasing their service life to levels that can compete with conventional technologies, the programme has awarded the project entitled FCH2Rail, under Grant Agreement No. 101006633 ([1]).

FCH2Rail is a project focused on developing, building, testing, demonstrating and homologating a scalable, modular and multi-purpose Fuel Cell Hybrid PowerPack (FCHPP) applicable for different rail applications (multiple units, mainline locomotives and shunting locomotives). It is also suitable for retrofitting existing electric and diesel trains, to reach TRL7.

The purpose of Deliverable D1.1 is to analyse and gather requirements on hydrogen trains from operational and infrastructural parameters. This is done within two steps. First a high-level line analysis is performed to collect infrastructural and operational characteristics for various countries in the European Union. In the second steps, representative use-cases are identified and simulated to evaluate detailed requirements on the FCHPP.

The first part of the document (section 1) defines requirements of interests. The defined requirements are described. A methodology is described to gather and evaluate these requirements from various data sources. Section 2 describes and characterises then the data used such as timetables, digital elevation models and Open Street Map. Section 3 states the rolling stock of the investigating countries Spain, Portugal, Germany and Slovakia. The vehicles, their fleet sizes and ages are shown and categorised by their usages.

Section 4 characterises all railway services suited for the operation of hydrogen (bi-mode) trains (i.e. line-based requirements) in the investigating countries on a higher level. For each service, the requirements defined in section 1 are visualised and put in respective to each other and to vehicle usages. The investigated countries are compared with each other. Section 5 describes a detailed investigation of various use-cases. A use-case is the specific operation of a vehicle on a certain line over a business day. A mechanical energy simulation is performed for each use-case. Simulation results are finally compared. In section 6 the findings of this study and achievable market potentials for generic FC trains are discussed.

Glossary of Terms

Acronyms	Description
CA	Consortium Agreement
GA	Grant Agreement
FCH2Rail	Fuel Cell Hybrid PowerPack for Rail Applications
DSM	Digital Surface Model
FCHPP	Fuel Cell Hydrogen Power Pack
ESS	Energy Storage System
FC	Fuel Cell
Bi-mode FCHMU	Bi-mode Fuel Cell Hybrid Multiple Unit
DMU	Diesel Multiple Unit
OSM	Open Street Map
BEMU	Battery electric multiple unit

Contents

1. Definition Of Requirements

This deliverable aims to identify and describe various line-based requirements and use-case based requirements. In this chapter, requirements of interest are defined. The application of these definitions will be described in chapters 4 "Line-based requirements" and 5 "Use-case based requirements".

As the derivation of requirements is done to enable and support the generic train development, the main perspective is on the vehicle. Therefore, service profiles instead of just railway tracks are considered here. A service is defined as a railway operation between two fixed start- and end stations scheduled and operated with a vehicle. The services will be considered on two levels: In the line analysis all routes with non-electrified parts in the study area are considered. In this step, only single trips are considered. On the second level specific use-cases, meaning the operation of a specific vehicle over a business day are considered. For these use-cases a more thorough analysis will be performed, including simulations of the respective traction energy demand at wheel. For this, the following requirements are evaluated:

Table 1: Line-based requirements

Requirement	Description	Unit	SI
Route length	Distance between start and end station.	Metre	m
Electrification degree	Percentage of the travelled route under catenary.	Percentage	%
Longest autonomy	Longest continuous catenary-free section in one trip.	Metre	m
Cumulated autonomy	Summed distance on non-electrified parts in one trip.	Metre	m
Start-end slope	Slope resulting from the elevation difference of the start and terminus station and the trip length.	Permille	‰
Net elevation gain	Absolute elevation difference between start and terminus station.	Metre	m
Average stop distance	Route length divided by number of stops.	Metre	m
Average velocity	Route length divided by trip time.	Kilometre per hour	Km/h

Table 2: Use-case-based requirements

Requirement	Description	Unit	SI
Trips per day	Maximum number of trips (start-to-end or return) of a specific vehicle over a business day.	Count	#

Daily distance	Cumulated route length over a business day.	Metre	m
Daily travel time	Cumulated travel time over a business day in minutes.	Minutes	min
Longest autonomy	Longest continuous catenary-free section over a business day.	Kilometre	Km/h
Cumulated autonomy	Summed distance on non-electrified parts over a business day.	Kilometre	Km/h

Requirements derived with mechanical energy simulations are described in Table 3. Energy and power are taken at wheel level. Auxiliary demand or train efficiencies are not going to be considered.

Table 3: Use-case attributes from simulation

Requirement	Description	Unit	SI
Traction energy at wheel.	Positive amount of energy needed to cover traction demand over time for catenary-free sections.	Energy	kWh
Recuperative braking energy at wheel.	Negative amount of energy needed to cover traction demand over time for catenary-free sections.	Energy	kWh
Specific traction energy at wheel (without recuperative braking energy).	Positive amount of energy divided by vehicle weight and covered kilometres for catenary-free sections.	Energy / Weight*Kilometre	kWh/(tkm)
Mean traction power at the wheel.	The average of the current power needed to cover traction energy at wheel level for catenary-free sections.	Power	kW
Peak traction power at the wheel.	The maximum traction power over the route at wheel level for catenary-free sections.	Energy	kW

1.1 Methodology for line-based requirements

In order to analyse the rail networks in term of the above defined line-based requirements various tools for the investigating countries are developed. The data used is described in section 2.

For Spain and Portugal, passenger railway services currently operated with diesel trains were identified. Lines that were known to be electrified during the making of this study were excluded from the analysis. If a service is operated in various way over the same routes (such as number of stations or varying vehicles) were considered as different services. From timetables station names, trip times, driving times and stop times were gathered. A routing algorithm was deployed to determine the routes over the rail network for each service. Next, a Dijkstra routing algorithm [1] was deployed over a noded Open Street Map (OSM) based routing network. For this vector-based rail networks from the OSM data model (keys:railway; unfit tracks such as industrial or tram tracks were filtered out) were acquired. The network was noded using the pg-routing tool framework for PostgreSQL. The stations in the gathered timetables were matched with OSM-stations and connected to the nodes of the routing network. For this a chained distance-query using stepwise matching distances from 0.00001 arcseconds to 0.0075 arcseconds were used. As Dijkstra is a shortest path-algorithm, deviations from the actual routes could be avoided by routing between each station along a service. OSM attributes such as electrification information, maximum speeds, tunnels and bridges were than reapplied to the acquired routes by a spatial overlay.

The elevation profiles were derived from a digital surface model (DSM). To compensate data inaccuracies in the DSM as well as infrastructure (i.e. tunnels, bridges, etc.) a set of geostatistical countermeasures were applied to derive a smooth elevation profile. Line base requirements were then derived (compare Table 1).

In Germany there is a multitude of routes and vehicles for passenger services operated not/partly under catenary. In Germany there is a nationwide timetable available, provided by German railway operators and client bodies. These have been extended with geo-routes. For Germany, all trips within the public timetable operated not or partly under catenary have been filtered. As the timetable data is at a high resolution (meaning each trip is included), similar trips were merged into services. For processing reasons, return journeys of a service were also considered separately in this dataset. As vehicle types per service are unknown, the rolling stock was described separately (compare section 3.3). The geo-routes available are not attributed with infrastructural information. In a stepwise nearest neighbour processing chain, the trips were attributed with maximum speeds and electrifications from OSM. While this process is sufficiently accurate to get a good overview of the requirements it has its limitations in terms of errors and gaps in data. Longest autonomies might be flawed in some cases as data gaps in electrification attributes could not be accounted for.

For Slovakia, the line-based requirements were abstracted manually for each service and delivered by ZSSK (Železničná spoločnosť Slovensko).

1.2 Simulation methodology

Use-cases were chosen for detailed investigation, i.e. for mechanical energy simulation. The use-cases were chosen to represent:

i) the most common operations and
ii) the most demanding operations.

They were chosen within workshops of the contributing project partners in conjunction with statistical measures of the line bases requirements.

The acquired and derived attributed routes generated in section 1 were translated into arrays and transferred into a simulation-friendly data structure. To consider possible circulations, the maximal possible circulation of a train over a business day was derived from the timetables, representing the worst-case circulation to define maximum autonomy over a business day. Based on the use-cases derived, simulation input files for longitudinal dynamic simulations were generated.

Prior in-depth knowledge specifically of the energy storage system (ESS), fuel cell (FC) as well as the drivetrain efficiencies is deliberately excluded. Furthermore, specific auxiliary demands, as cabin air conditioning or battery and fuel cell cooling are excluded in this study as well. Instead indicative characteristic values in terms of cumulated traction energy and time-based power demand at the wheels are evaluated. A more concrete powertrain layout is topic to subsequent Deliverable D1.4.

A power demand profile is obtained with the Trajectory Planner Tool (TPT). This algorithm, developed by DLR, represents a longitudinal dynamic simulation of rail vehicles. Input variables are timetable and route data as well as vehicle variables, such as, mass, traction power and acceleration. The TPT calculates the speed profile, which is exclusively composed of acceleration, deceleration and cruising phases. Hereby, a search algorithm is deployed, which merges aforementioned acceleration, cruising and braking phases together to meet the given timetable and applicable speed limits. [2]. Two velocity profiles are calculated. A profile with maximum possible speed and a profile with a reduced velocity. The applicable search criterion for the *Reduced- Velocity Profile* is to minimise average speed without violating the timetable. If a timetable compliant solution cannot be achieved with this approach, the *All-Out-Profile* is applied as a fallback solution. The different profiles are shown in Figure 1.

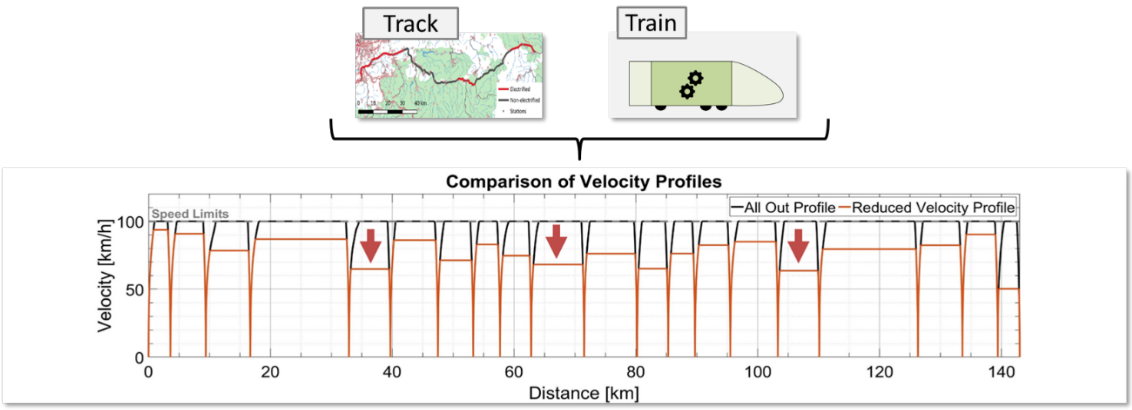

Figure 1: Comparison "All-Out-Profile" and "Reduced Velocity Profile"

As a result of the speed trajectory and the train-specific characteristics, the power profiles are generated at wheel level.

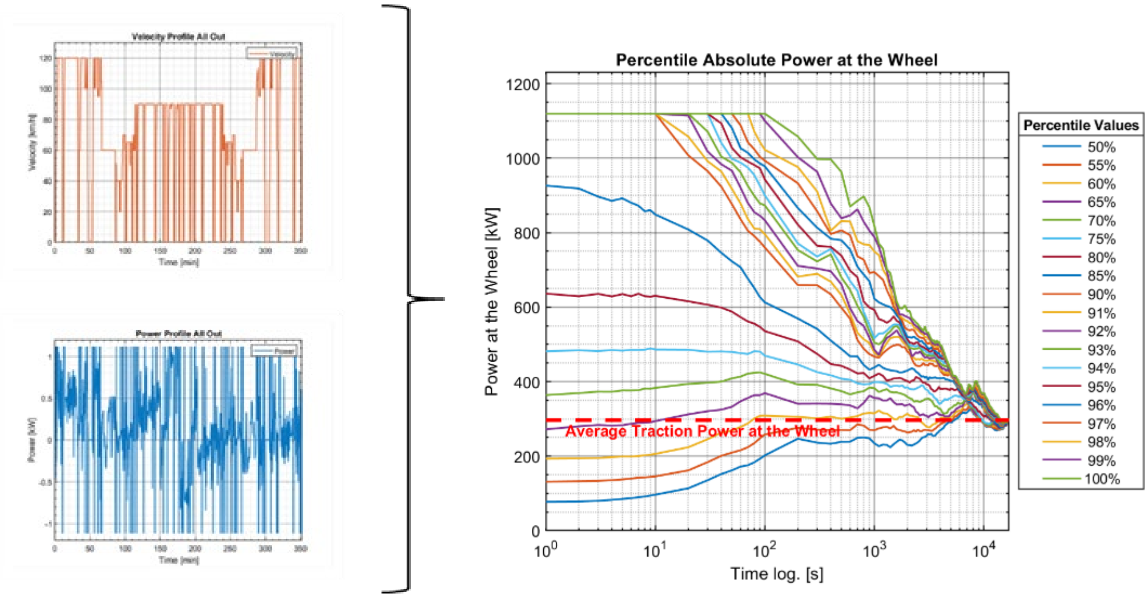

Figure 2: TPT generated Velocity and Power Profile (left) and time weighted load curve at the wheel of the use-case Zaragoza – Canfranc – Zaragoza.

The complete demand profile, as seen on the left side of Figure 2, is averaged over a range of suitable moving time windows. As this study focuses on the investigation of **bi-mode** FCHMU, only the non-electrified sections of the use-case are consulted for the further study. Power requirements for the most demanding sections in use-cases are indicated by high percentiles in the time weighted load curve (i.e. the 100th percentile represents the time window with the highest average load in the driving circle; here 1120 kW over 100 seconds). This deliverable covers requirements arising from operation and infrastructure. Analysis on components is part of subsequent deliverables such as D1.3 [3] and D1.4 [4].

2. Data And Inputs

This chapter describes the data used in the analysis of line-based requirements und use-case based requirements.

The project partners Renfe and IP provided timetables of railway services operated partly or completely catenary-free. They provided station names, locations, distances, stop times, arrival times and departure times (accuracy one minute). Furthermore, they provided types and characteristics of the vehicles operated on the services as well as passenger loads and number of circulations. Infrastructural managers IP and Adif provided information about current and future electrification, gauges, elevation information, shunting yards and associated shunting locomotives. CAF provided vehicle specifications needed for mechanical simulations.

From public data sources Open Street Map data was used to assess route characteristics such as electrification, gauge and speed limits. Missing and inconsistent attributes were compensated with information from infrastructure managers (see above) and with geodata from the national centre for Geographic Information (CNIG, Centro Nacional de Información Geográfica) [5], namely vector files of the transport networks (RT, Redes de Transporte (RT). To assess slopes and elevations JAXA ALOS DSM [6] was used with a 0.1 to 0.1 grid size (approx. 30 x 30 metres) and vector files from the CNIG (see above). For the analyses of Germany, the used timetables are based on GTFS-data provided by DELFI [7] and pre-processed by GTFS.de [8].

The data sets produced within this task have been enriched with metadata and uploaded. The data is published under the DOIs *10.5281/zenodo.6355894* and *10.5281/zenodo.6359030*.

3. Rolling Stock

In this chapter the diesel-bound rolling stock of each investigating country will briefly be described. The here described vehicles with an emphasis on diesel multiple units (DMU) can potentially be substituted by fuel cell trains. In relation to this, the railway systems are described in terms of gauges, electrifications and operational characteristics in D1.3 [3].

3.1 Spain

3.1.1 Vehicles for passenger services

In non-electrified or part-electrified **passenger** railway services, three kind of vehicles are used: i) multiple units for Iberian gauge, ii) multiple units for metre gauge and iii) mainline locomotives carrying Talgo coaches. Table 4 to Table 6 list the vehicles currently in operation.

3.1.1.1 DMU Iberian gauge:

Table 4: DMU Iberian gauge in Spain

Vehicle	Capacity (Seats)	Max Speed [km/h]	Autonomy [km]	Fleet Size	Picture
S592 MD	228	120		45	
S592 Cercanías	200	120			
S 592.2 MD	200	140			
S 594	126	160	1000	23	
S 596	56	120	1000	23	
S 598	188	160	1000	21	
S 599	184+1	160	1000	50	

3.1.1.2 DMU metric gauge:

Table 5: DMU metric gauge in Spain

Vehicle	Capacity (Seated and Standing)	Max Speed [km/h]	Fleet Size	Construction /Status	Picture
S 2400	216	80	29	1983-86 refurbished 1998-2000	
S 2600	299	80	24	1966 – 74 refurbished 1994-1997	
S 2700	90	120	17	2009-2010	
S 2900	78	100	12	2010-2011	

3.1.1.3 Mainline Locomotives for passenger railway services:

Table 6: Mainline locomotives for passenger services in Spain

Vehicle	Traction	Max Speed [km/h]	Fleet Size	Construction /Status	Gauge [mm]	Picture
S334	Diesel-electric	200	28	2006	1668	

S333.300	Diesel-electric	120/160	32	2002	1668	

3.1.2 Shunting locomotives

The dominant types of shunting locomotives in Spain are Class 310 and Class 311. These are owned and operated by Adif on several shunting yards across the country. Adif will purchase 22 Stadler Eurodual hybrid locomotives (diesel + electric) for 1435 gauge and there is a forecast to purchase eight similar locomotives for 1668 mm and three more for 1000 mm.

Table 7:Shunting locomotives in Spain

Vehicle	Traction	Max Speed [km/h]	Fleet Size	Construction/Status	Gauge [mm]	Picture
310	Diesel-electric	110	55 (54)	1989	1435	
311.1	Diesel-electric	90	51 (39)	1986	1435	
319.2	Diesel-electric	120	5	1965	1435/1668	

319.3	Diesel-electric	140	2	1965	1435/ 1668	
321	Diesel-electric	120	6	1966	1435	

*Image sources: https://www.listadotren.es/

3.2 Portugal

In the upcoming section the Portuguese DMU-stock will be described. In Portugal there are three DMU-types currently in operation, with a total fleet of 48 vehicles. As electrification plans are to be rolled-out near term, it is expected that parts of the fleet will drop out of operation. Mainline locomotives with diesel propulsion are not in operation.

Table 8: DMUs in Portugal

Vehicle	Max Speed [km/h]	Fleet Size	Picture
UDD 450	120	19	
UTD 592	90	7	

UDD 9600	90	22	

3.3 Germany

In Germany, a multitude of diesel-fuelled trains are in operation. Pagenkopf et.al. (2020) [9] describe and characterise the rolling stock for passenger services in Germany. Figure 3 shows the most common DMU operated in Germany and respective construction years from 2000 to 2019. As can be seen at the beginning of the 2000 decade, more vehicles where produced than in the years from 2006. Assuming a typical vehicle service life of approx. 30 years, this indicates fleet renewal in the next decade.

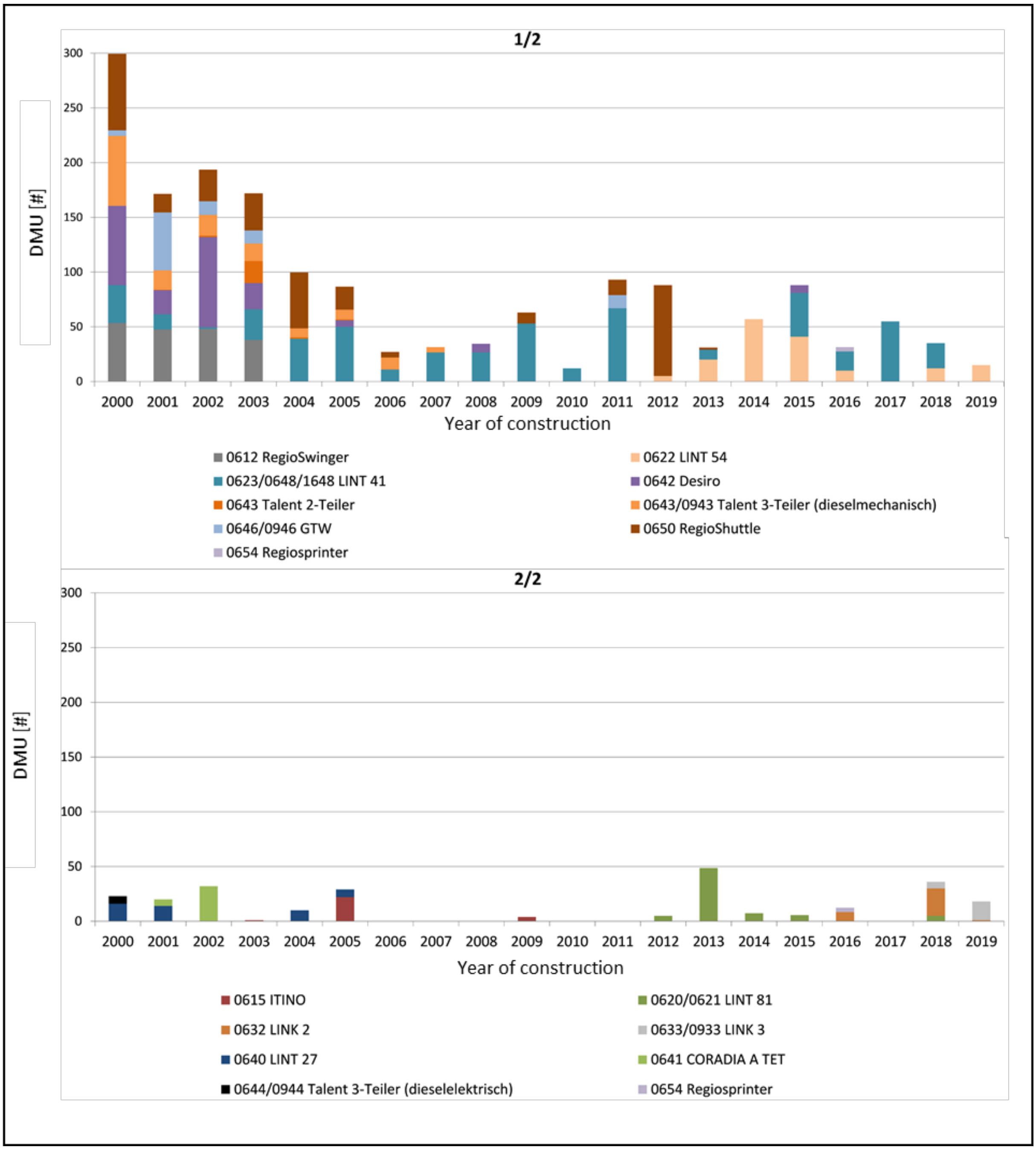

Figure 3: Construction years of DMU`S in Germany (adapted from [9])

In Pagenkopf et.al. (2022) [10], German rolling stock of shunting locomotives where analysed. Figure 4 shows the number of newly built and refurbished diesel or diesel-hybrid shunters between 1990 and 2019. The data does not distinguish between propulsion technology for the time series. In 2020 approx. 60% of new built shunters had diesel combustion engines and 40 % had diesel-hybrid propulsion.

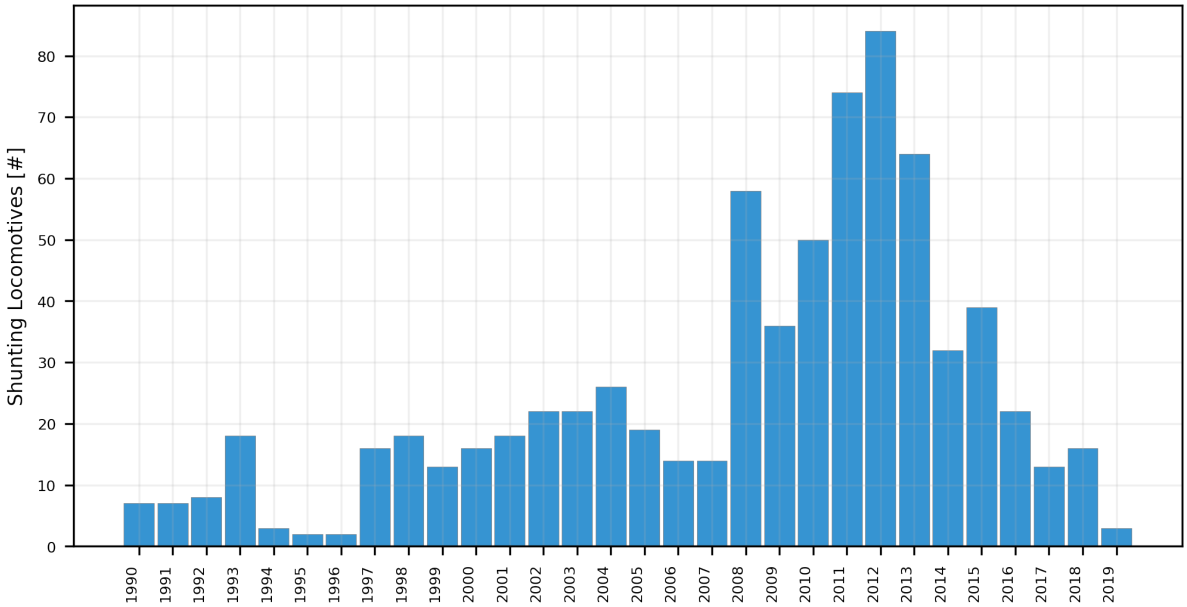

Figure 4: Construction years of shunting locomotives in Germany (adapted from [10]).

Alternative propulsion technologies

In Germany, new propulsion technologies for multiple units are under development. In 2018 the world's first two hydrogen electric multiple units were put in scheduled passenger service at Elbe-Weser-Netz between Cuxhaven, Bremerhaven, Bremervörde and Buxtehude. Battery trains of the Stadler Akku Flirt type have been ordered for NAH.SH's northern and eastern tender network (to be used in regular service from 2022) and for Pfalznetz in southern Germany (to be used in regular service from 2025).

In shunting operation, hybridised diesel locomotives have been replacing more and more diesel locomotives in recent years, both concerning retrofits but even more so in terms of new-build locomotives (e.g. Alstom Prima H3). In 2022, up to 50 catenary electric shunting locomotives with additional batteries for last mile operations, have been ordered at Vossloh Locomotives (Type DM 20-EBB). When it comes to hydrogen locomotives, up to now, there are a couple of research and demonstrator projects across Germany and Europe (e.g. by PESA) targeting new-build and retrofitting diesel locomotives both to fuel cell electric and to hydrogen internal combustion engine powertrains. However, as of January 2022, no large order on hydrogen locomotives has been put across the market so far, probably mainly because, these locomotives are still in a pre-commercial development phase.

3.4 Slovakia

Seven different DMU models are currently in operation in Slovakia. The drive technologies are diesel-hydraulic and diesel-electric. 80% of the transport service in Slovakia takes place under catenary. A minor number of tracks are due to electrification. The DMU fleet is dominated by DMU type ŽOS Vrutky

Regio Mover (53 vehicles). Other DMU-types used in Slovakia are 840, 425.9 (metre gauge), 230, 310, 812, 813 and 861. Mainline locomotives operated are Type 757 and ÖBB 2016.

For Route 140 from Nové Zámky to Prievidza, ZSSK intends to introduce two FCH units on this route. After successful pilot deployment, there are intentions to replace all diesel units with FCH units for these lines, i.e. overall 12 units by the end of 2030.

4. Line-based Requirements

This section describes line-based requirements as described in section 1. Line-based requirements have been gathered for railway services which are completely or partly catenary-free. If a route is serviced with various vehicles and/or stations they are considered to be separate services as the energy demand varies. The methodology of this chapter is described in section 1.1.

4.1 Line analysis Spain and Portugal

This chapter describes line-based requirements for Spain and Portugal. In Spain and Portugal 73 services were considered for analysis.

4.1.1 Route Length, electrification degree, longest autonomy and cumulated autonomy

This section covers route lengths and electrifications/autonomies. The distributions of the related line-based requirements are shown in Figure 5.

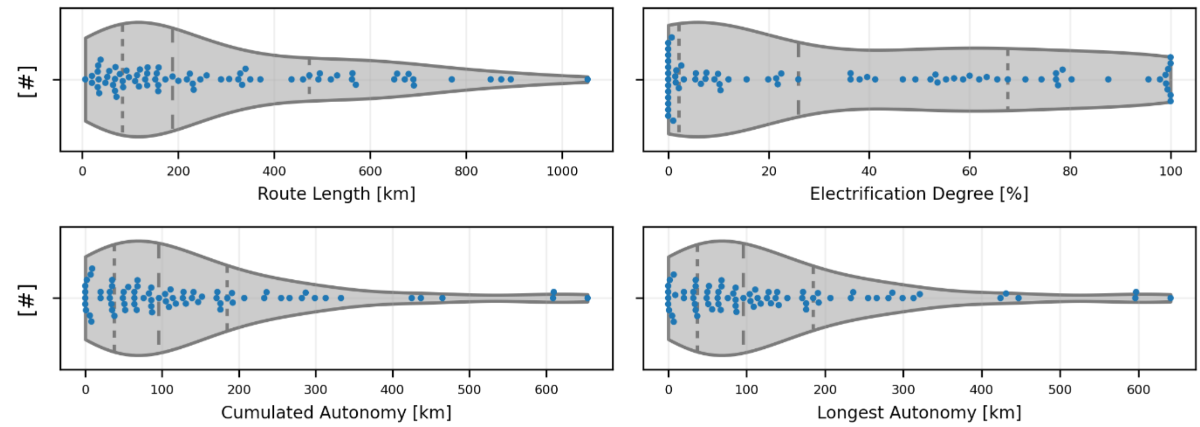

Figure 5: Distribution of route length, electrification degree, longest autonomy and cumulated autonomy for Spain and Portugal.

Service lengths are distributed between 6 and 1100 km length. Especially low route lengths are short transit services, for instance the commuter line C-3 Alacant-Terminal - Sant Vicent Universitat, where mostly students are transported from the city centre to the university. The electrification is shown in the upper right pane. Electrification degrees of 100 percent are considered in this analysis when DMU are operated on these tracks. There can be many reasons for this. For instance, it can apply that the vehicle will be used on a different service alter and that it is cheaper to use a DMU under catenary then to change vehicle and driver. As there are many possible operational reasons it was assumed that operation with bi-mode trains on these lines will be profitable or beneficial.

Figure 6 left pane shows the sorted lengths of all services and the lengths of their electrified sections. Non-electrified sections on part-electrified routes represent autonomy requirements (right side). The autonomy is the sum of lengths of all non-electrified sections. The right pane shows the autonomies for all Spanish and Portuguese lines considered, stacked with the electrified length and sorted by autonomy length. The lines with the highest autonomies are the ones with the lowest electrification degree, and the one with the lowest autonomies are the ones with the highest electrification degree. As this only represents single trips, target autonomy requirements for diesel trains can substantially differ by the number of trips for a vehicle. Circulations and daily autonomies are considered in the detailed analysis covered in section 5.

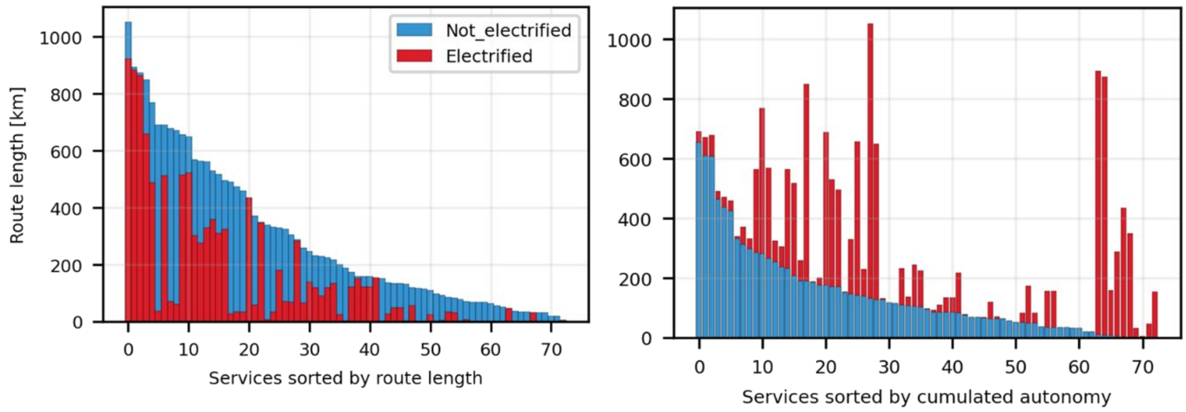

Figure 6: Sorted route length, electrified sections and autonomies.

Figure 7 shows the distribution of route lengths (left) and autonomies (right) for various service types. Mainline locomotives cover services with general longer distances and in relation longer autonomies. Multiple units used on metre gauge are commonly shorter with shorter autonomies.

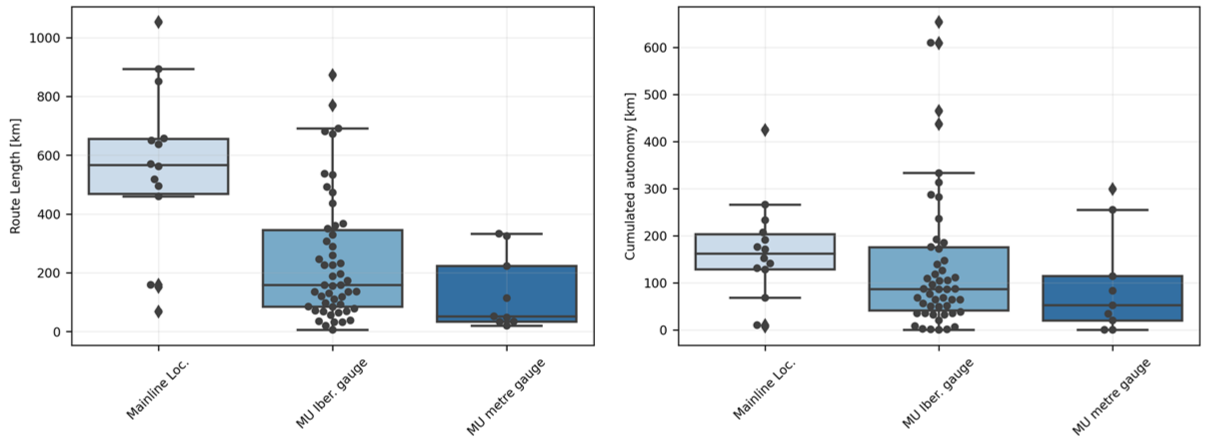

Figure 7: Distributions of route lengths and cumulated autonomy per service type in Spain and Portugal.

Figure 8 shows the annual train kilometres under catenary (blue) and not under catenary (red) for rolling stock vehicle types. It can be seen that some vehicles account for a majority of train kilometres (S252, AUT 2400). The distance covered by vehicle types are shown in Figure 8. Vehicles with a smaller variance (i.e. a smaller box) have specific usages in terms of distances. Larger boxes represent more various usages

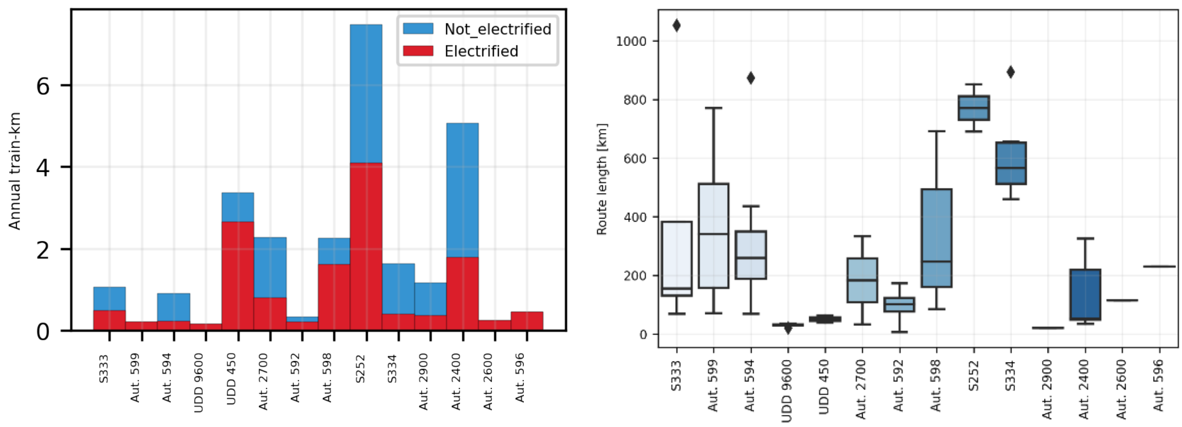

Figure 8: Annual train kilometre and route length per vehicle for Spain/Portugal.

The frequency of services (i.e. trips per day) range between 2 (often connecting periphery stations with long driving times) and 55 (commuter lines connecting bigger centres with the surroundings). As can be seen in Figure 9, short services tend to have higher frequencies than long-distance services.

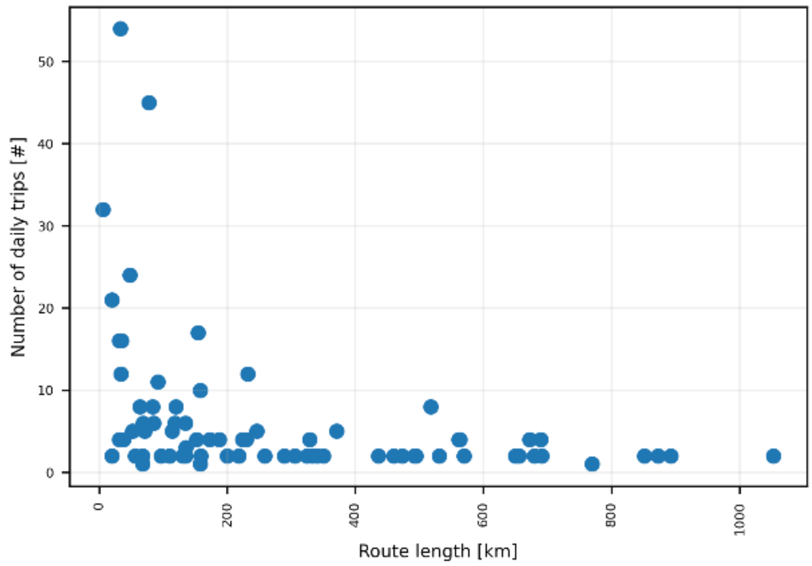

Figure 9: Daily trips over route length for Spain and Portugal.

4.1.2 Average stop distance and average speed

During a railway trip, the acceleration phases are usually the most energy-intensive processes. A low stop distance means that vehicles have to start frequently, resuming in higher energy demands. If the stop distance is low and the average velocity is high, high demands on the FCHPP are to be expected. Low average velocities can indicate long standing times in stations or difficult terrain. Figure 10 shows the distribution of both parameters.

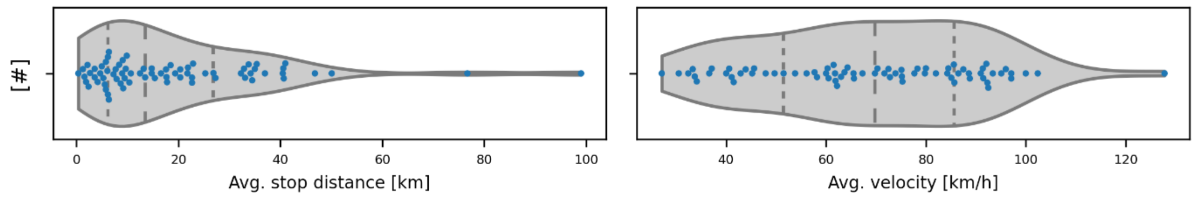

Figure 10: Distribution of average stop distances and average velocities for Spain and Portugal.

Figure 11 shows the average stop distance plotted over the average velocity for various vehicle types. The upper right area in the left scatter plot represents high demanding lines. Mainline locomotives cover the longest routes, followed by DMU on Iberian gauge. Metre gauge lines are often operated on low average velocities. The scatter plot on the right shows the same distribution for various vehicle models.

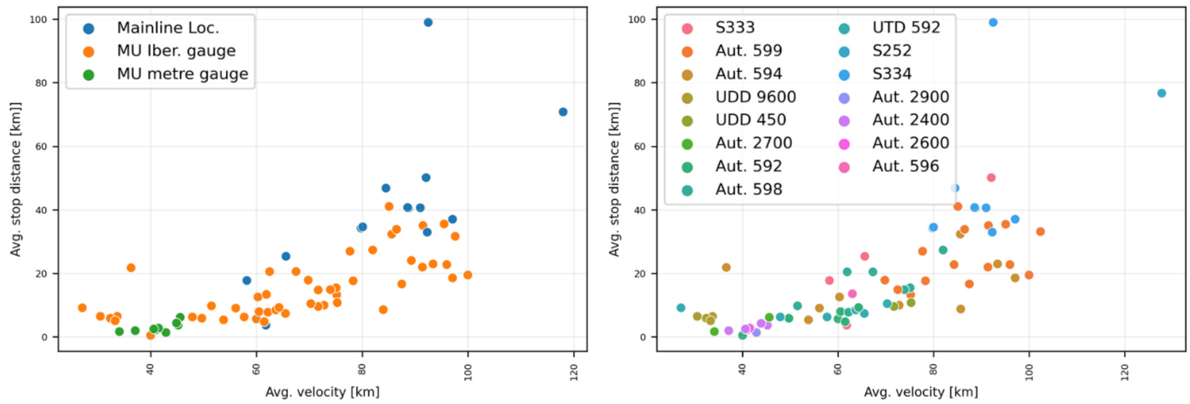

Figure 11: Average velocity over average stop distance for Spain and Portugal.

4.1.3 Start-to-end slope, start-to-end elevation gain

Elevation gains and gradients have significant influence on the energy demand of routes. While the total elevation gain mainly influences the total consumption and the average power of the fuel cell and battery components, high gradients indicate high peak powers of the FCHPP. Figure 12 shows the distribution of absolute elevation gains between start station and terminal station. A quarter of the routes have elevation gains below 27 m and 50 % of the routes have elevation gains below 195 metres. The highest elevation gains are at 980 metres. This is the elevation difference between the start elevation and the end elevation. Demanding topologies throughout the route are not considered. Those are reflected in the use-cases analysis in chapter 5. Slopes vary between 1.6 ‰ and 11.7 ‰ with the median at 0.85 ‰.

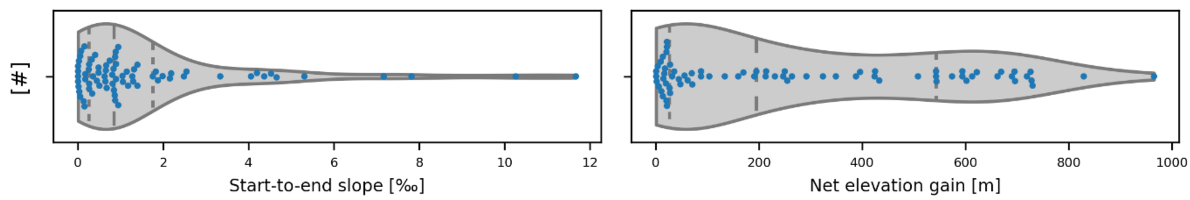

Figure 12: Distribution of start-to-end slopes and net elevation gains for Spain and Portugal.

High-demand services and low demand services can be identified in conjunction with the average stop distance and the average velocity. Figure 13 shows service attributes plotted over three axes. Most demanding points can be found in the upper front corner where the average stop distance is low, the average speed is high and elevation gains and or slopes are high. As seen before, mainline locomotives and some DMU-services account for the most demanding lines while metre gauge services have low demanding also in terms of elevation.

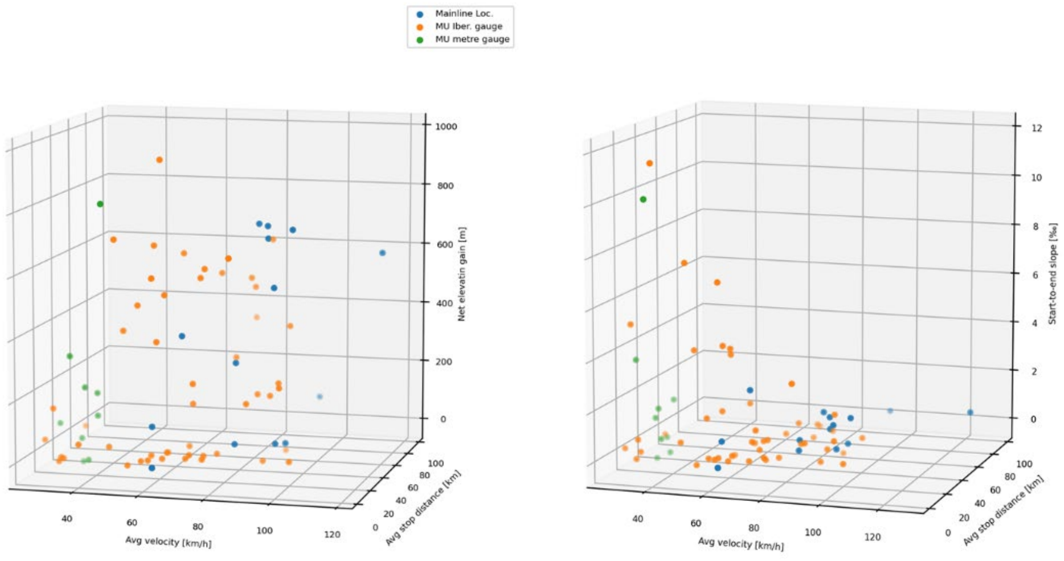

Figure 13: 3D-scatterplots of avg. velocity, avg. stop distance and net elevation gains/ start-to-end-slopes.

4.2 Line analysis Germany

This chapter describes line-based requirements for Germany. In Germany 1417 varying services were considered for analysis. This high number is because in the GTFS timetable, each trip over a year is included. Similar trips (same stations and similar stop/arrival times) were merged as well as turnaround trips. Very rare trips (< 30 per year) were excluded. Nevertheless, trips of a service vary very often in start/end stations and number of stations, much more than in Spain, Portugal and Slovak.

4.2.1 Route Length, electrification degree, longest autonomy and cumulated autonomy.

This section covers route lengths and electrifications/autonomies. The distributions of the related line-based requirements are shown in Figure 14.

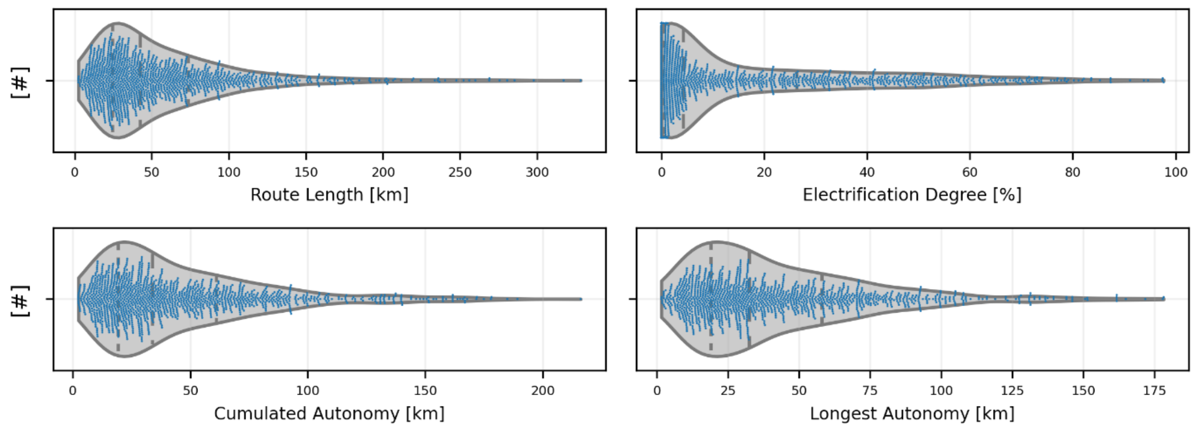

Figure 14: Distribution of route length, electrification degree, longest autonomy and cumulated autonomy for Germany.

Service lengths are distributed between 2 and 330 km length. Low electrification degrees are common (median = 4.5 %). Figure 15 left pane shows the sorted lengths of all services and the lengths of their electrified sections. The right upper pane shows the autonomies for all German lines considered, stacked with the electrified length and sorted by autonomy length. Electrification degrees are evenly distributed over route lengths and autonomies. Autonomies range between 2 and 220 km.

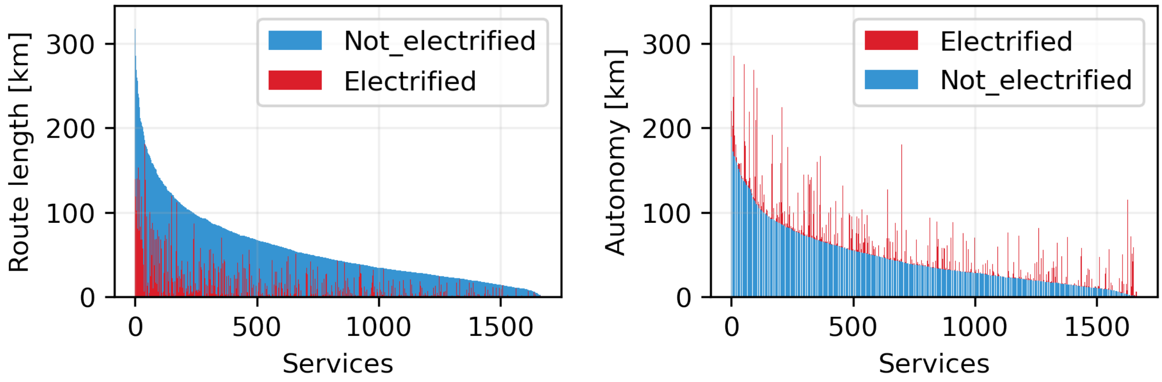

Figure 15:Sorted route length, electrified sections and autonomies.

The frequency of services (i.e. trips per day) range between 1 (often trips at the beginning or end of a business day, leaving or arriving depots) and 59. As can be seen in Figure 16 short services tend to have higher frequencies than long-distance services.

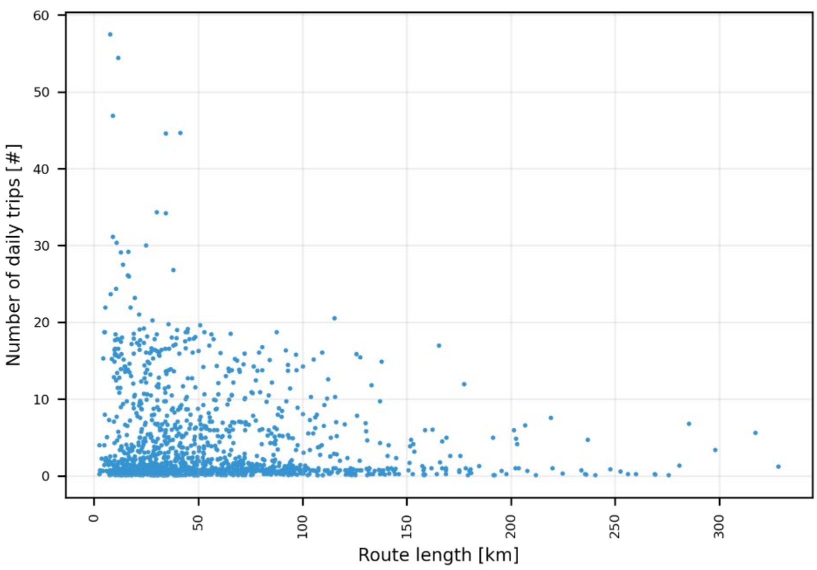

Figure 16: Daily trips against route length for Germany.

4.2.2 Average stop distance and average speed

During a railway trip, the acceleration phases are usually the most energy-intensive processes (compare 4.1.2). Figure 17 shows the distribution of both parameters. Average stop distances range between 800 metres and 39 km with the majority between 3.4 (25 %) and 7.3 (75 %). Average velocities (including stop times) range between 30 km/h and 111 km/h.

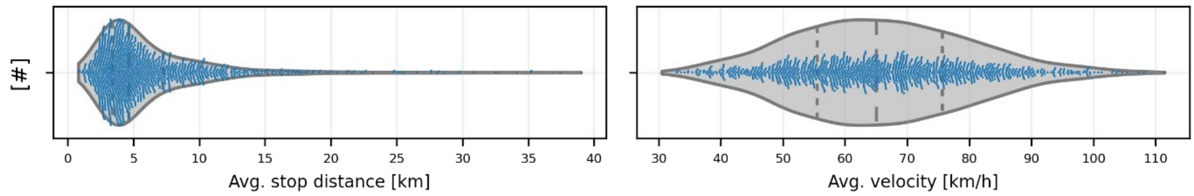

Figure 17: Distribution of average stop distances and average velocities for Germany.

Figure 18 shows the average stop distance plotted over the average speed. The upper right area in the scatter plot represents high demanding lines. The figure also shows that longer lines tend to have longer stop distances.

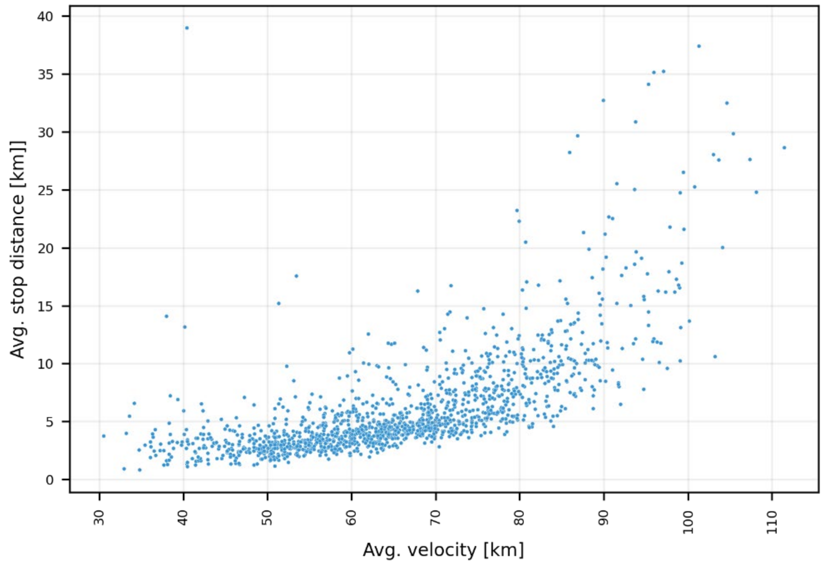

Figure 18: Average velocity over average stop distance for Germany.

4.2.3 Start-to-end slope, start-to-end elevation gain

Elevation gains and gradients have significant influence on the energy demand of routes (see section 4.1.3). Figure 19 shows the distribution of net elevation gains between start station and terminal station. A quarter of the routes have elevation gains below 20 m and 50 % of the routes have elevation gains below 57 metres. The highest gains occurring account for up to 607 m altitude change.

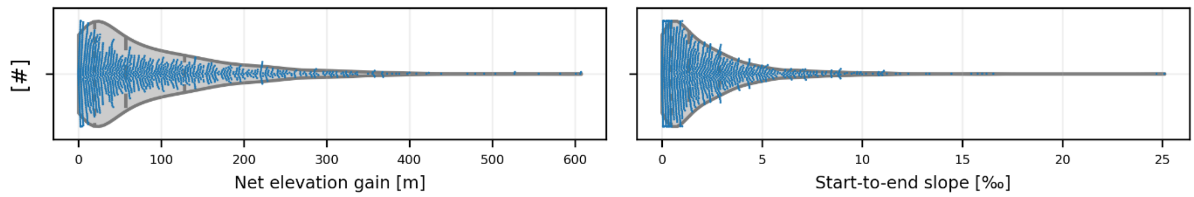

Figure 19: Distribution of start-to-end slopes and net elevation gains for Germany.

4.3 Line analysis Slovakia

This chapter describes line-based requirements for Slovak. In Slovak 51 services were considered for analysis.

4.3.1 Route Length, electrification degree, longest autonomy and cumulated autonomy

This section covers route lengths and electrifications/autonomies. The distributions of the related line-based requirements are shown in Figure 20.

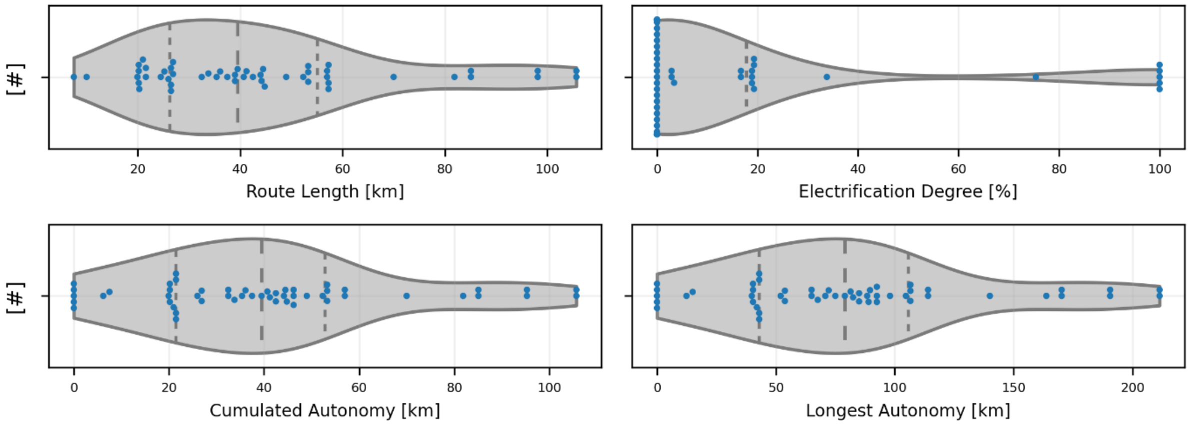

Figure 20:Distribution of route length, electrification degree, longest autonomy and cumulated autonomy for Slovakia.

Service lengths are distributed between 7.5 and 106 km in length. Low electrification degrees are common (75 % of services have electrification degrees below 18 %) Part-electrified routes are rare. Figure 21 left pane shows the sorted lengths of all services and the lengths of their electrified sections. The right upper pane shows the autonomies for all Slovakian lines considered, stacked with the electrified length and sorted by autonomy length. Autonomies range between 0 and 106 km.

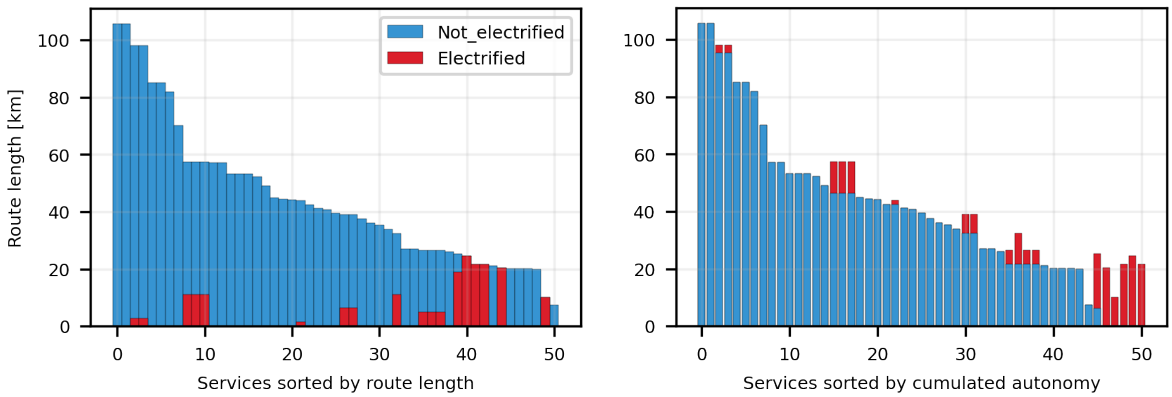

Figure 21: Sorted route length, electrified sections and autonomies.

Figure 22 left pane shows the annual train kilometres under catenary (blue) and not under catenary (red) for rolling stock vehicle types. It can be seen that some vehicles account for a majority of train kilometres (types 2016, 861 and 757) i.e. those are the most common vehicles. The right pane shows vehicles over route lengths. Vehicles with a smaller variance (i.e. a smaller box) have specific usages in terms of distances. Larger boxes represent more various usages.

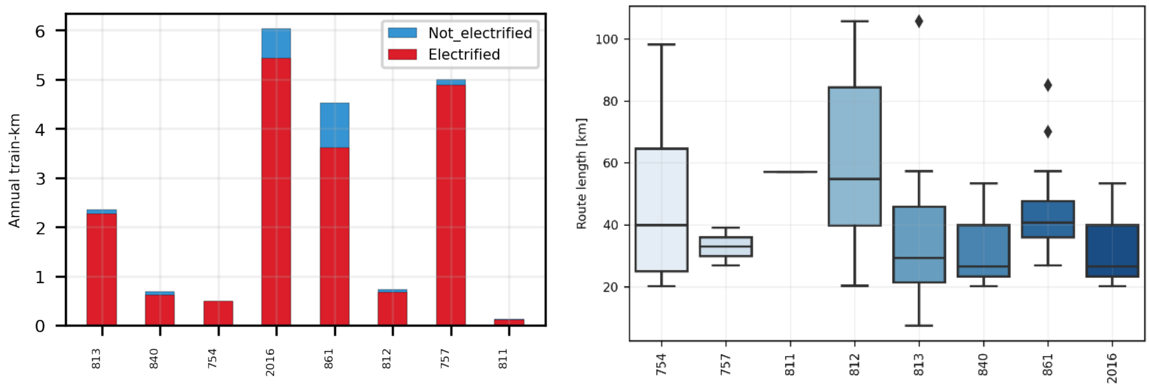

Figure 22: Annual train kilometre and route length per vehicle for Slovakia.

Unlike in other countries, frequencies are evenly distributed along route lengths, i.e. long routes have similar frequencies than short routes (Figure 23).

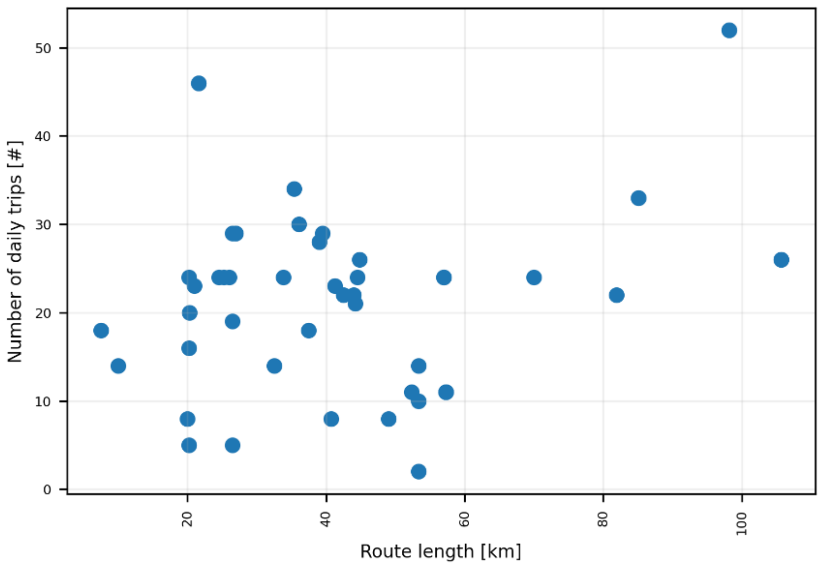

Figure 23: Daily trips over route length for Slovakia.

4.3.2 Average stop distance and average speed

During a railway trip, the acceleration phases are usually the most energy-intensive processes (compare 4.1.2). Figure 24 shows the distribution of both parameters. Average stop distances range between 1.9 km and 7.2 km with the majority between 2.8 km (25 %) and 4 km (75 %). Average speeds range between 30 km/h and 54 km/h.

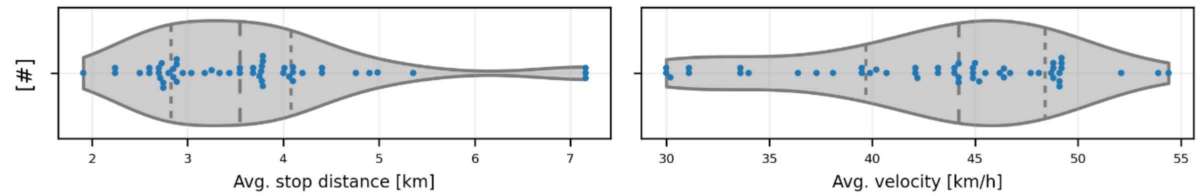

Figure 24: Distribution of average stop distances and average velocities for Slovakia.

Figure 25 shows the average stop distance plotted over the average speed for various vehicles. The upper right area represents high-demand lines, often covered with Type 813.

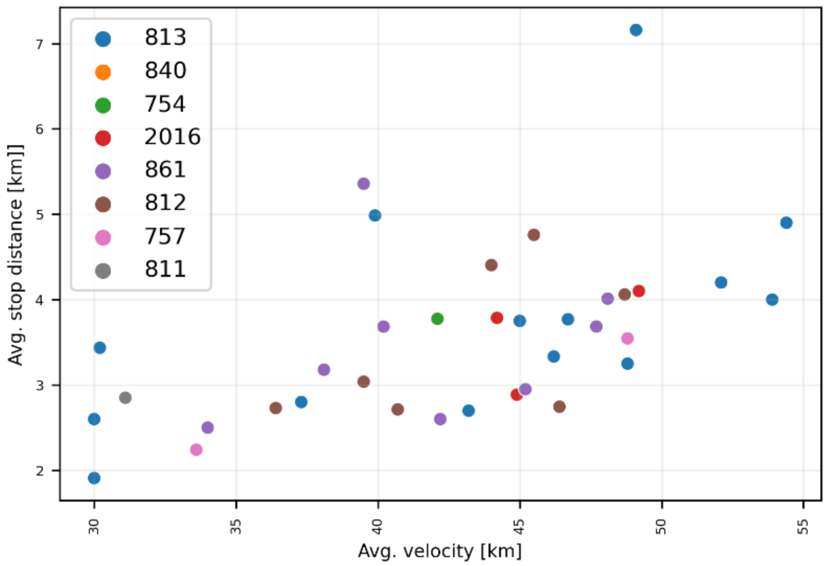

Figure 25: Average velocity over average stop distance for Slovakia.

4.3.3 Start-to-end slope, start-to-end elevation gain

Elevation gains and gradients have significant influence on the energy demand of routes (see section 4.1.3). Figure 26 shows the distribution of net elevation gains between start station and terminal station. A quarter of the routes have elevation gains below 38 m and 50 % of the routes have elevation gains below 120 metres. The highest gains occurring are 552 metre of altitude change.

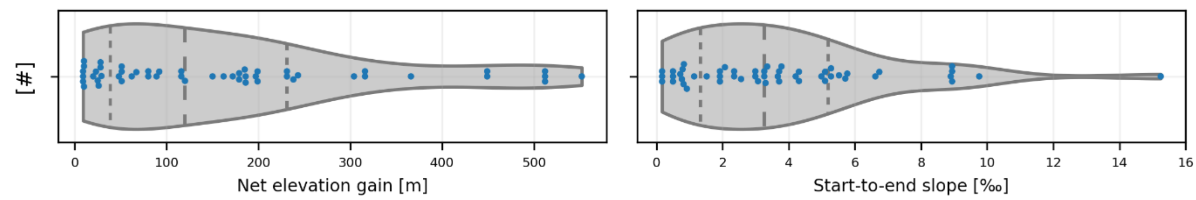

Figure 26: Distribution of start-to-end slopes and net elevation gains for Slovakia.

4.4 Summary of line-based requirements

In this section line-based requirements are compared for the four investigated countries.

In Spain and Portugal route lengths are longer than in Germany and Slovakia with longer autonomies on average. Related to this, the average stop distances also tend to be higher in Spain and Portugal. Average velocities are similar in Germany, Spain and Portugal while being slower in Slovakia. Net elevation gains are highest in Spain on average; however some German lines range up to 600 m elevation gain.

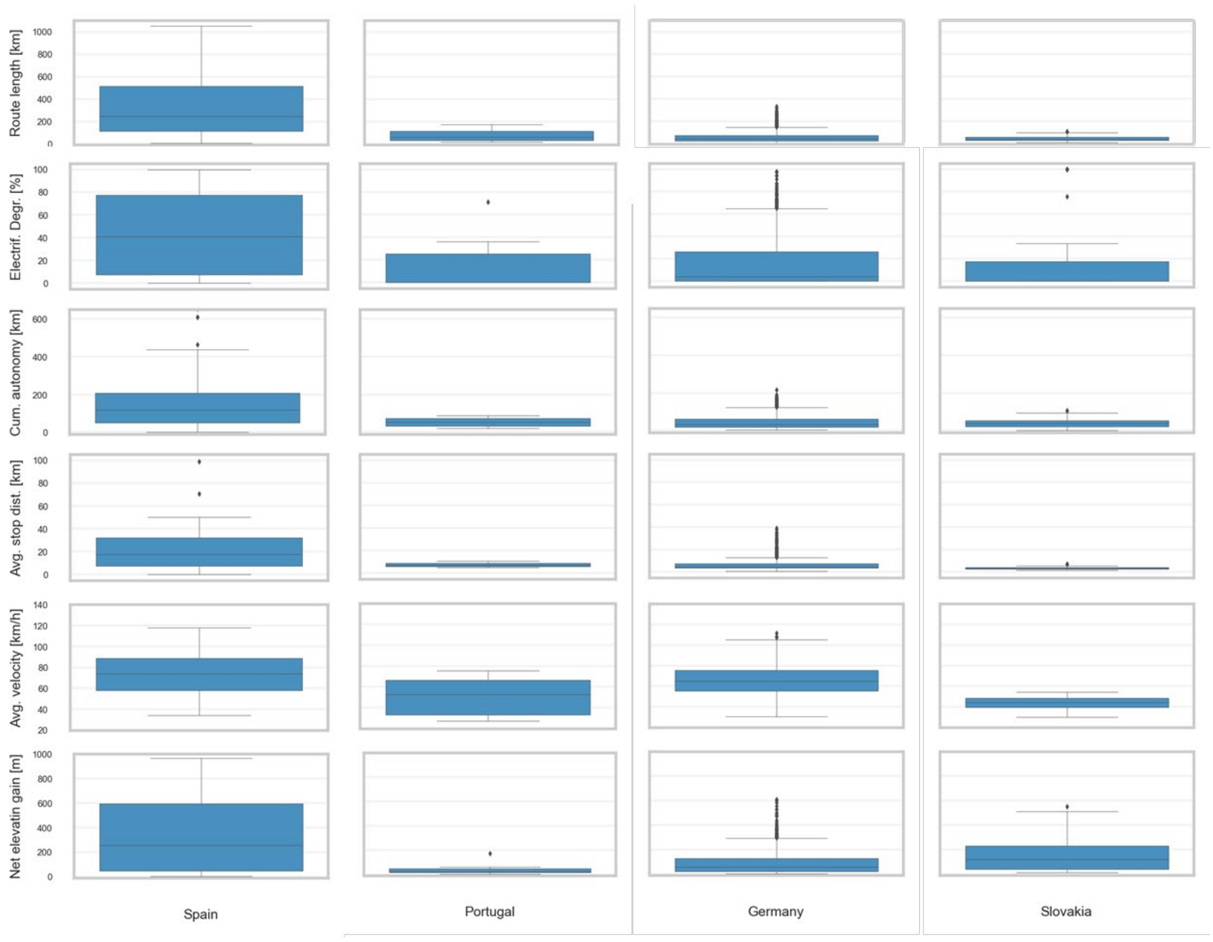

Figure 27: Comparison of distributions of line-based requirements across countries.

5. Use-case Based Requirements

This chapter describes use-cases and requirements derived from use-cases. All considered use-cases are presented in detail and the infrastructural and operational requirements are shown. For each multiple unit use-case a mechanical energy simulation has been performed. The results for multiple units are summarised in sub chapter 5.1.3.

The use-cases were selected in a way that they represent i) common operation ii) common infrastructure and iii) common vehicles. To assign use-cases as representative as possible, workshops were held with the contributing project partners as well as with members of German railway client bodies (BAG-SPNV, Bundesarbeitsgemeinschaft Schienenpersonennahverkehr). In these workshops, important, challenging or representative services were identified. These were supplemented by further use-cases based on attributes of the whole railway network being considered. There are use-cases for multiple units in Spain, Portugal and Germany. For mainline locomotives two use-cases were identified. As shunting locomotives usually do not operate on assigned routes, a generic use-case was designed.

In this deliverable the traction power demand is obtained at wheel level meaning only power and energy for traction. The currently running diesel units cannot recuperate energy. However, as the investigation covers multiple units with electric drives, it is assumed electrical brakes are available. Auxiliary demands, traction drive efficiencies and block sizes are issues of subsequent deliverables D1.2, D1.3 [3] & D1.4. [4] The characteristics of vehicles used for simulations are oriented on the DMU rolling stock namely S592, S594, S599, Lint41 BR648 and Regio Shuttle BR650. The used timetables can deviate from the actual timetables. This is due to seasonal changes in the timetable and the accuracy of the public timetables (resolution in minutes). During the project, the knowledge base on the used data broadened respective changes have been made to the data set, e.g. stop times & electrification patterns. Departure was chosen to create the longest possible autonomy. To determine the trips per day, the longest possible circulation for a train within the timetable was derived.

5.1 Use-cases multiple units

In this chapter, the use-cases for multiple units will be presented. Use-case based requirements will be stated such as power and energy requirements at wheel level to be covered by fuel cell system and battery. The use-cases are input for simulations in subsequent deliverables.

5.1.1 Spain/Portugal

5.1.1.1 Zaragoza-Canfranc

Table 9: Use-case Zaragoza - Canfranc

Service:	*Zaragoza – Canfranc*
Stops [#]:	14
Vehicle:	Aut. 596; Aut. 599

Additional information:

- Zaragoza-Huesca corridor is a **three-rail track** (1435 mm and 1668 mm)
- The 25 kV catenary is useable only for 1435 mm trains

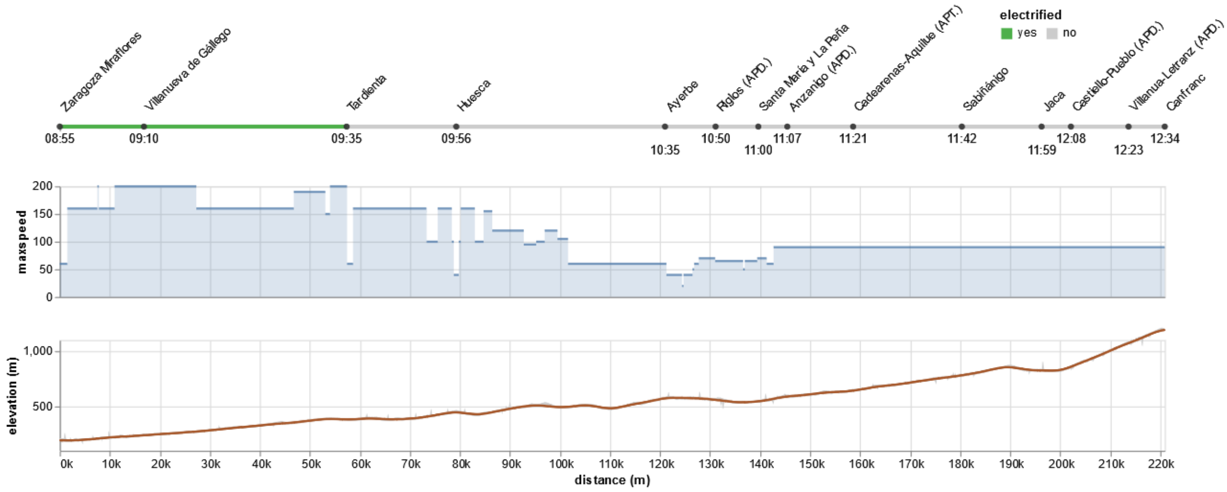

Figure 28: Operational profile Zaragoza-Canfranc

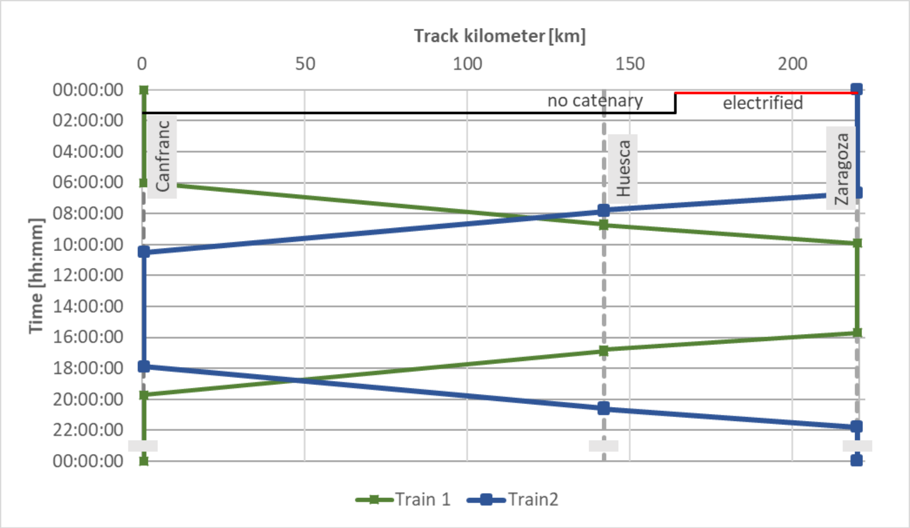

Figure 29: Vehicle operation over a business day for Zaragoza-Canfranc

Table 10: Line-based requirements for Zaragoza – Canfranc.

Use-case attribute	Value	Unit
Route length	221	km
Electrification degree	26	%
Start-end elevation gain	998	m
Start-end slope	4.52	‰
Travel time	4.02	h
Average stop distance	15.8	km
Average velocity	55	Km/h

Table 11: Use-case based requirements for Zaragoza – Canfranc.

Use-case attribute	Value	Unit
Maximum trips per day	2	#
Daily distance	442	Km
Daily travel time	7.92	h
Longest autonomy	327	Km
Cumulated autonomy over a business day	327	Km

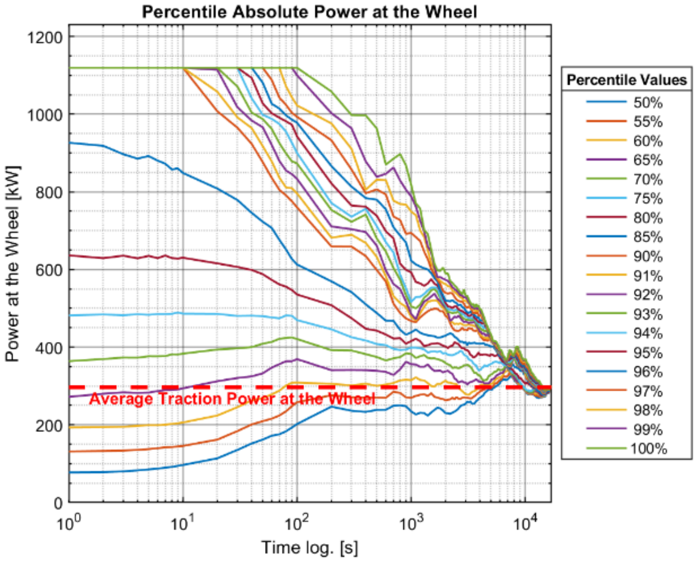

Figure 30: Time weighted load curve for Zaragoza - Canfranc.

5.1.1.2 Madrid – Soria

Table 12: Use-case Madrid - Soria

Service:	***Madrid - Soria***
Stops [#]:	10
Vehicle:	AUT 599

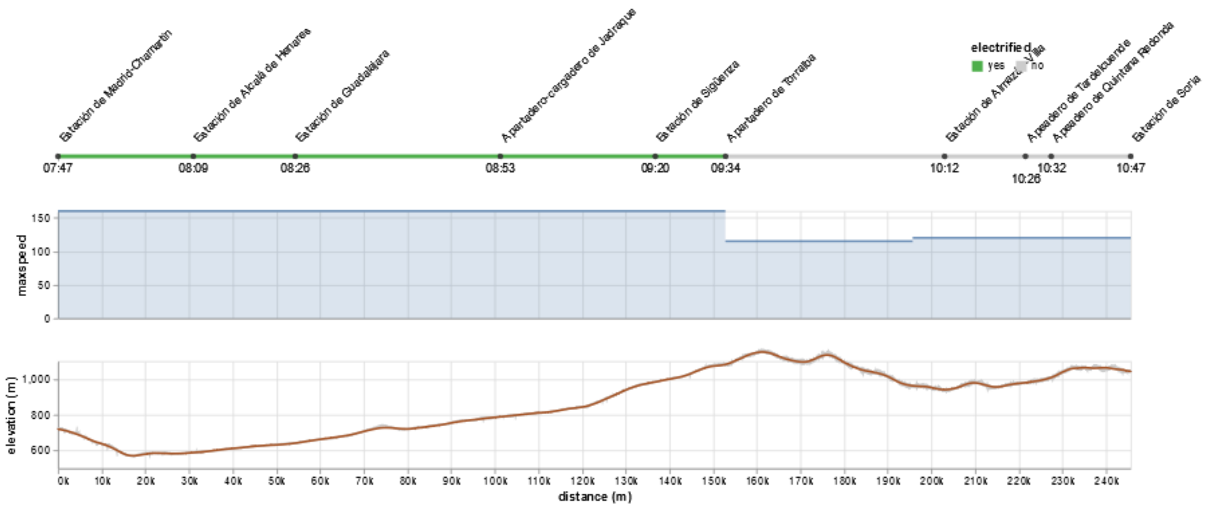

Figure 31: Operational profile Madrid - Soria

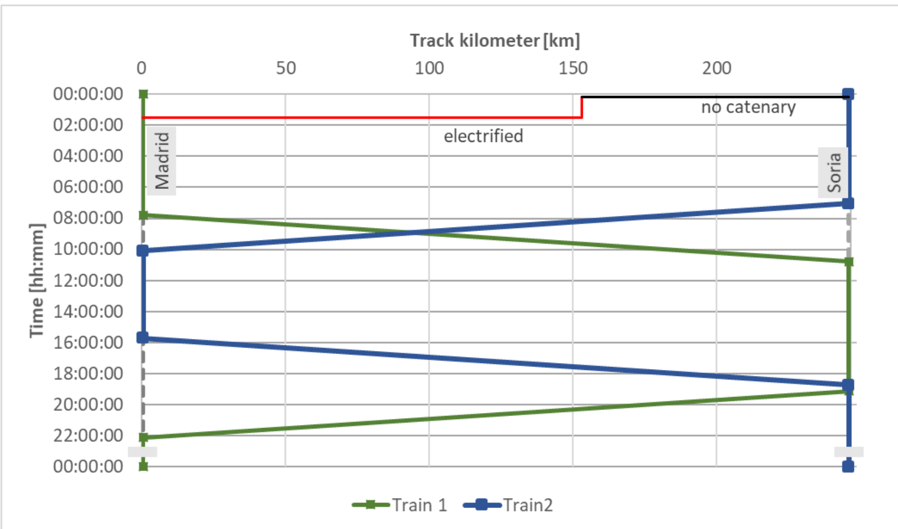

Figure 32: Vehicle operation over a business day for Madrid - Soria.

Table 13: Line-based requirements for Madrid - Soria.

Use-case attribute	Value	Unit
Route length	246	km
Electrification degree	62	%
Start-end elevation gain	323	m
Start-end slope	1.32	‰
Travel time	3.5	h
Average stop distance	24.56	km
Average velocity	70.2	Km/h

Table 14: Use-case based requirements for Madrid - Soria.

Use-case attribute	Value	Unit
Trips per day	3	#
Daily distance	737	Km
Daily travel time	10.5	h
Longest autonomy	93	Km
Cumulated autonomy over a business day	279	Km

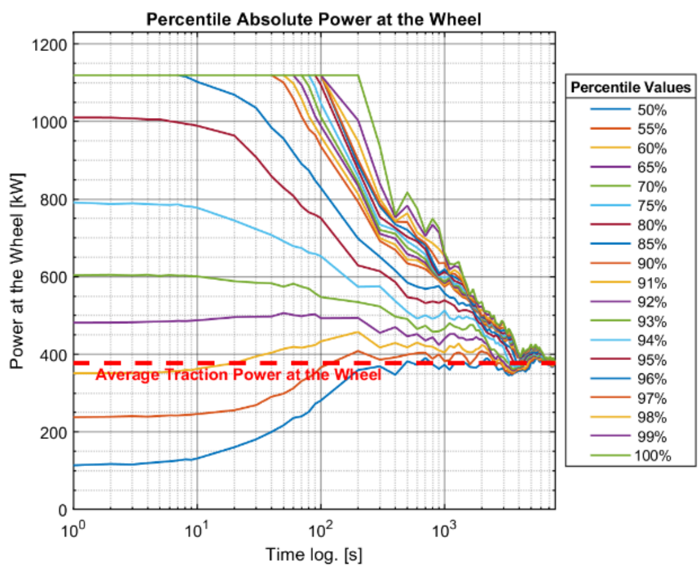

Figure 33: Time weighted load curve for Madrid - Soria.

5.1.1.3 Madrid – Talavera de la Reina

Table 15: Use-case Madrid - Talavera de la Reina.

Service:	**Madrid - Talavera de la Reina**
Stops [#]:	6
Vehicle:	AUT 599

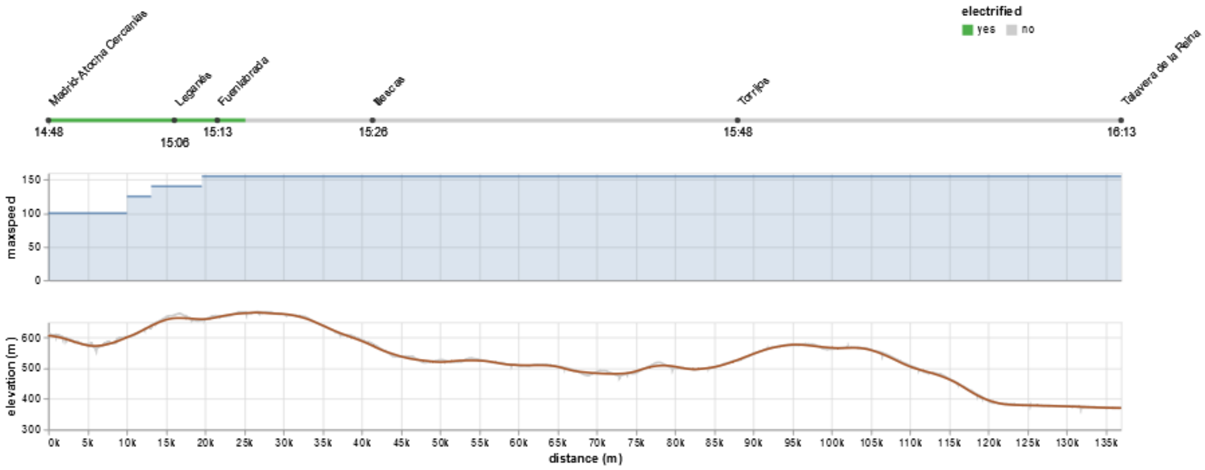

Figure 34: Operational profile Madrid - Talavera de la Reina.

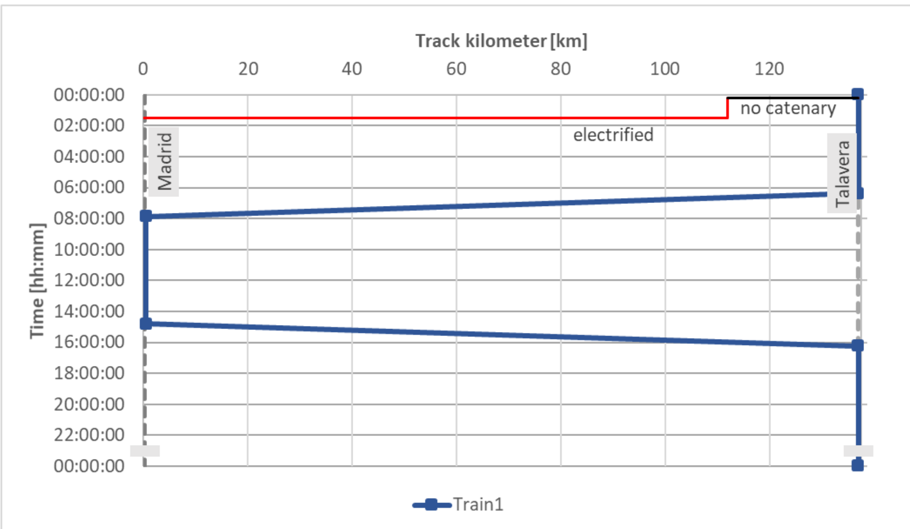

Figure 35: Vehicle operation over a business day for Madrid - Talavera de la Reina.

Table 16: Line-based requirements for Madrid - Talavera de la Reina.

Use-case attribute	Value	Unit
Route length	137	km
Electrification degree	18	%
Start-end elevation gain	18	m
Start-end slope	237	‰
Travel time	1.73	h
Average stop distance	2.08	km
Average velocity	22.83	Km/h

Table 17: Use-case based requirements for Madrid - Talavera de la Reina.

Use-case attribute	Value	Unit
Trips per day	2	#
Daily distance	274	Km
Daily travel time	4.17	h
Longest autonomy	112	Km
Cumulated autonomy over a business day	224	Km
Avg. speed limitation	130	Km/h

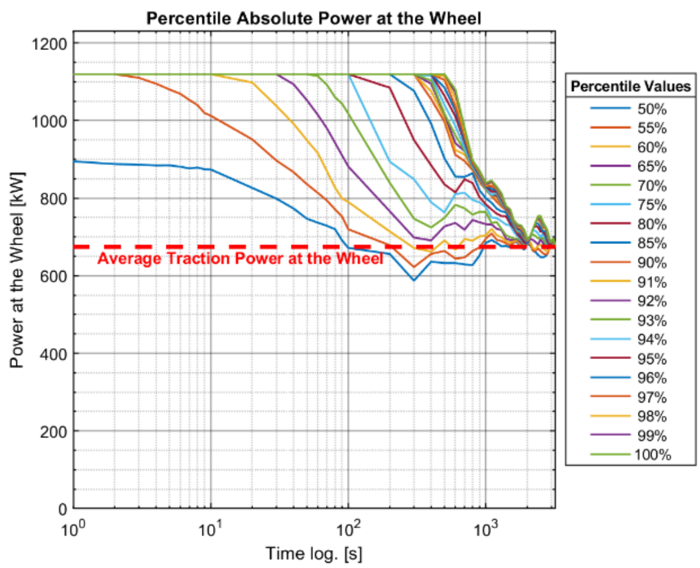

Figure 36: Time weighted load curves for Madrid - Talavera de la Reina.

5.1.1.4 Valencia – Alcoy/Alcoi

Table 18: Use-case Valencia - Alcoy.

Service:	*Valencia – Alcoy/Alcoi*
Stops [#]:	13
Vehicle:	AUT 592

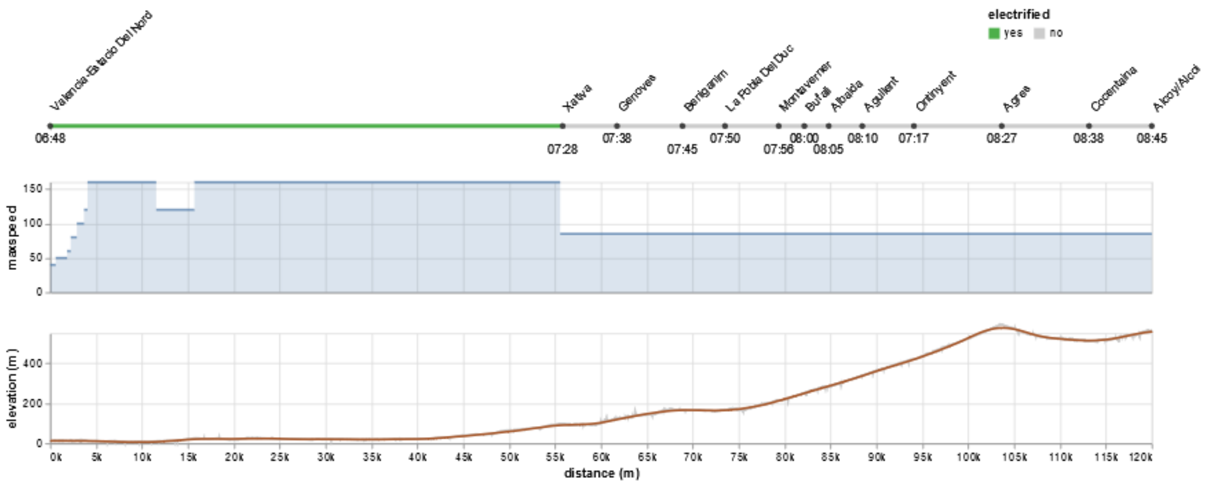

Figure 37: Operational profile Valencia - Alcoy.

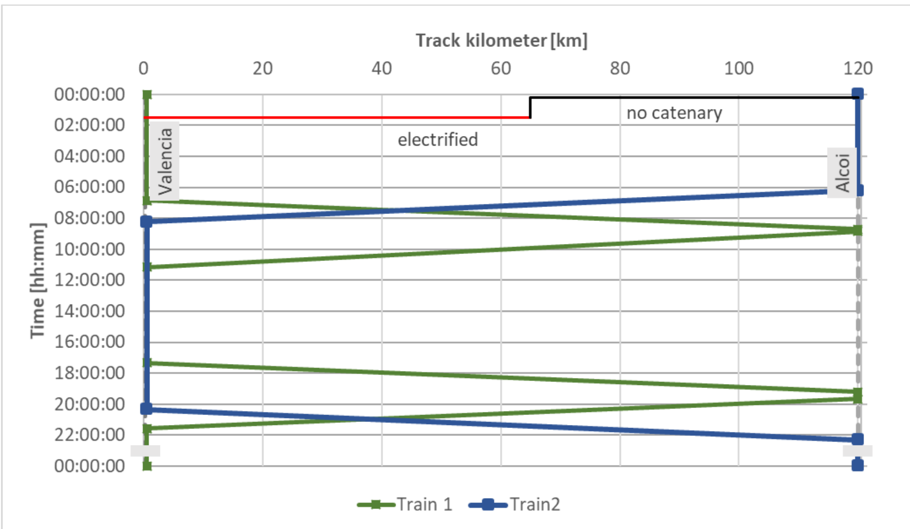

Figure 38: Vehicle operation over a business day for Valencia - Alcoy.

Table 19: Line-based requirements for Valencia - Alcoy.

Requirement	Value	Unit
Route length	120	km
Electrification degree	46	%
Start-end elevation gain	545	m
Start-end slope	4.54	‰
Travel time	2.08	h
Average stop distance	9.23	km
Average velocity	57.6	Km/h

Table 20: Use-case based requirements for Valencia - Alcoy.

Route specific and operational requirements	Value	Unit
Trips per day	4	#
Daily distance	480	Km
Daily travel time	8.33	h
Longest autonomy	64	Km
Cumulated autonomy over a business day	258	Km

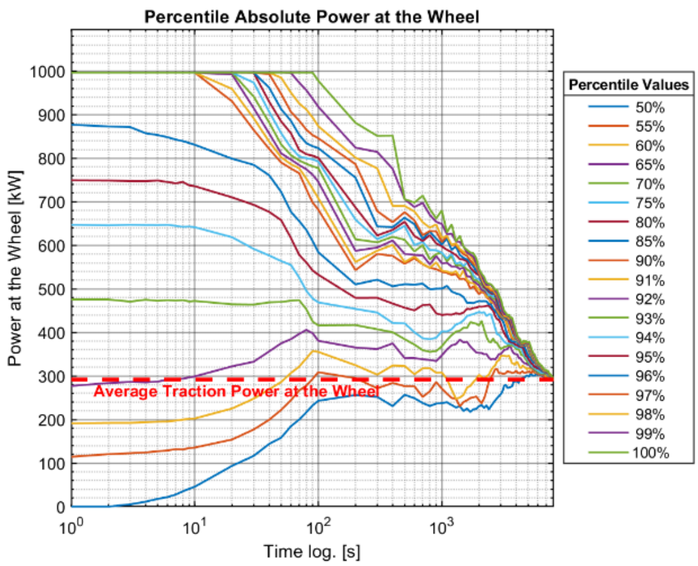

Figure 39: Time weighted load curves for Valencia - Alcoy.

5.1.1.5 Valencia – Zaragoza

Table 21: Use-case Valencia - Zaragoza.

Service:	*Valencia - Zaragoza*
Stops [#]:	26
Vehicle:	AUT 599

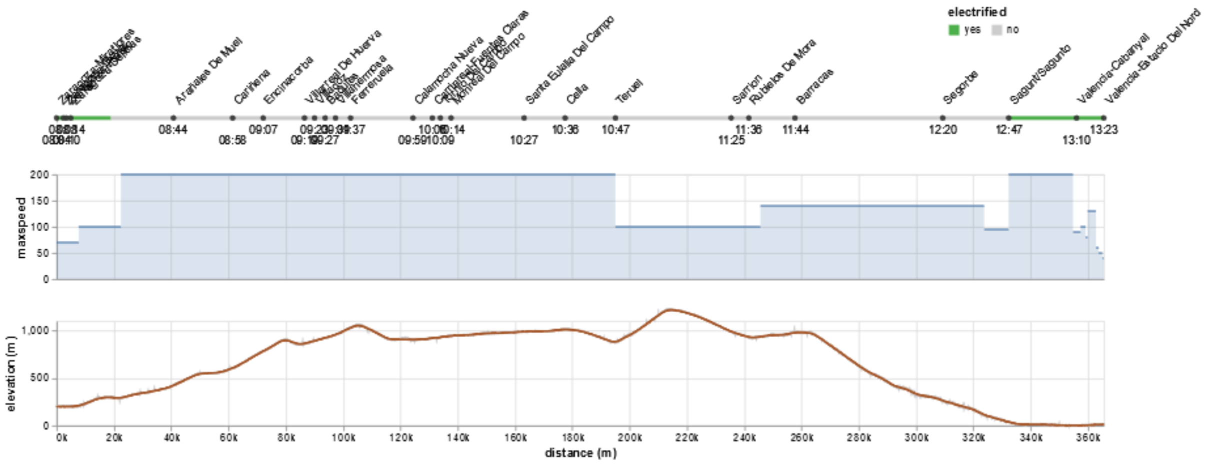

Figure 40: Operational profile Valencia - Zaragoza.

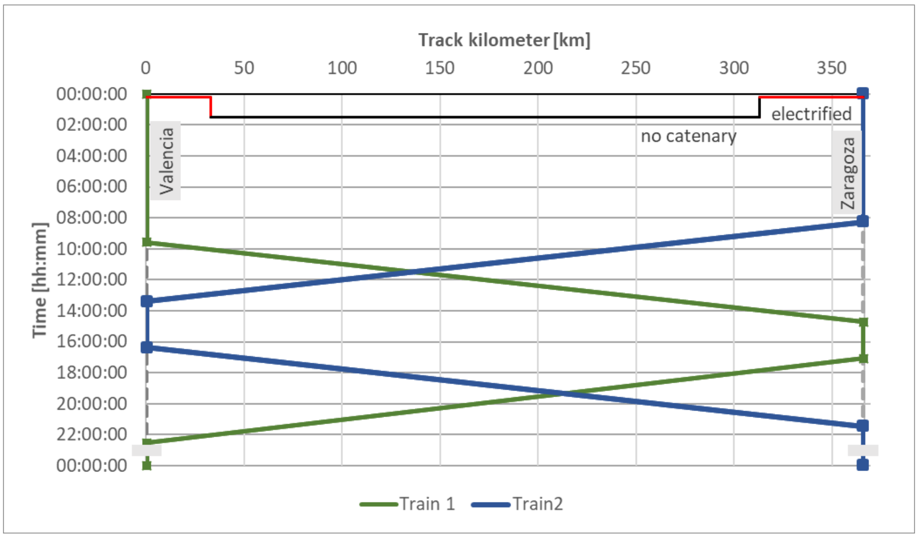

Figure 41: Vehicle operation over a business day for Valencia - Zaragoza.

Table 22: Line-based requirements for Valencia - Zaragoza.

Requirement	Value	Unit
Route length	366	km
Electrification degree	14	%
Start-end elevation gain	187	m
Start-end slope	0.51	‰
Travel time	5.75	h
Average stop distance	14.06	km
Average speed	63.6	Km/h

Table 23: Use-case based requirements for Valencia - Zaragoza.

Route specific and operational requirements	Value	Unit
Trips per day	2	#
Daily distance	731	Km
Daily travel time	11.5	h
Longest autonomy	313	Km
Cumulated autonomy over a business day	627	Km

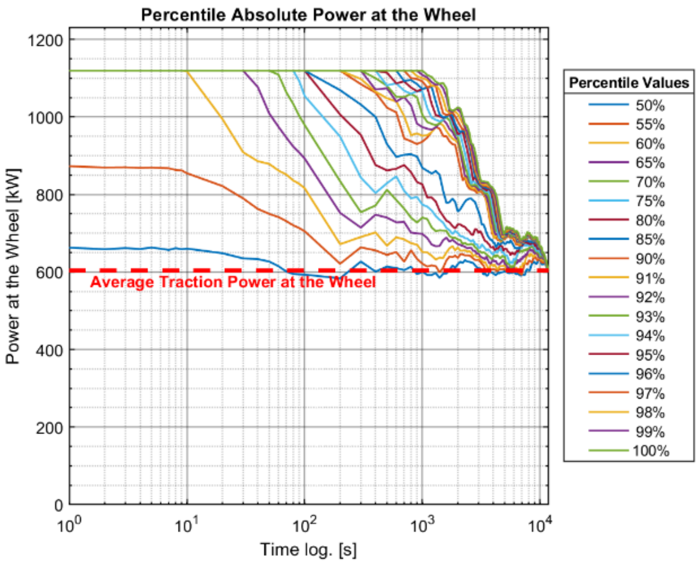

Figure 42: Time weighted load curves for Valencia - Zaragoza.

5.1.1.6 A Coruña – Ferrol

Table 24: Use-case A Coruña – Ferrol.

Service:	*A Coruña – Ferrol*
Stops [#]:	13
Vehicle:	AUT 594

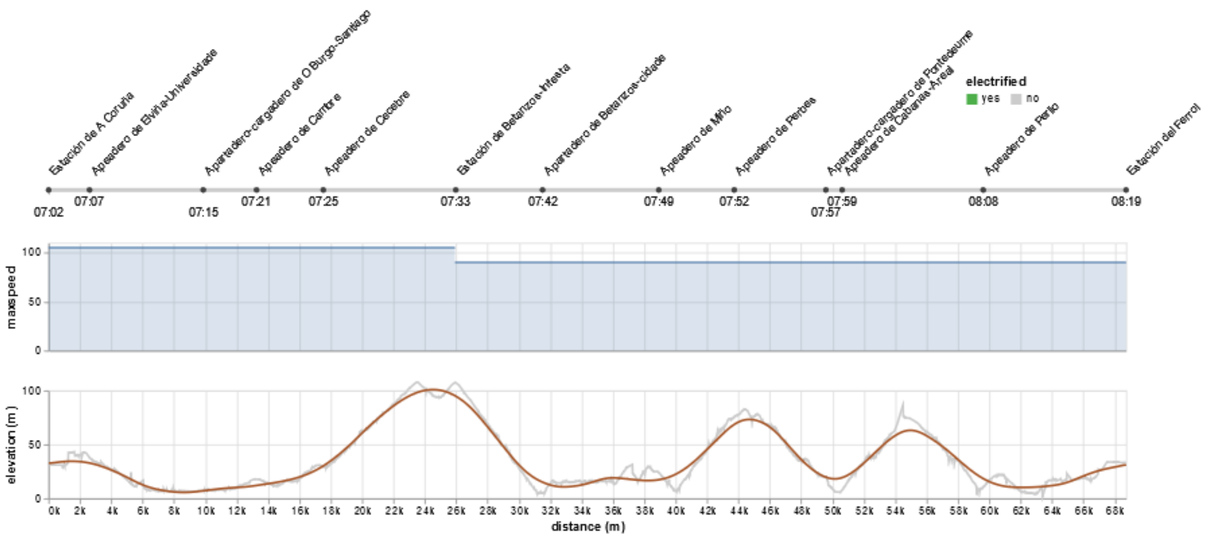

Figure 43: Operational profile A Coruña – Ferrol.

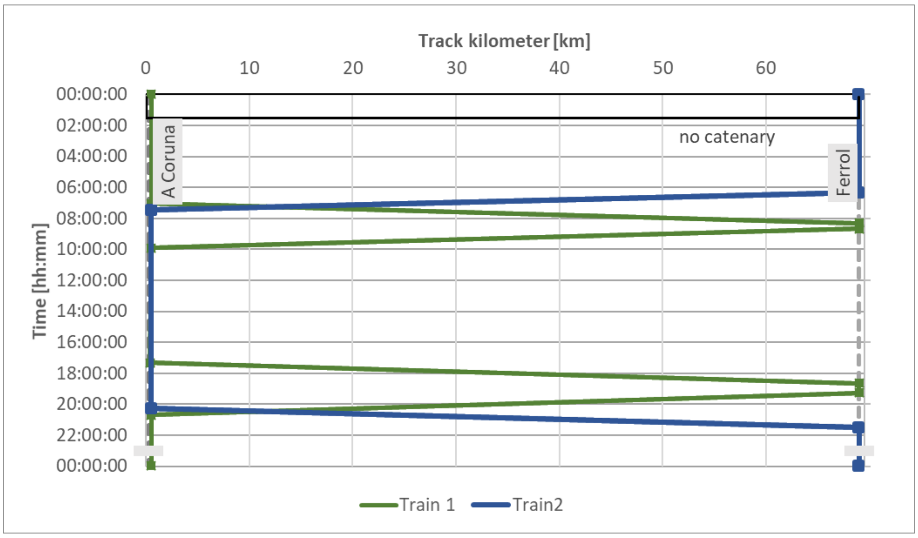

Figure 44:Vehicle operation over a business day for A Coruña – Ferrol.

Table 25: Line-based requirements for A Coruña – Ferrol.

Requirement	Value	Unit
Route length	69	km
Electrification degree	0	%
Start-end elevation gain	1	m
Start-end slope	0.02	‰
Travel time	1.97	h
Average stop distance	5.29	km
Average speed	34.9	Km/h

Table 26: Use-case based requirements for A Coruña – Ferrol.

Route specific and operational requirements	Value	Unit
Trips per day	2	#
Daily distance	137	Km
Daily travel time	3.93	h
Longest autonomy	69	Km
Cumulated autonomy over a business day	137	Km

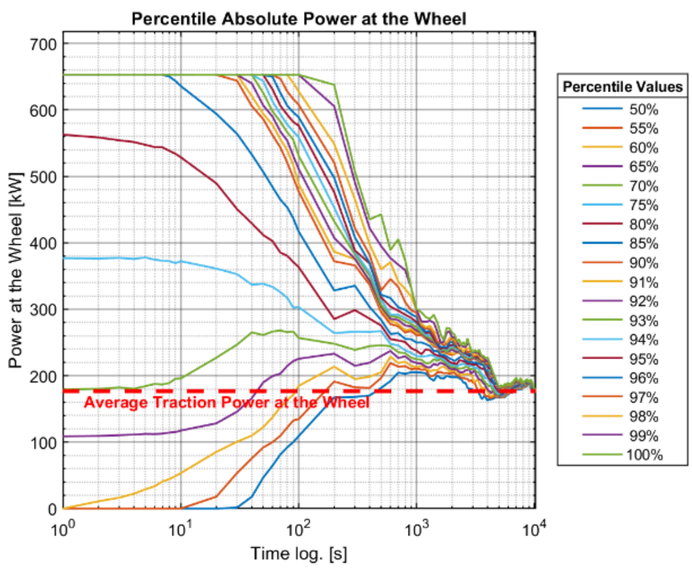

Figure 45: Time weighted load curves for A Coruña – Ferrol.

5.1.1.7 A Coruña - Monforte

Table 27: Use-case A Coruña – Monforte.

Service:	*A Coruña – Monforte*
Stops [#]:	19
Vehicle:	AUT 594

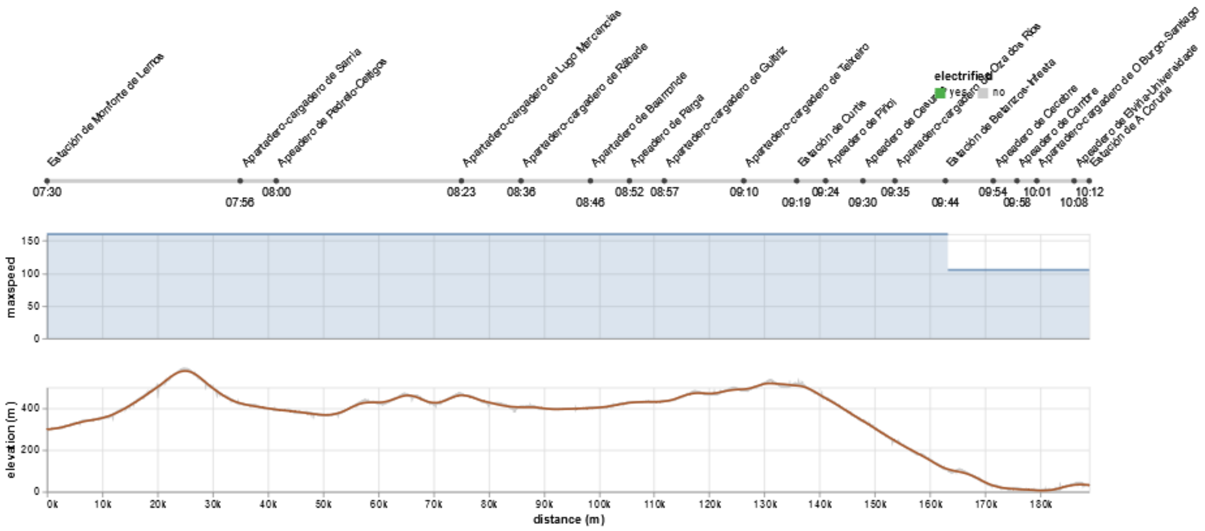

Figure 46: Operational profile A Coruña – Monforte.

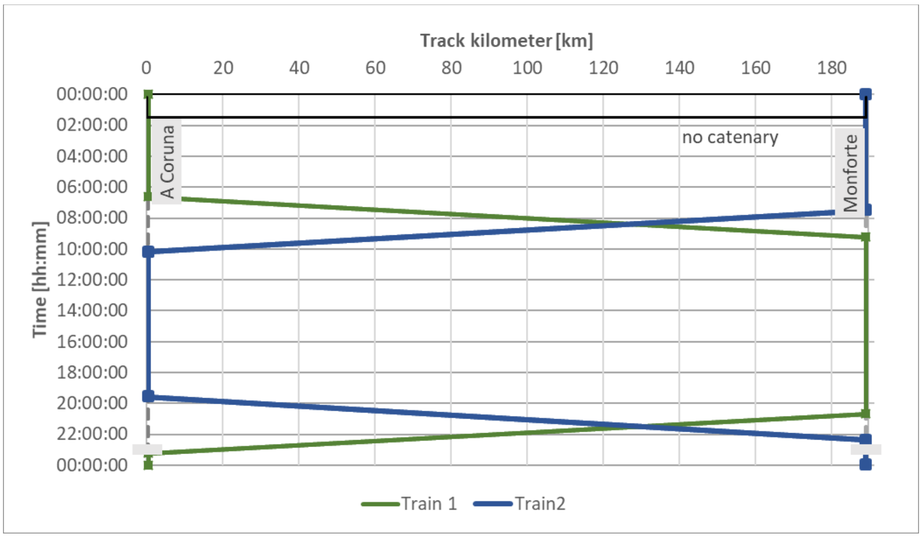

Figure 47: Vehicle operation over a business day for A Coruña – Monforte.

Table 28: Line-based requirements for A Coruña – Monforte.

Requirement	Value	Unit
Route length	189	km
Electrification degree	0	%
Start-end elevation gain	267	m
Start-end slope	1.41	‰
Travel time	3	h
Average stop distance	9.94	km
Average speed	62.9	Km/h

Table 29: Use-case based requirements for A Coruña – Monforte.

Route specific and operational requirements	Value	Unit
Trips per day	2	#
Daily distance	378	Km
Daily travel time	6	h
Longest autonomy	189	Km
Cumulated autonomy over a business day	378	Km

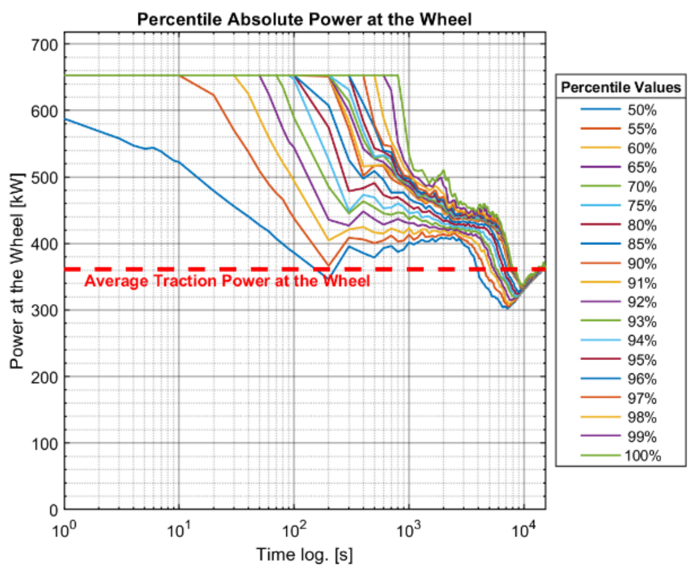

Figure 48: Time weighted load curves for A Coruña – Monforte.

5.1.1.8 Madrid – Sevilla

Table 30: Use-case Madrid - Sevilla.

Service:	***Madrid - Sevilla***
Stops [#]:	25
Vehicle:	AUT 599

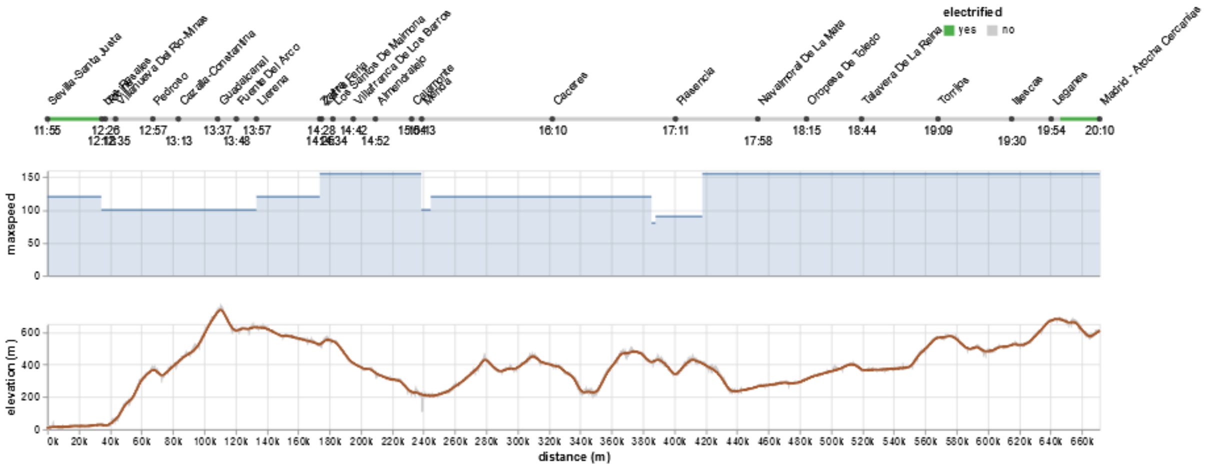

Figure 49: Operational profile Madrid - Sevilla.

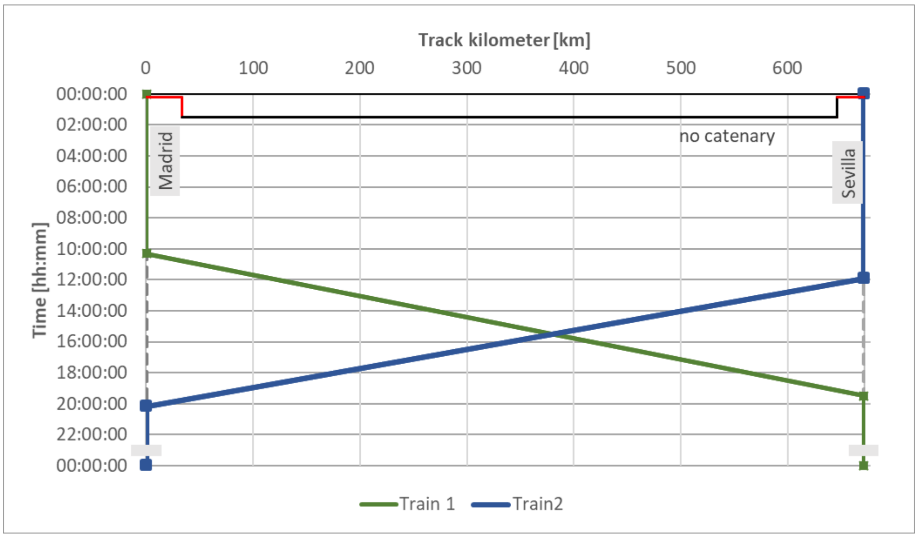

Figure 50: Vehicle operation over a business day for Madrid - Sevilla.

Table 31: Line-based requirements for Madrid - Sevilla.

Requirement	Value	Unit
Route length	671	km
Electrification degree	9	%
Start-end elevation gain	599	m
Start-end slope	0.89	‰
Travel time	7.77	h
Average stop distance	26.85	km
Average speed	86.4	Km/h

Table 32: Use-case based requirements for Madrid - Sevilla.

Route specific and operational requirements	Value	Unit
Trips per day	1	#
Daily distance	671	Km
Daily travel time	7.77	h
Longest autonomy	612	Km
Cumulated autonomy over a business day	612	Km

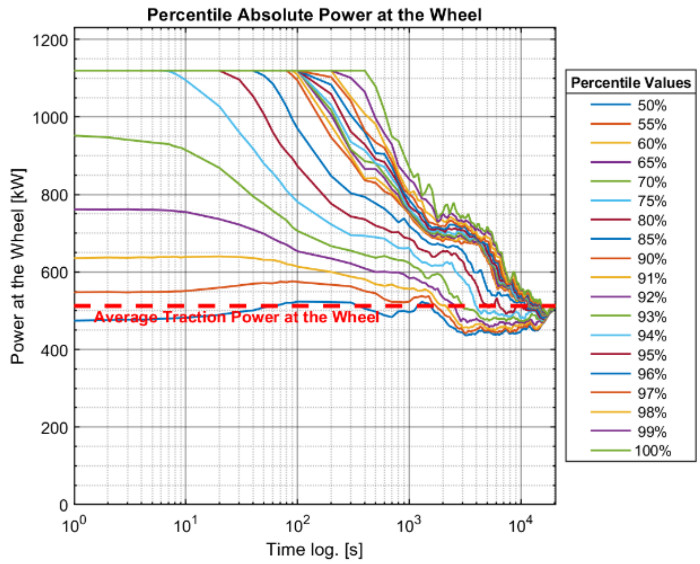

Figure 51: Time weighted load curves for Madrid - Sevilla.

5.1.1.9 Murcia del Carmen – Alacant

Table 33: Use-case Murcia del Carmen - Alacant.

Service:	*Murcia del Carmen – Alacant*
Stops [#]:	8
Vehicle:	AUT 592

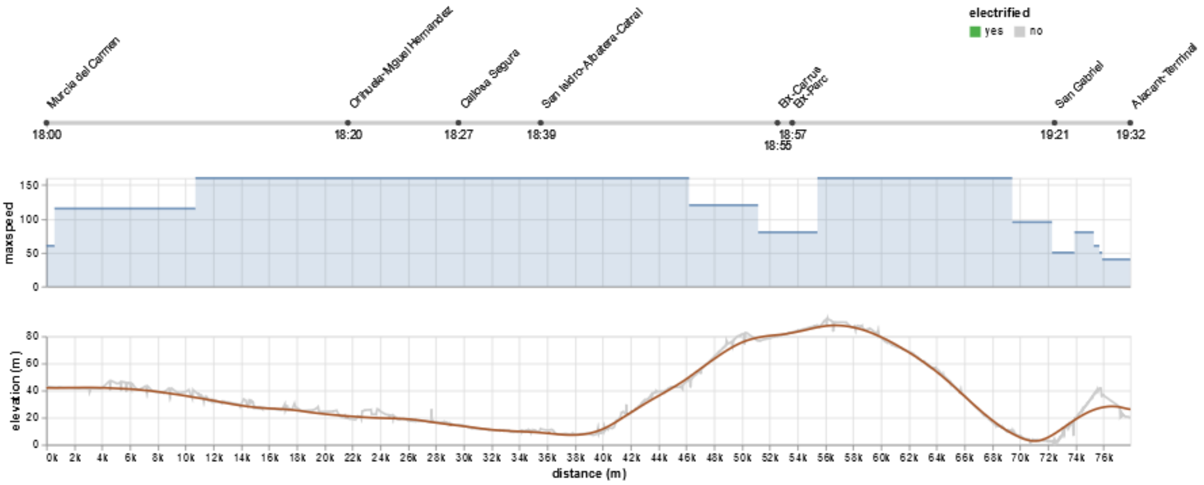

Figure 52: Operational profile Murcia del Carmen - Alacant.

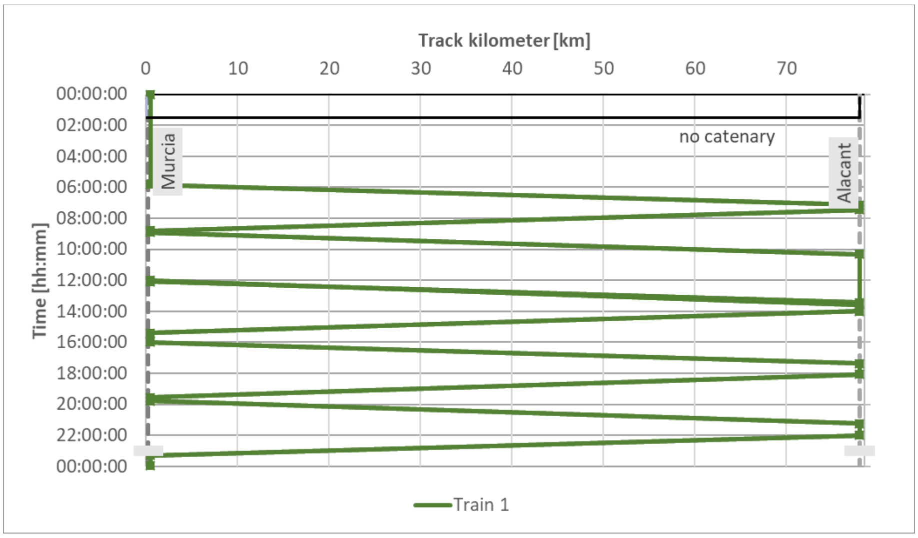

Figure 53: Vehicle operation over a business day for Murcia del Carmen - Alacant.

Table 34: Line-based requirements for Murcia del Carmen - Alacant.

Requirement	Value	Unit
Route length	78	km
Electrification degree	0	%
Start-end elevation gain	16	m
Start-end slope	0.21	‰
Travel time	1.68	h
Average stop distance	9.74	km
Average speed	46.3	Km/h

Table 35: Use-case based requirements for Murcia del Carmen - Alacant.

Route specific and operational requirements	Value	Unit
Trips per day	10	#
Daily distance	779	Km
Daily travel time	16.83	h
Longest autonomy	78	Km
Cumulated autonomy over a business day	779	Km

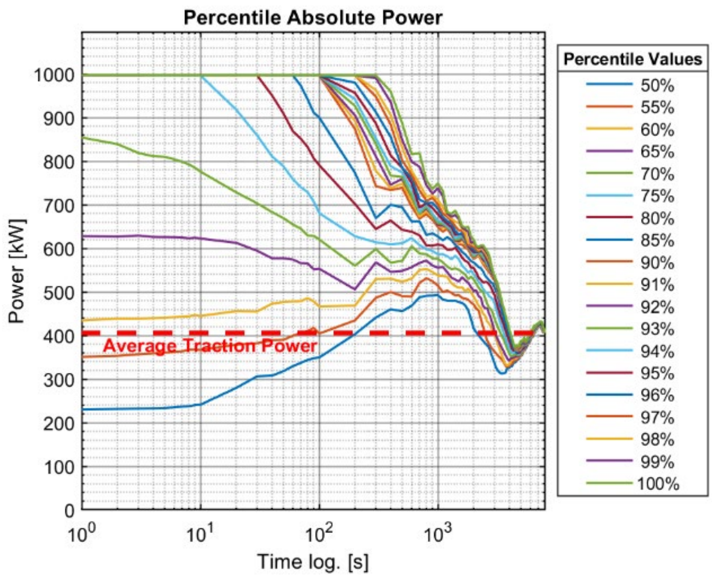

Figure 54: Time weighted load curves for Murcia del Carmen - Alacant.

5.1.1.10 Madrid – Sevilla

Table 36: Use-case Madrid - Sevilla.

Service:	***Madrid - Sevilla***
Stops [#]:	25
Vehicle:	AUT 599

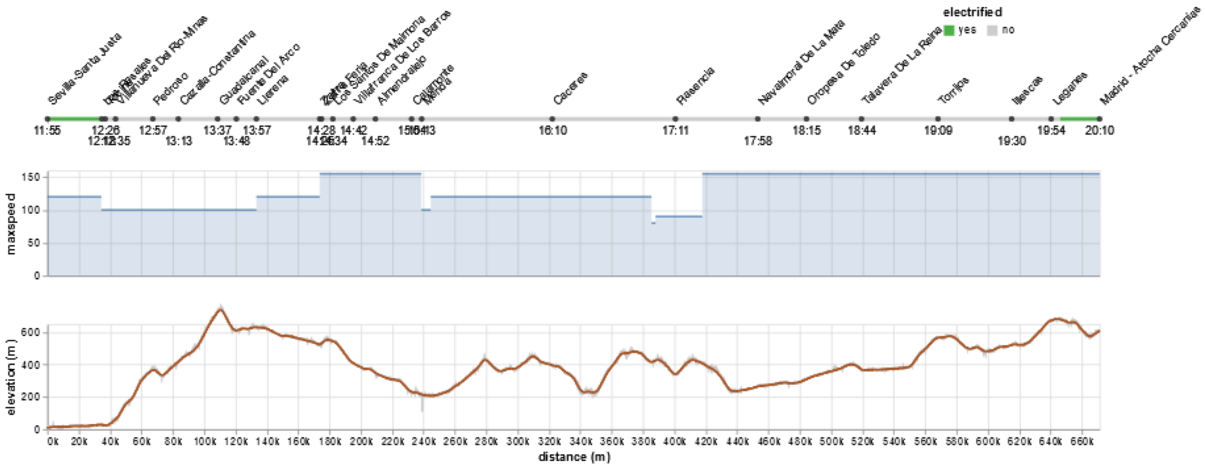

Figure 55: Operational profile Madrid - Sevilla.

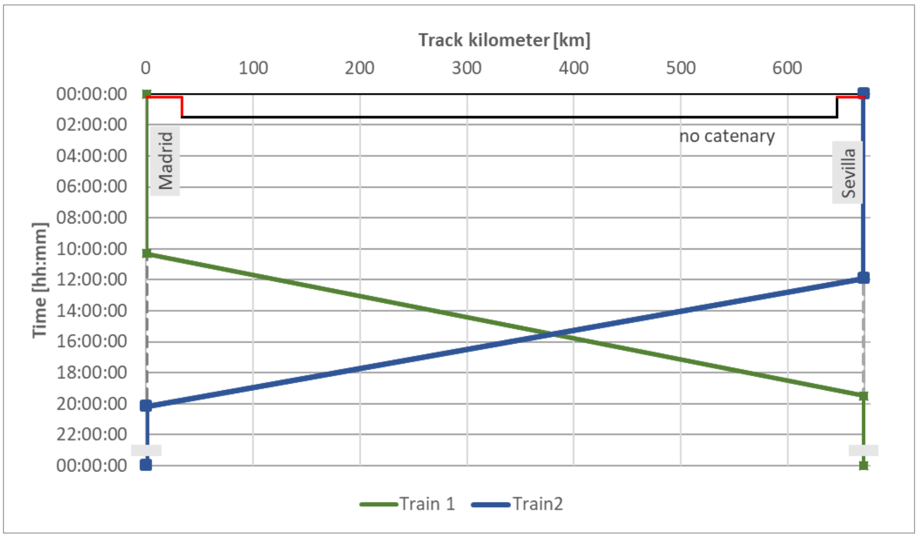

Figure 56: Vehicle operation over a business day for Madrid - Sevilla.

Table 37: Line-based requirements for Madrid - Sevilla.

Requirement	Value	Unit
Route length	671	km
Electrification degree	9	%
Start-end elevation gain	599	m
Start-end slope	0.89	‰
Travel time	7.77	h
Average stop distance	26.85	km
Average speed	86.4	Km/h

Table 38: Use-case based requirements for Madrid - Sevilla.

Route specific and operational requirements	Value	Unit
Trips per day	1	#
Daily distance	671	Km
Daily travel time	7.77	h
Longest autonomy	612	Km
Cumulated autonomy over a business day	612	Km

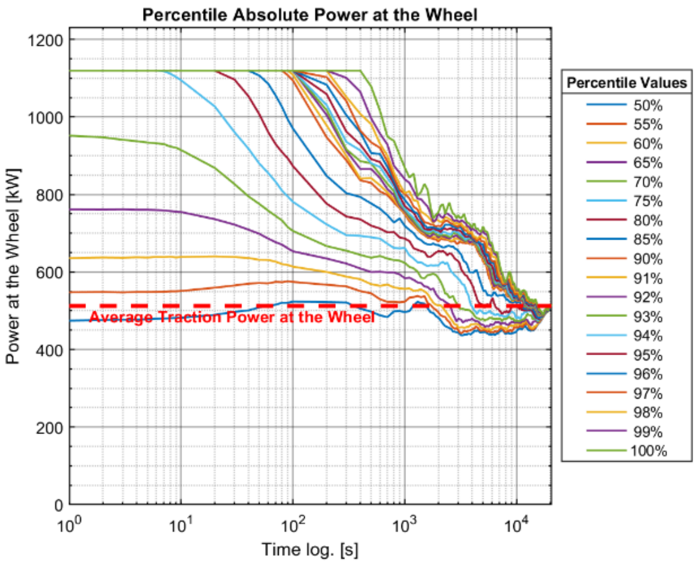

Figure 57: Time weighted load curves for Madrid - Sevilla.

5.1.1.11 Porto – Vigo

Table 39: Use-case Porto - Vigo.

Service:	*Porto - Vigo*
Stops [#]:	19
Vehicle:	AUT 592

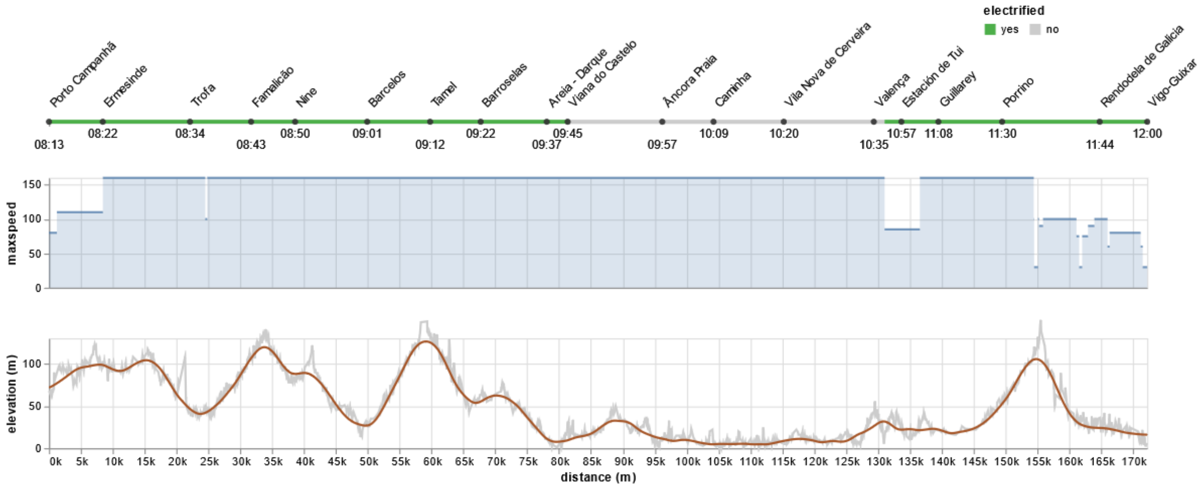

Figure 58: Operational profile Porto – Vigo (service currently not active - assumed timetable).

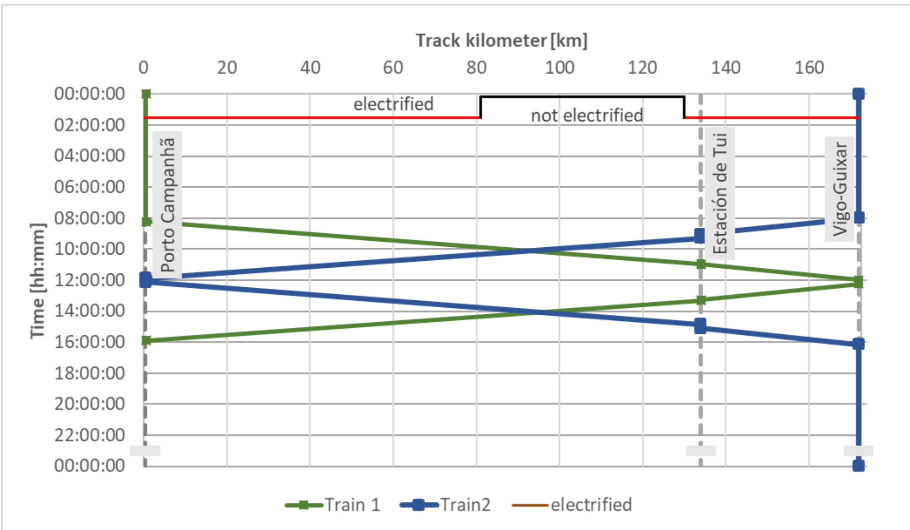

Figure 59: Vehicle operation over a business day for Porto – Vigo (service currently not active - assumed timetable).

Table 40: Line-based requirements for Porto - Vigo.

Requirement	Value	Unit
Route length	172	km
Electrification degree	72	%
Start-end elevation gain	50	m
Start-end slope	0.3	‰
Travel time	03:49	h
Average stop distance	9.05	km
Average speed	45	Km/h

Table 41: Use-case based requirements Porto - Vigo.

Route specific and operational requirements	Value	Unit
Trips per day	2	#
Daily distance	344	Km
Daily travel time	07:39	h
Longest autonomy	49	Km
Cumulated autonomy over a business day	98	Km

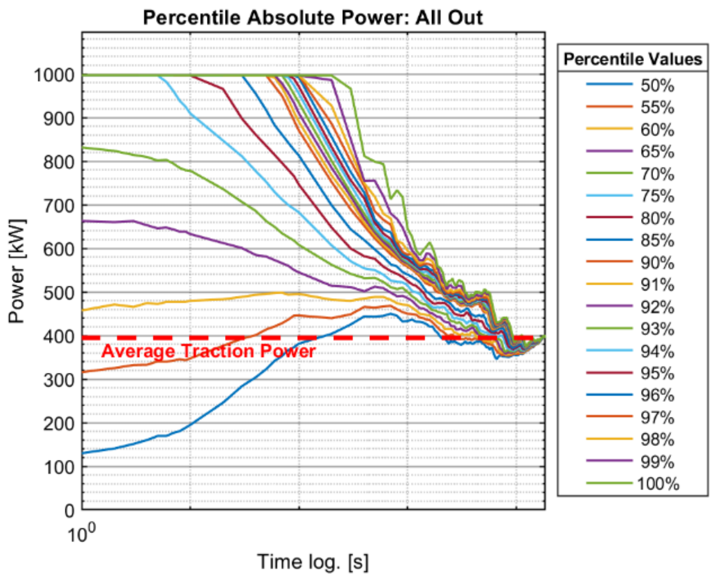

Figure 60: Time weighted load curves for Porto - Vigo.

5.1.2 Germany

5.1.2.1 Emmelshausen - Boppard

Table 42: Use-case Emmelshausen - Boppard.

Service:	*Emmelshausen – Boppard*
Stops [#]:	6
Vehicle:	Regio Shuttle RS1

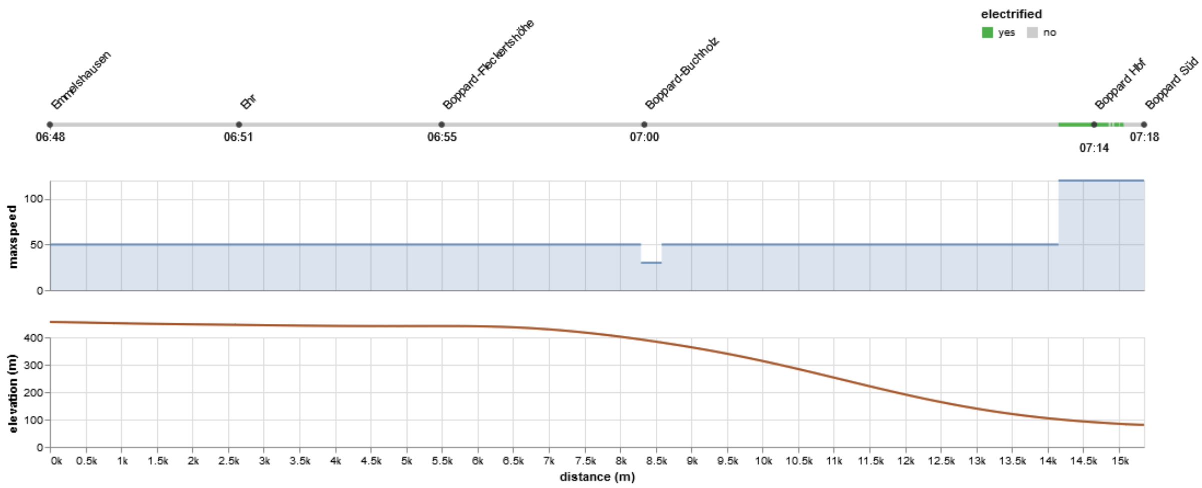

Figure 61: Operational profile Emmelshausen - Boppard.

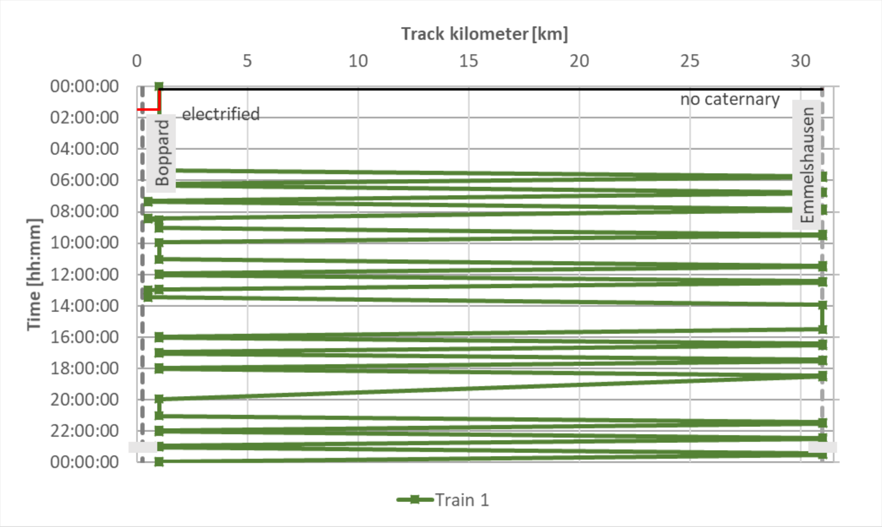

Figure 62: Vehicle operation over a business day for Emmelshausen - Boppard.

Table 43: Line-based requirements for Emmelshausen - Boppard.

Requirement	Value	Unit
Route length	15	km
Electrification degree	6	%
Start-end elevation gain	375	m
Start-end slope	24.43	‰
Travel time	0.5	h
Average stop distance	2.56	km
Average speed	30.7	Km/h

Table 44: Use-case based requirements for Emmelshausen - Boppard.

Route specific and operational requirements	Value	Unit
Trips per day	28	#
Daily distance	430	Km
Daily travel time	14	h
Longest autonomy	14	Km
Cumulated autonomy over a business day	406	Km

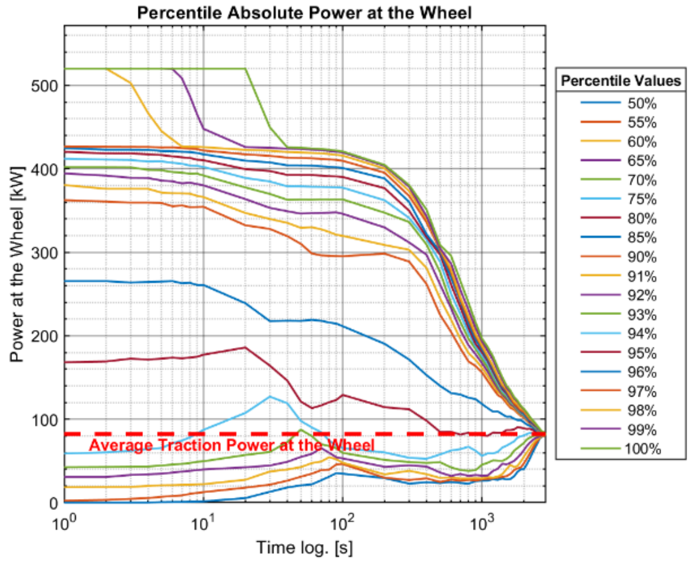

Figure 63: Time weighted load curves for Emmelshausen – Boppard.

5.1.2.2 Erfurt - Rennsteig

Table 45: Use-case Erfurt - Rennsteig.

Service:	*Erfurt - Rennsteig*
Stops [#]:	18
Vehicle:	Regio Shuttle RS1

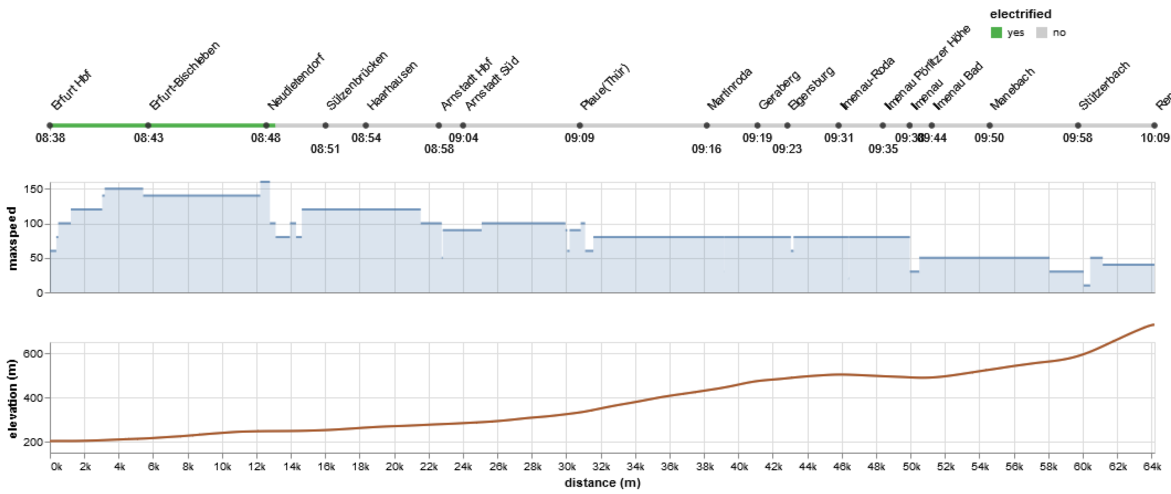

Figure 64: Operational profile Erfurt - Rennsteig.

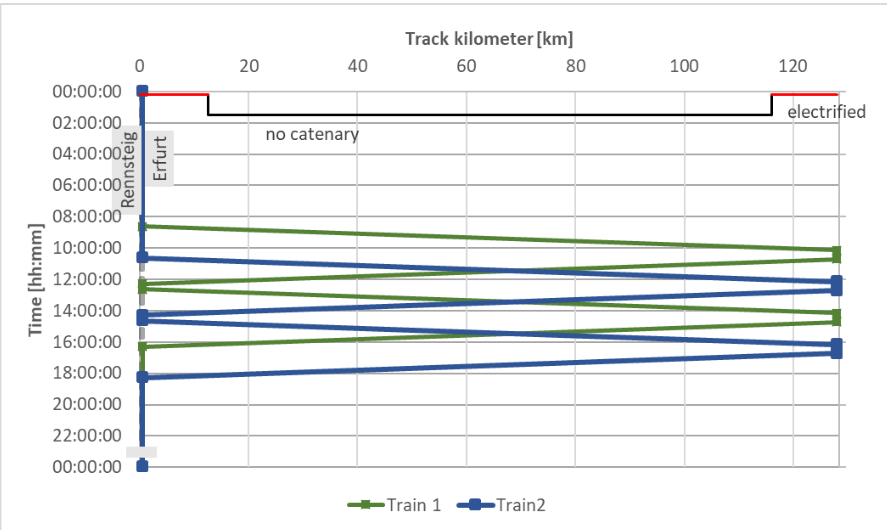

Figure 65: Vehicle operation over a business day for Erfurt - Rennsteig.

Table 46: Line-based requirements for Erfurt - Rennsteig.

Requirement	Value	Unit
Route length	64	km
Electrification degree	20	%
Start-end elevation gain	526	m
Start-end slope	8.19	‰
Travel time	1.52	h
Average stop distance	3.57	km
Average speed	42.3	Km/h

Table 47: Use-case based requirements for Erfurt - Rennsteig.

Route specific and operational requirements	Value	Unit
Trips per day	4	#
Daily distance	257	Km
Daily travel time	6.07	h
Longest autonomy	51	Km
Cumulated autonomy over a business day	204	Km

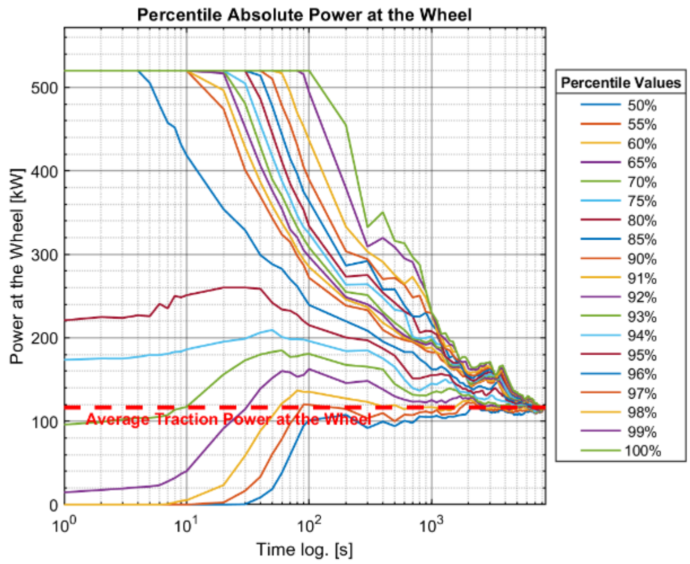

Figure 66: Time weighted load curves for Erfurt Rennsteig.

5.1.2.3 Stuttgart - Aulendorf

Table 48: Stuttgart - Aulendorf.

Service:	*Stuttgart - Aulendorf*
Stops [#]:	14
Vehicle:	Shuttle RS1

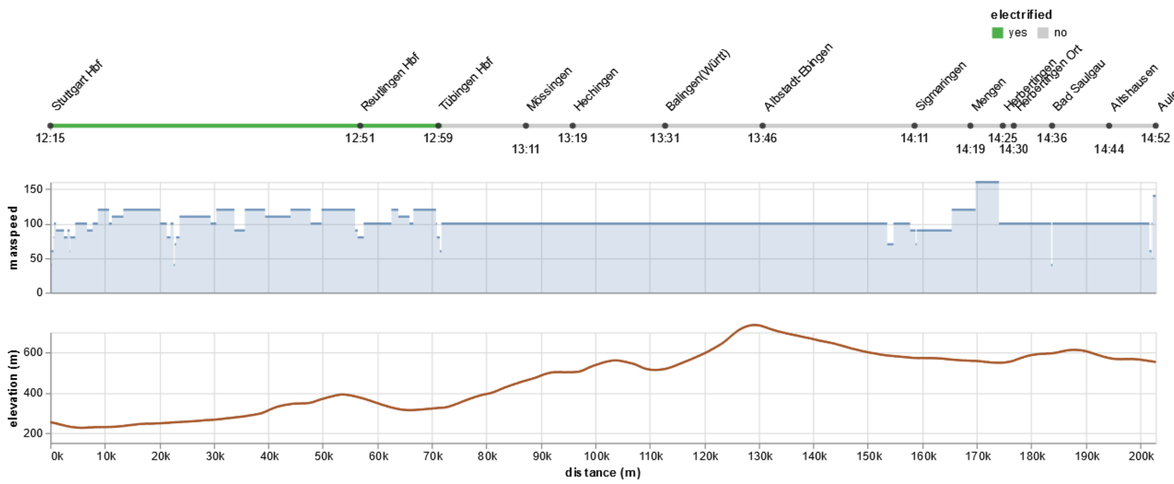

Figure 67: Operational profile Stuttgart - Aulendorf.

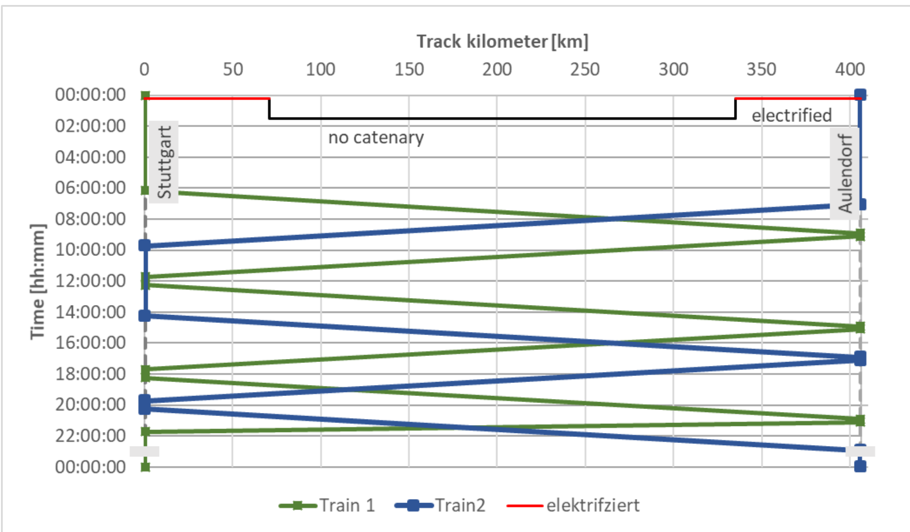

Figure 68: Vehicle operation over a business day for Stuttgart - Aulendorf.

Table 49: Line-based requirements for Stuttgart - Aulendorf.

Requirement	Value	Unit
Route length	203	km
Electrification degree	35	%
Start-end elevation gain	300	m
Start-end slope	1.48	‰
Travel time	2.62	h
Average stop distance	14.49	km
Average speed	77.5	Km/h

Table 50: Use-case based requirements for Stuttgart - Aulendorf.

Route specific and operational requirements	Value	Unit
Trips per day	6	#
Daily distance	1217	Km
Daily travel time	15.7	h
Longest autonomy	131	Km
Cumulated autonomy over a business day	786	Km

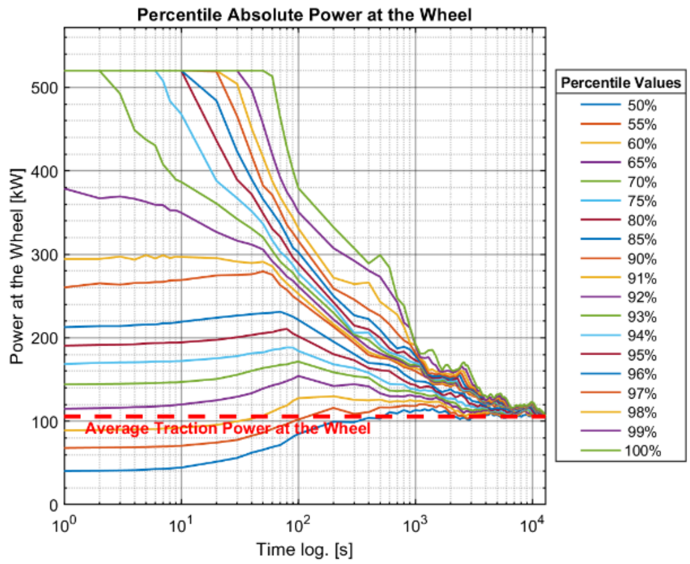

Figure 69: Time weighted load curves for Stuttgart Aulendorf.

5.1.2.4 Bremen -Osnabrück

Table 51: Use-case Bremen - Osnabrück.

Service:	*Bremen -Osnabrück*
Stops [#]:	22
Vehicle:	Lint 41 /BR648

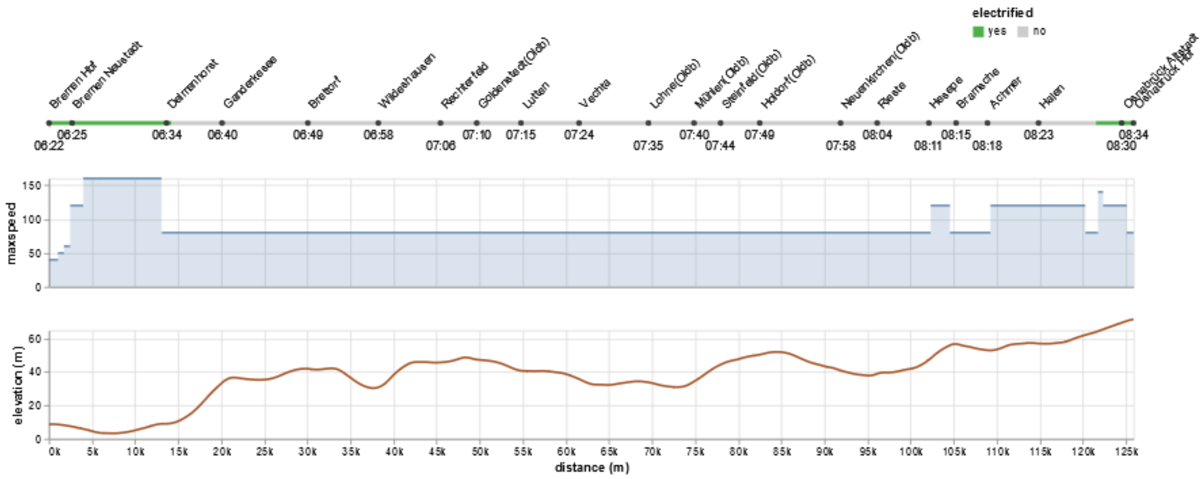

Figure 70: Operational profile Bremen - Osnabrück.

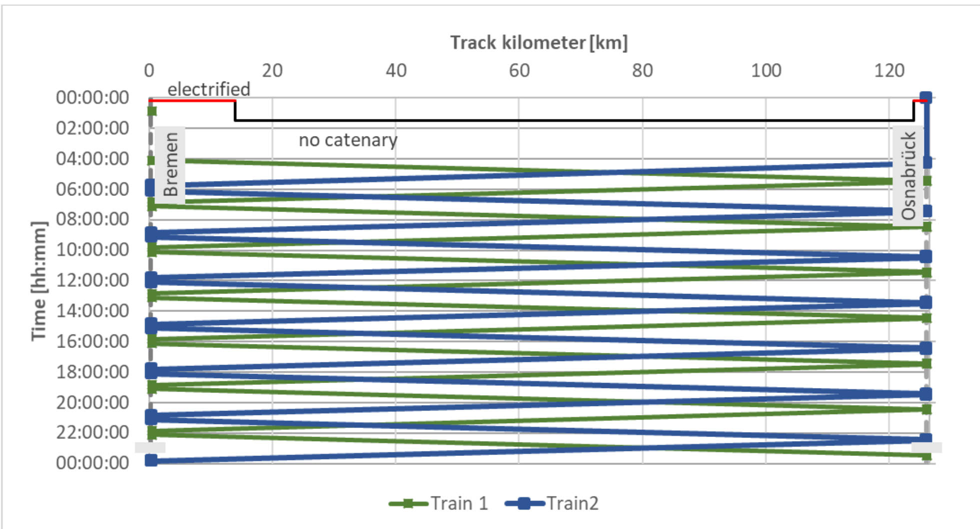

Figure 71: Vehicle operation over a business day for Bremen - Osnabrück.

Table 52: Line-based requirements for Bremen - Osnabrück.

Requirement	Value	Unit
Route length	126	km
Electrification degree	15	%
Start-end elevation gain	63	m
Start-end slope	0.5	‰
Travel time	2.2	h
Average stop distance	5.72	km
Average speed	57.2	Km/h

Table 53: Use-case based requirements for Bremen - Osnabrück.

Route specific and operational requirements	Value	Unit
Trips per day	8	#
Daily distance	1007	Km
Daily travel time	17.6	h
Longest autonomy	107	Km
Cumulated autonomy over a business day	858	Km

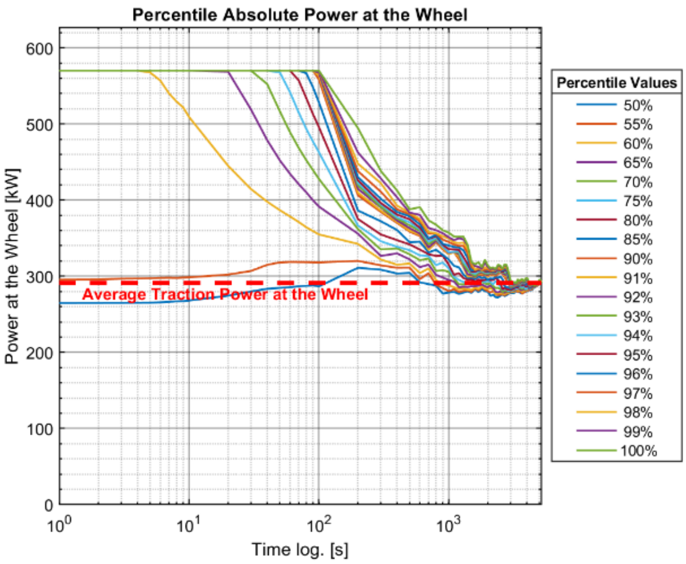

Figure 72: Time weighted load curves for Bremen -Osnabrück.

5.1.2.5 Düsseldorf - Kleve

Table 54: Use-case Düsseldorf - Kleve.

Service:	*Düsseldorf - Kleve*
Stops [#]:	13
Vehicle:	Lint 41 /BR648

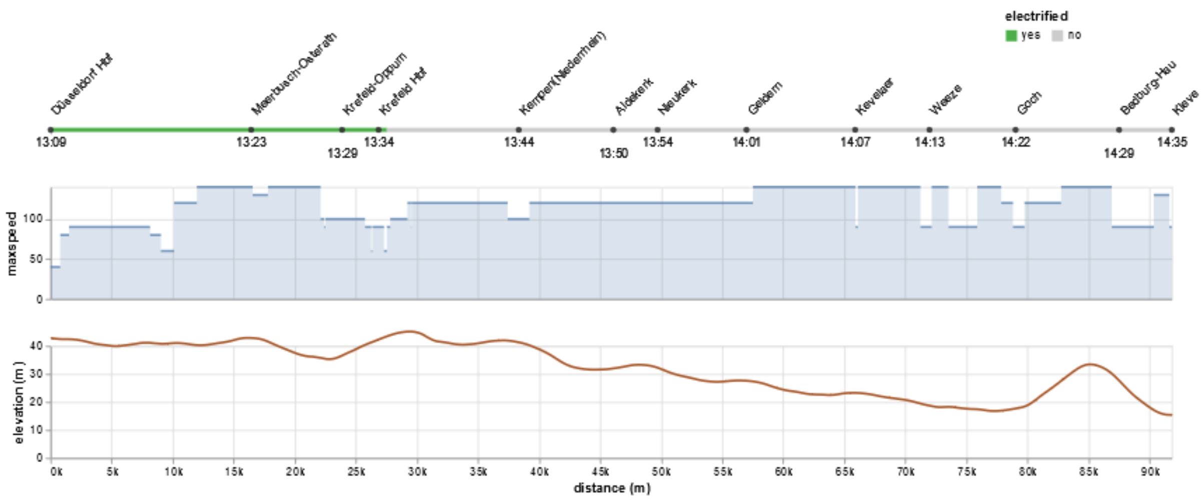

Figure 73: Operational profile Düsseldorf - Kleve.

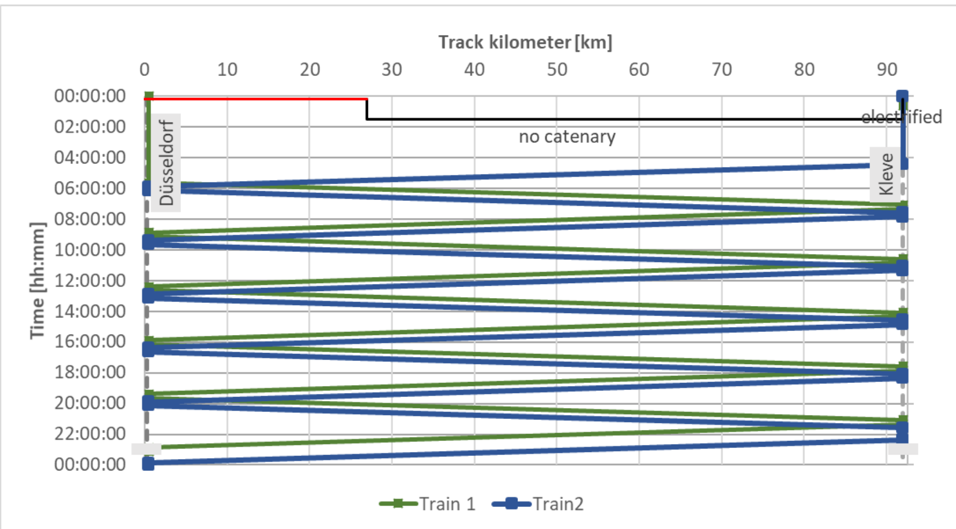

Figure 74: Vehicle operation over a business day for Düsseldorf - Kleve.

Table 55: Line-based requirements for Düsseldorf - Kleve.

Requirement	Value	Unit
Route length	92	km
Electrification degree	30	%
Start-end elevation gain	27	m
Start-end slope	0.3	‰
Travel time	1.43	h
Average stop distance	7.06	km
Average speed	64.1	Km/h

Table 56: Use-case based requirements for Düsseldorf - Kleve.

Route specific and operational requirements	Value	Unit
Trips per day	11	#
Daily distance	1010	Km
Daily travel time	15.77	h
Longest autonomy	64	Km
Cumulated autonomy over a business day	707	Km

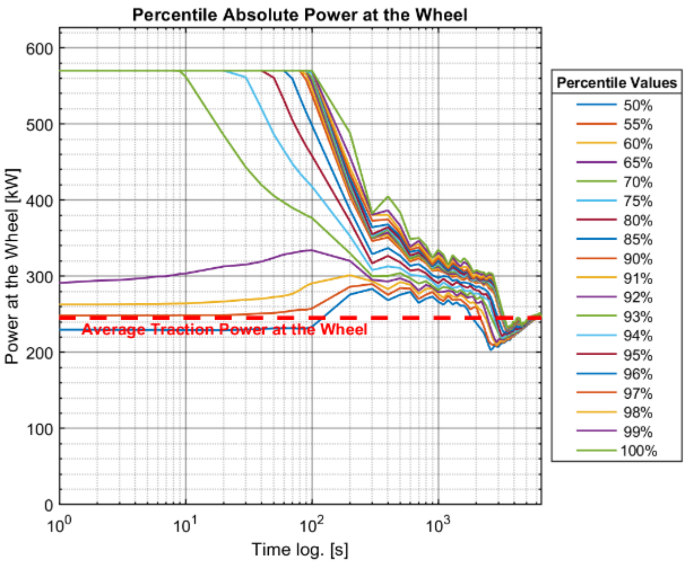

Figure 75: Time weighted load curves for Düsseldorf -Kleve.

5.1.2.6 Augsburg - Ingolstadt

Table 57: Use-case Augsburg - Ingolstadt.

Service:	*Ausgburg - Ingolstadt*
Stops [#]:	11
Vehicle:	Lint 41 /BR648

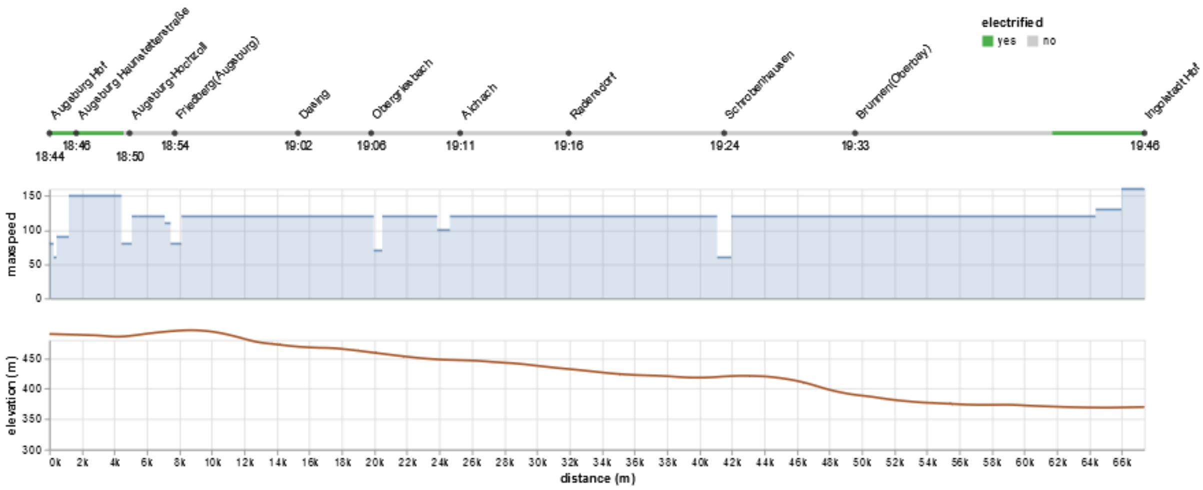

Figure 76: Operational profile Augsburg - Ingolstadt.

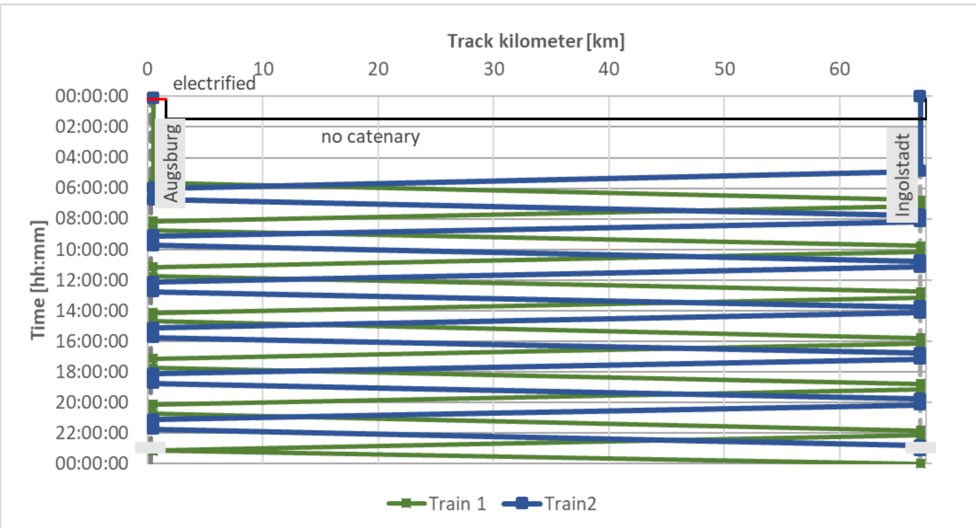

Figure 77: Vehicle operation over a business day for Augsburg - Ingolstadt.

Table 58: Line-based requirements for Augsburg - Ingolstadt.

Requirement	Value	Unit
Route length	67	km
Electrification degree	15	%
Start-end elevation gain	120	m
Start-end slope	1.78	‰
Travel time	1.03	h
Average stop distance	6.13	km
Average speed	65.2	Km/h

Table 59: Use-case based requirements for Augsburg - Ingolstadt.

Route specific and operational requirements	Value	Unit
Trips per day	14	#
Daily distance	943	Km
Daily travel time	14.47	h
Longest autonomy	57	Km
Cumulated autonomy over a business day	800	Km

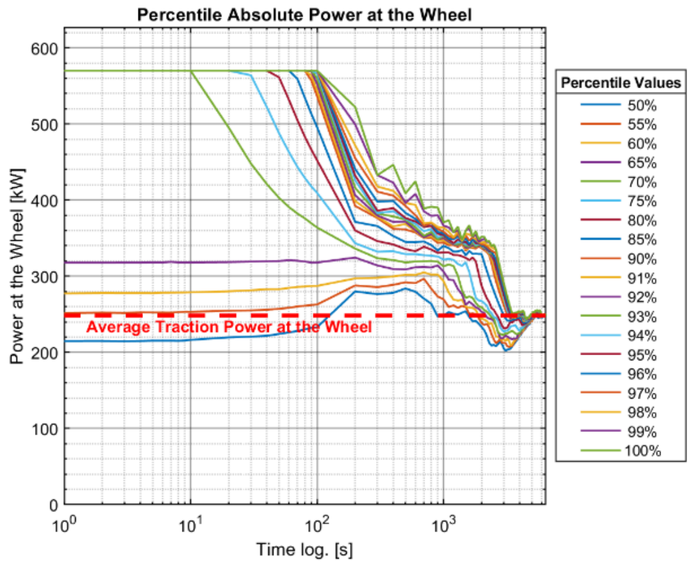

Figure 78: Time weighted load curves for Augsburg - Ingolstadt.

5.1.2.7 Cuxhaven - Bremerhaven

Table 60: Use-case Cuxhaven - Bremerhaven.

Service:	***Cuxhaven - Bremerhaven***
Stops [#]:	6
Vehicle:	Lint 41 /BR648

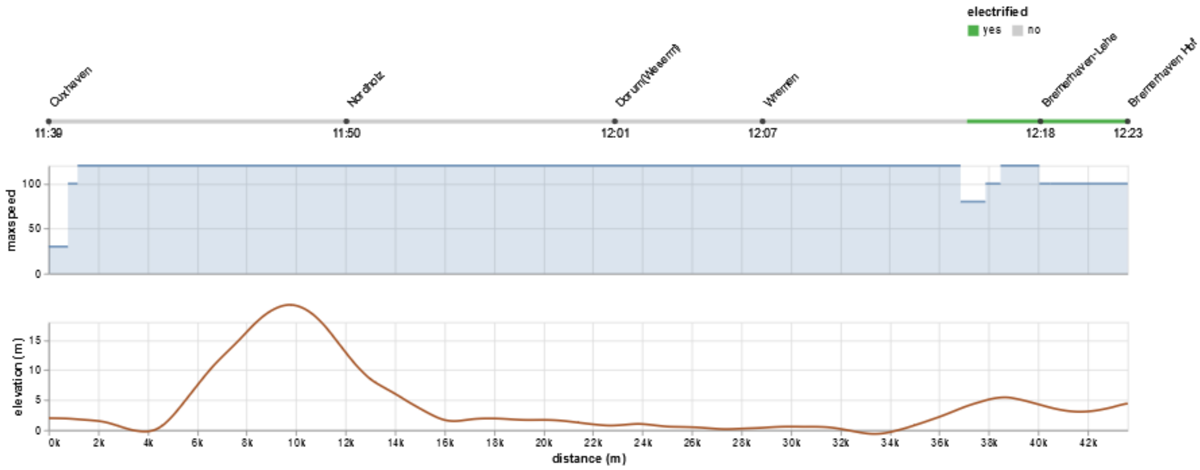

Figure 79: Operational profile Cuxhaven - Bremerhaven.

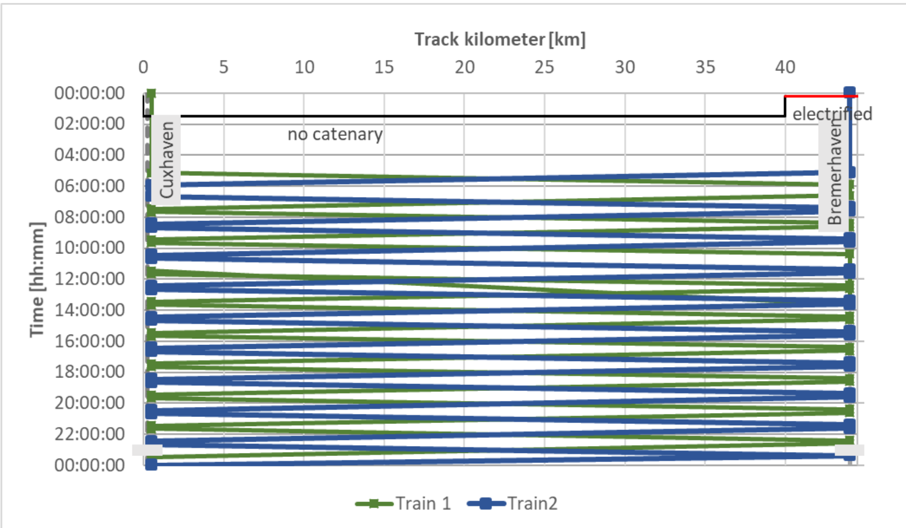

Figure 80: Vehicle operation over a business day for Cuxhaven - Bremerhaven.

Table 61: Line-based requirements for Cuxhaven - Bremerhaven.

Requirement	Value	Unit
Route length	44	km
Electrification degree	15	%
Start-end elevation gain	3	m
Start-end slope	0.06	‰
Travel time	0.73	h
Average stop distance	7.27	km
Average speed	59.5	Km/h

Table 62: Use-case based requirements for Cuxhaven - Bremerhaven.

Route specific and operational requirements	Value	Unit
Trips per day	18	#
Daily distance	785	Km
Daily travel time	13.2	h
Longest autonomy	37	Km
Cumulated autonomy over a business day	668	Km

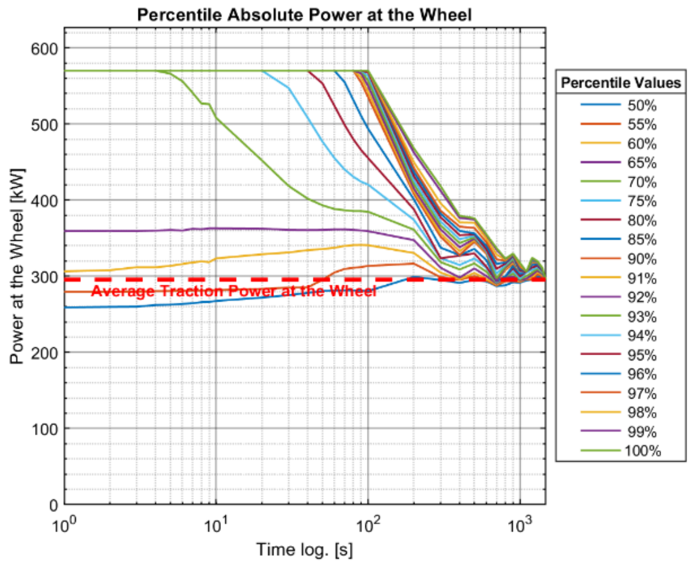

Figure 81: Time weighted load curves for Cuxhaven -Bremerhaven.

5.1.2.8 Göttingen - Nordhausen

Table 63:Use-case Göttingen - Nordhausen.

Service:	***Göttingen – Nordhausen***
Stops [#]:	15
Vehicle:	Lint 41 /BR648

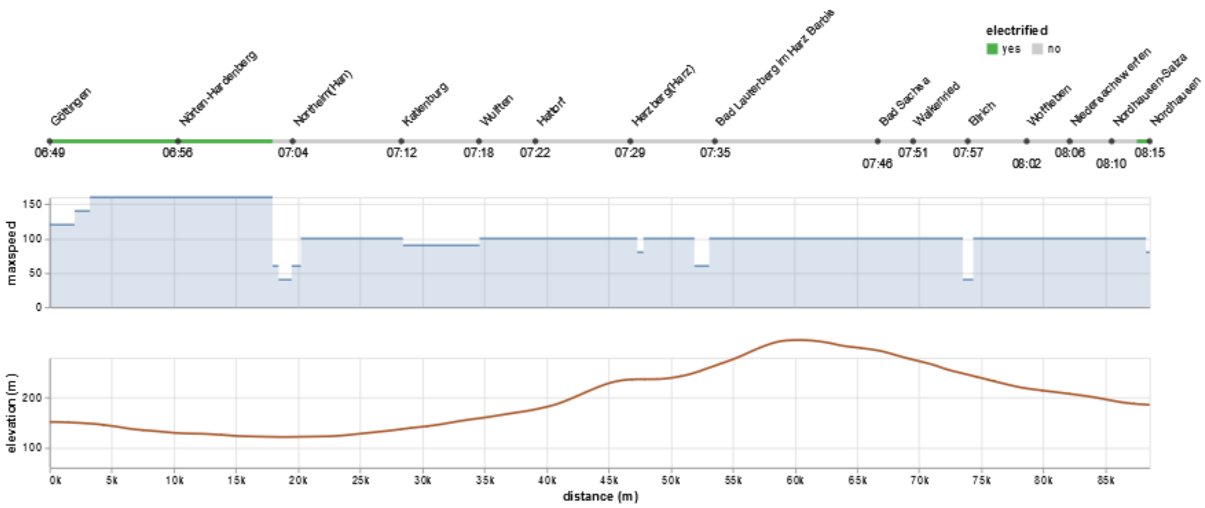

Figure 82: Operational profile Göttingen - Nordhausen.

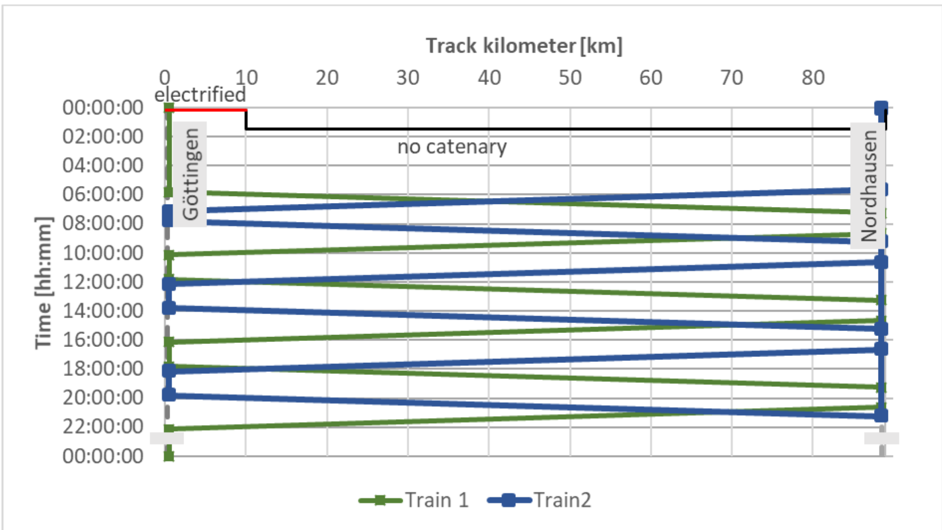

Figure 83: Vehicle operation over a business day for Göttingen - Nordhausen.

Table 64: Line-based requirements for Göttingen - Nordhausen.

Requirement	Value	Unit
Route length	89	km
Electrification degree	21	%
Start-end elevation gain	34	m
Start-end slope	0.39	‰
Travel time	1.43	h
Average stop distance	5.9	km
Average speed	61.8	Km/h

Table 65: Use-case based requirements for Göttingen - Nordhausen.

Route specific and operational requirements	Value	Unit
Trips per day	6	#
Daily distance	531	Km
Daily travel time	8.6	h
Longest autonomy	70	Km
Cumulated autonomy over a business day	417	Km

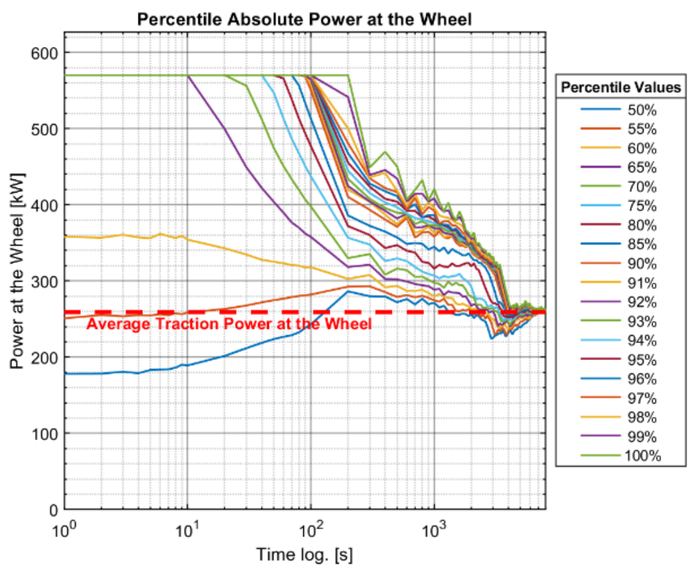

Figure 84: Time weighted load curves for Göttingen – Nordhausen.

5.1.2.9 Eberswalde - Templin

Table 66: Use-case Eberswalde - Templin.

Service:	*Eberswalde – Templin*
Stops [#]:	12
Vehicle:	Regio Shuttle RS1

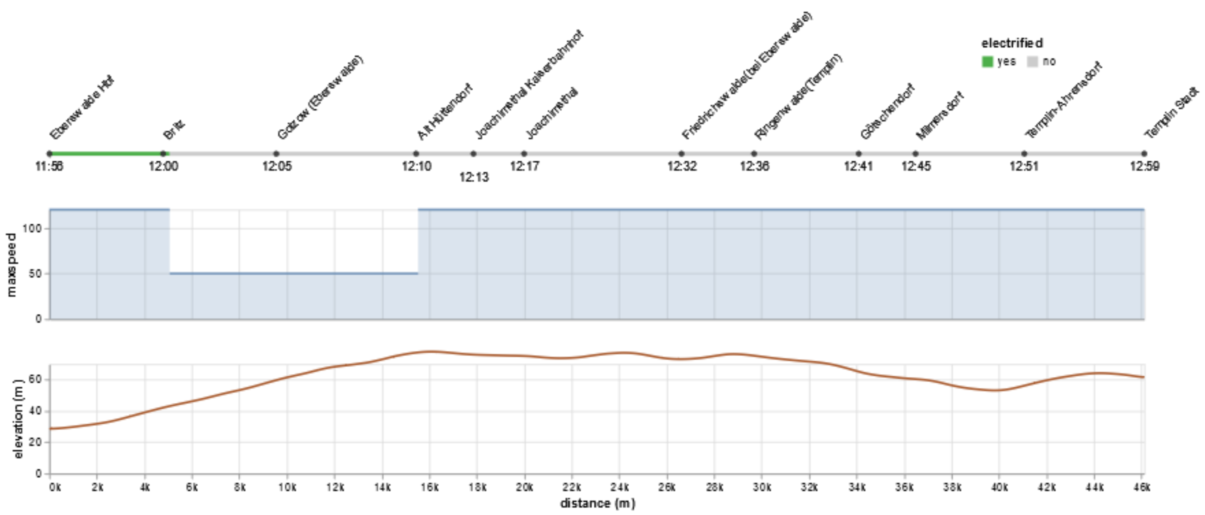

Figure 85: Operational profile Eberswalde - Templin.

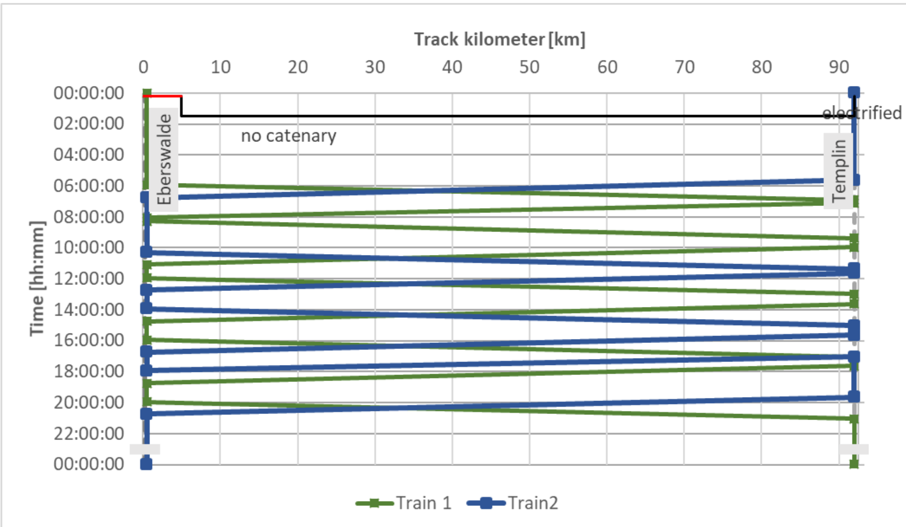

Figure 86: Vehicle operation over a business day for Eberswalde - Templin.

Table 67: Line-based requirements for Eberswalde - Templin.

Requirement	Value	Unit
Route length	46	km
Electrification degree	11	%
Start-end elevation gain	33	m
Start-end slope	0.71	‰
Travel time	1.05	h
Average stop distance	3.84	km
Average speed	43.9	Km/h

Table 68: Use-case based requirements for Eberswalde - Templin.

Route specific and operational requirements	Value	Unit
Trips per day	9	#
Daily distance	415	Km
Daily travel time	9.45	h
Longest autonomy	41	Km
Cumulated autonomy over a business day	369	Km

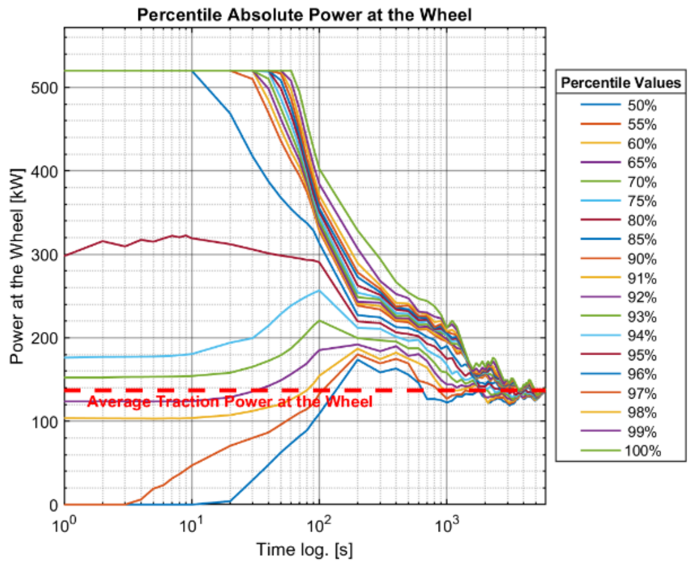

Figure 87: Time weighted load curves for Eberswalde – Templin.

5.1.2.10 Blumberg - Rottweil

Table 69: Blumberg - Rottweil.

Service:	*Blumberg – Rottweil*
Stops [#]:	26
Vehicle:	Regio Shuttle RS1

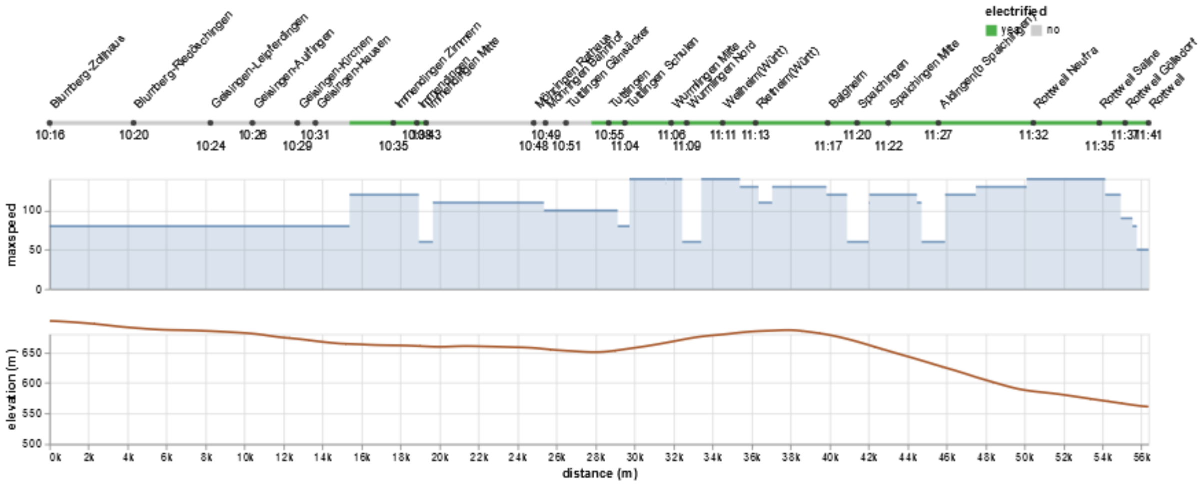

Figure 88: Operational profile Blumberg - Rottweil.

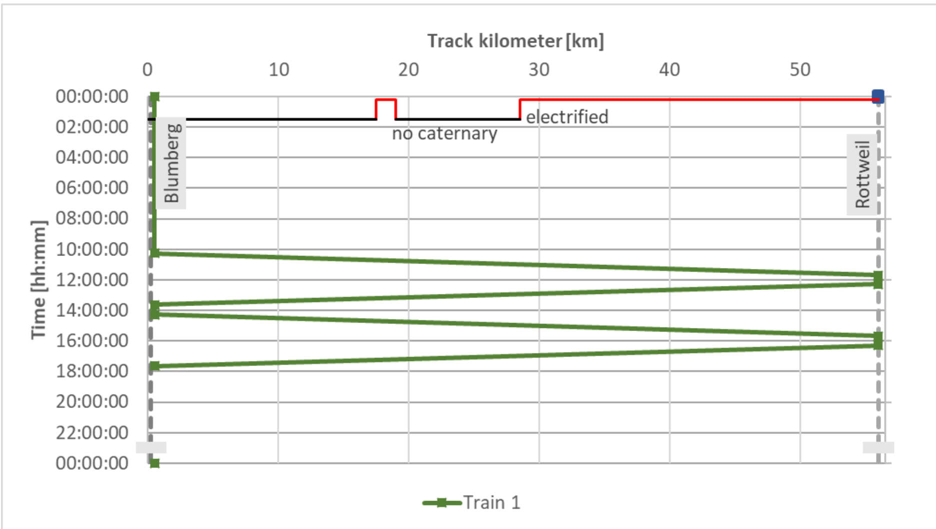

Figure 89: Vehicle operation over a business day for Blumberg - Rottweil.

Table 70: Line-based requirements for Blumberg - Rottweil.

Requirement	Value	Unit
Route length	56	km
Electrification degree	58	%
Start-end elevation gain	140	m
Start-end slope	2.49	‰
Travel time	1.42	h
Average stop distance	2.17	km
Average speed	39.8	Km/h

Table 71: Use-case based requirements for Blumberg - Rottweil.

Route specific and operational requirements	Value	Unit
Trips per day	4	#
Daily distance	225	Km
Daily travel time	5.67	h
Longest autonomy	15	Km
Cumulated autonomy over a business day	95	Km

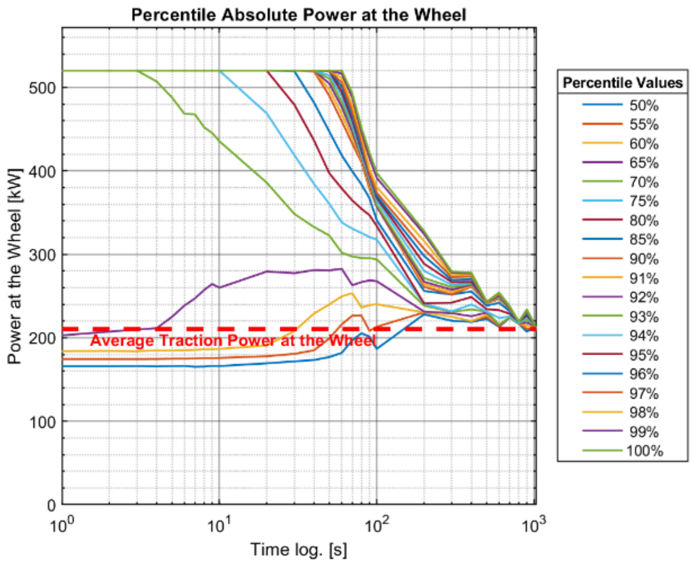

Figure 90: Time weighted load curves for Blumberg - Rottweil.

5.1.2.11 Magdeburg - Bernburg

Table 72: Use-case Magdeburg - Bernburg.

Service:	***Magdeburg - Bernburg***
Stops [#]:	10
Vehicle:	Lint 41 /BR648

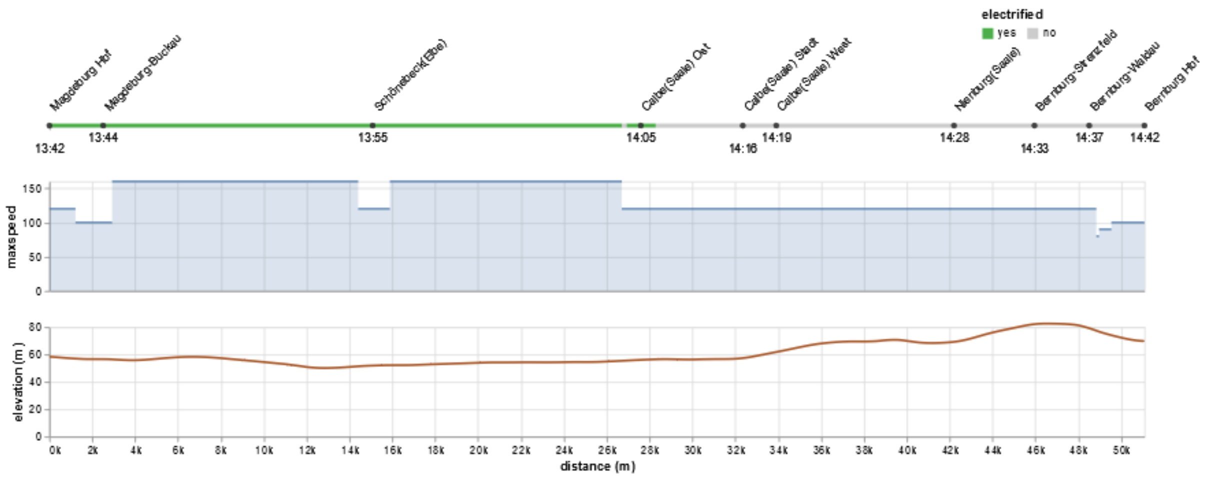

Figure 91: Operational profile Magdeburg - Bernburg.

Table 73: Line-based requirements for Magdeburg - Bernburg.

Requirement	Value	Unit
Route length	51	km
Electrification degree	55	%
Start-end elevation gain	11	m
Start-end slope	0.22	‰
Travel time	1	h
Average stop distance	5.11	km
Average speed	51.1	Km/h

Table 74: Use-case based requirements for Magdeburg - Bernburg.

Route specific and operational requirements	Value	Unit
Trips per day	5	#
Daily distance	255	Km
Daily travel time	5	h
Longest autonomy	23	Km
Cumulated autonomy over a business day	115	Km

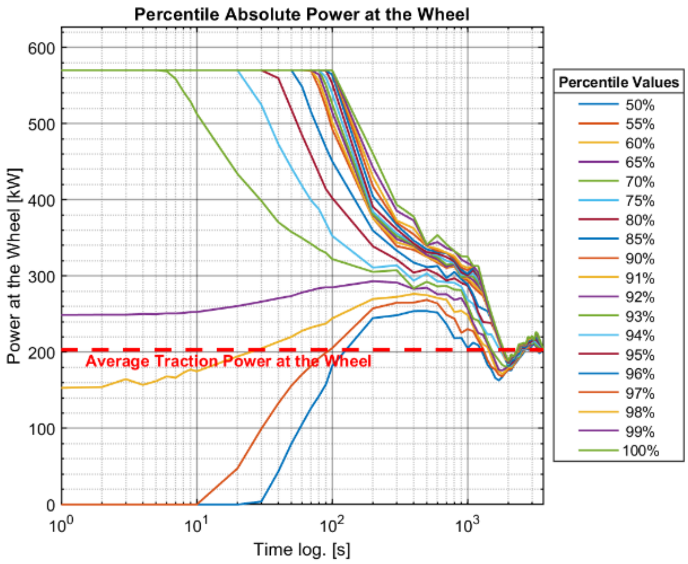

Figure 92: Time weighted load curves for Magdeburg – Bernburg.

5.1.2.12 Pforzheim - Horb

Table 75: Use-case Pforzheim - Horb.

Service:	*Pforzheim - Horb*
Stops [#]:	18
Vehicle:	Regio Shuttle RS1

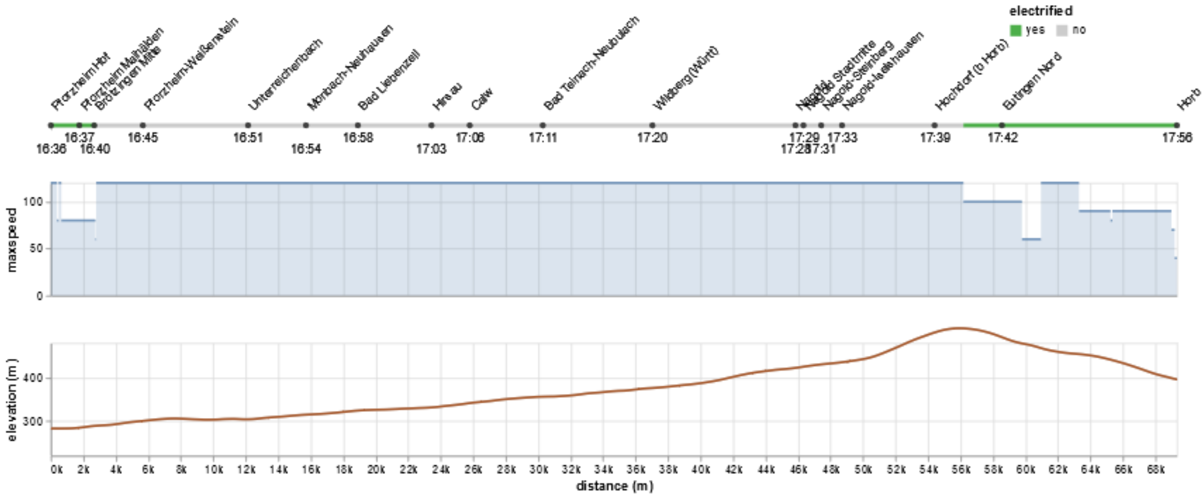

Figure 93: Operational profile Pforzheim - Horb.

Table 76: Line-based requirements for Pforzheim - Horb.

Requirement	Value	Unit
Route length	69	km
Electrification degree	23	%
Start-end elevation gain	113	m
Start-end slope	1.64	‰
Travel time	1.33	h
Average stop distance	3.85	km
Average speed	52	Km/h

Table 77: Use-case based requirements for Pforzheim - Horb.

Route specific and operational requirements	Value	Unit
Trips per day	8	#
Daily distance	555	Km
Daily travel time	10.67	h
Longest autonomy	53	Km
Cumulated autonomy over a business day	427	Km

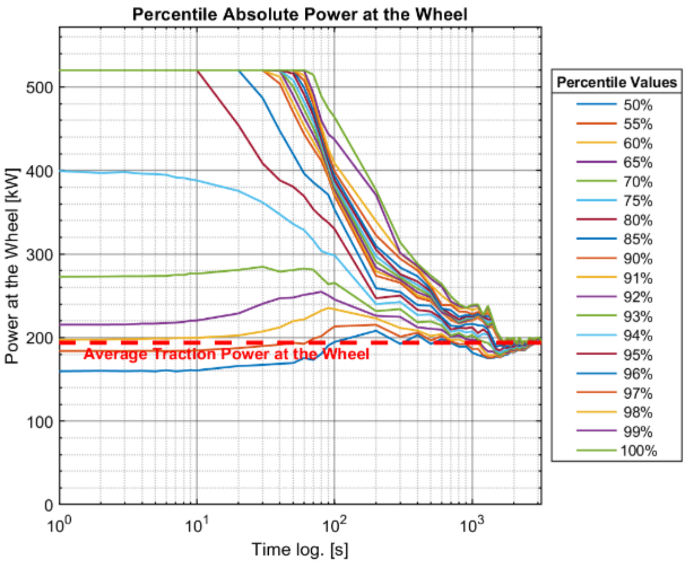

Figure 94: Time weighted load curves for Pforzheim – Horb.

5.1.2.13 Sigmaringen - Memmingen

Table 78: Use-case Sigmaringen - Memmingen.

Service:	*Sigmaringen - Memmingen*
Stops [#]:	17
Vehicle:	Regio Shuttle RS1

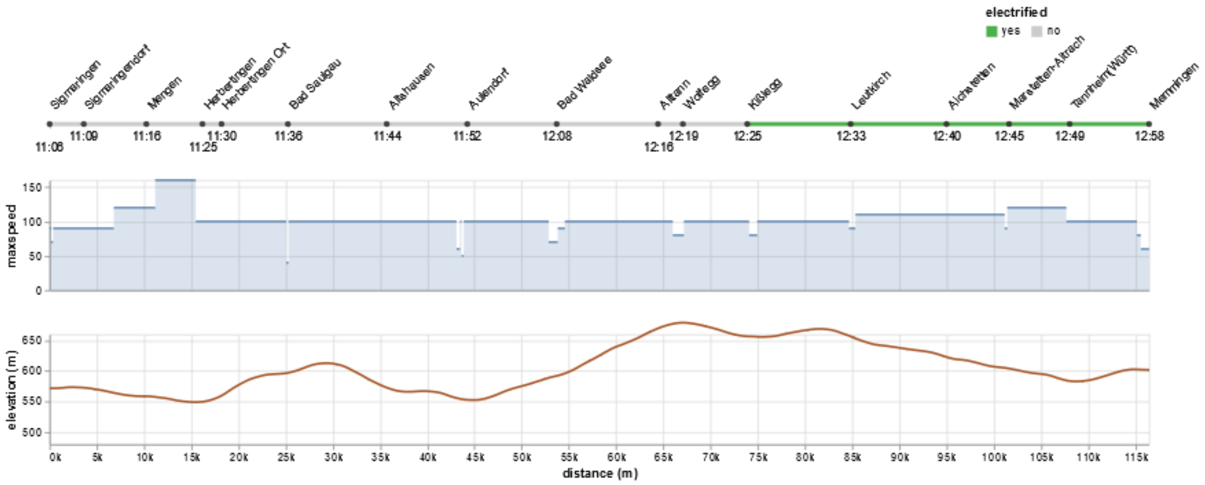

Figure 95: Operational profile Sigmaringen - Memmingen.

Table 79: Line-based requirements for Sigmaringen - Memmingen.

Requirement	Value	Unit
Route length	116	km
Electrification degree	37	%
Start-end elevation gain	30	m
Start-end slope	0.26	‰
Travel time	1.87	h
Average stop distance	6.85	km
Average speed	62.4	Km/h

Table 80: Use-case based requirements for Sigmaringen - Memmingen.

Route specific and operational requirements	Value	Unit
Trips per day	4	#
Daily distance	466	Km
Daily travel time	7.47	h
Longest autonomy	74	Km
Cumulated autonomy over a business day	295	Km

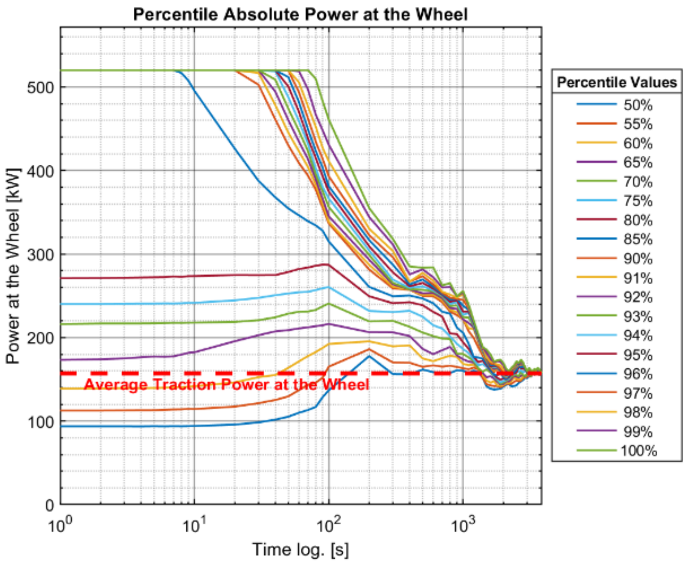

Figure 96: Time weighted load curves for Sigmaringen – Memmingen.

5.1.3 (Summary of) use-case based requirements for multiple units

This chapter summarises the results of the use-case based analysis. Autonomies and lengths of electrified sections are shown in Figure 97. Figure 98 shows traction energy at wheel and potential recuperative braking energy at wheel for the chosen most demanding non-electrified contiguous section. It is noted at this point, that the simulated vehicles do not have the possibility to recover energy through recuperative braking. However, as this study aims to investigate on an electric powertrain, it can be assumed that recuperation will be available. Henceforth, a theoretical electric braking curve based on the electric traction curve is assumed. Figure 99 shows the specific traction energy at wheel without recuperative braking energy. Figure 100 shows average traction power at the wheel for catenary-free sections. Figure 101 shows the maximal traction power at wheel for catenary-free sections. The methodology to assess the traction powers and energies are described in section 1.2.

Figure 97 shows the daily distances for each use-case. While the Spanish use-cases have larger route lengths the circulations in Germany are higher, leading to similar or higher daily autonomies, resp. autonomy requirements. Especially on lines with high frequencies, these requirements (e.g. Stuttgart – Aulendorf) depend largely on the number of vehicles operated on the service.

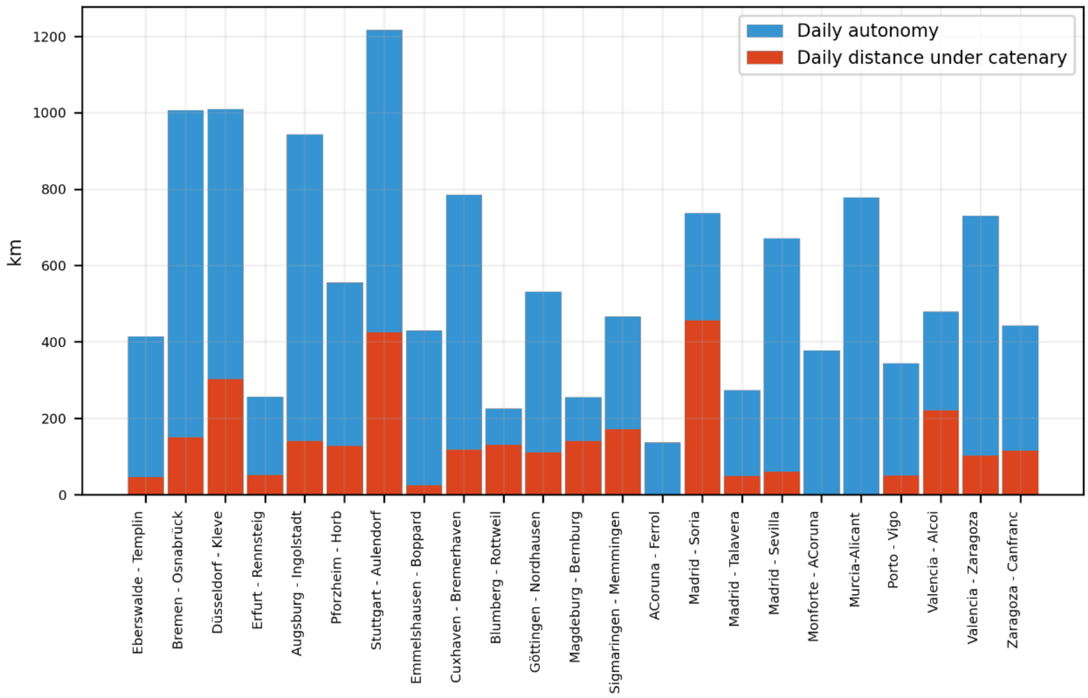

Figure 97: Use-cases daily autonomies.

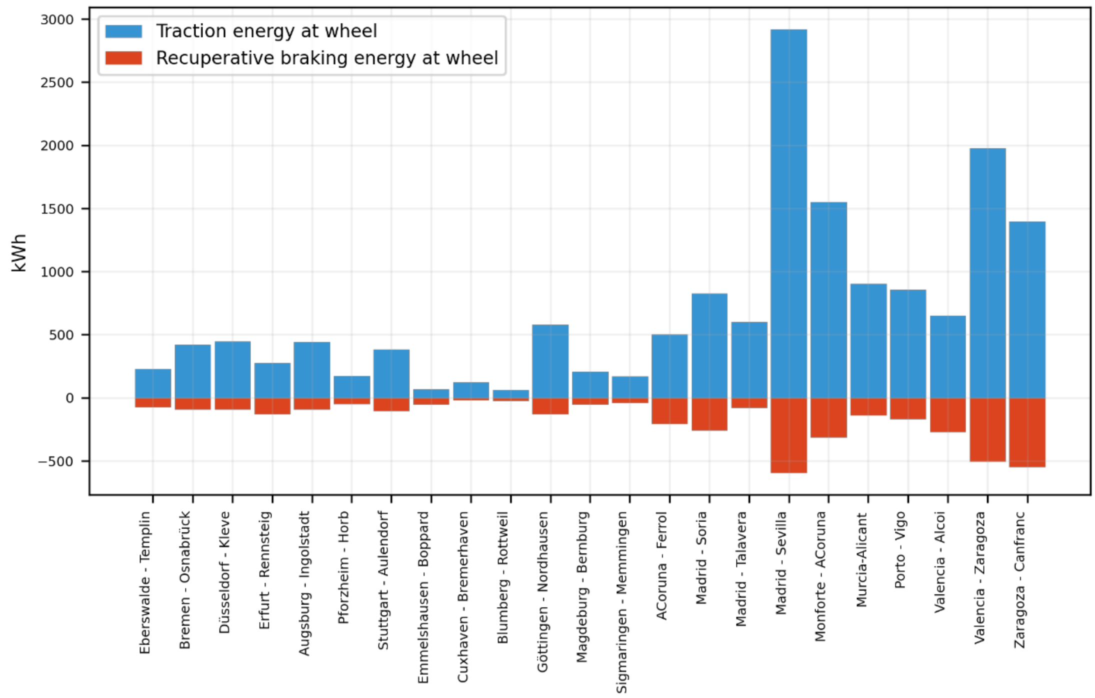

Figure 98: Traction energy at wheel and recuperative braking energy at wheel for the most demanding non-electrified section.

Figure 92 shows the traction energy at wheel level for non-electrified sections. The energy is simulated for an entire circulation. The energy therefore reflects mainly the route length but also the vehicle mass which is larger for the Spanish use-cases (comp. section 5). To compare use-cases in terms of energy demand Figure 99 shows the specific traction energy at wheel per tonne kilometre. This graph indicates that topographic challenging lines (such as Zaragoza – Canfranc) can be less demanding in terms of energy if the operational characteristic (e.g. low speeds on steep sections) are low. The other way around, routes with flat topologies (such as Blumberg – Rottweil) might be especially challenging, in this case due to constant stopping and acceleration (avg. stop distance 2.4 km). This of course strongly depends on the vehicle used and the necessary auxiliary demands which are not considered here. Again, both graphs are for catenary-free sections only, reflecting demands on the FCHPP.

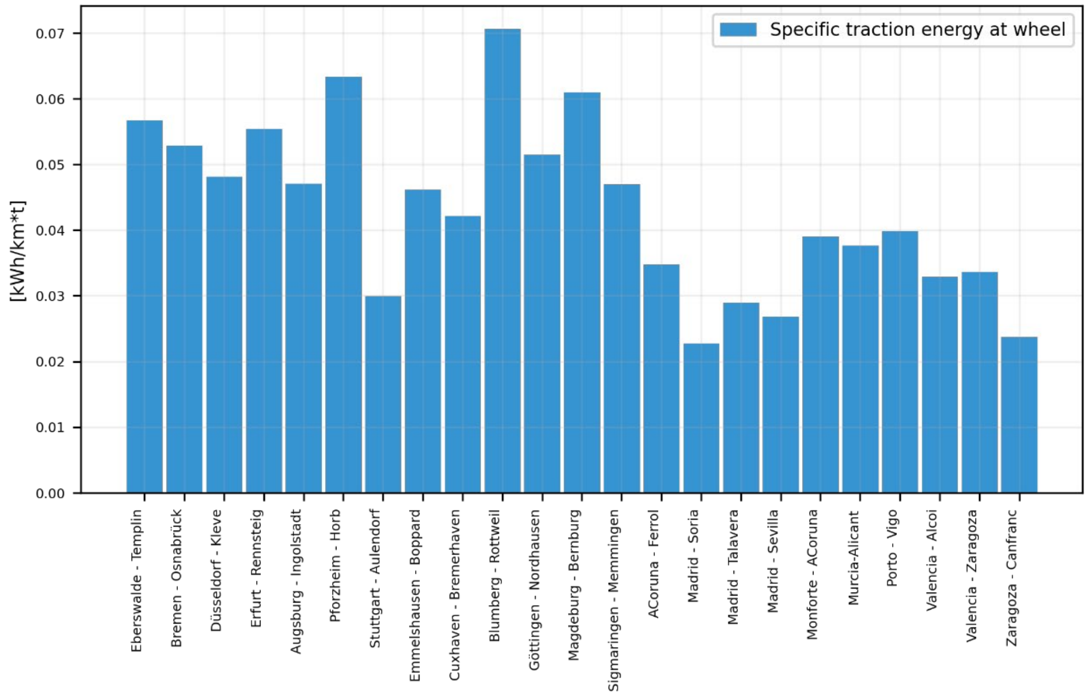

Figure 99: Specific traction energy at wheel (without recuperative braking energy) for the most demanding non-electrified section.

The traction energy at wheel indicates the energy amount to be stored on the vehicles (i.e. hydrogen tanks and traction battery capacity). The average power over catenary-free sections shown in Figure 100 indicates requirements on the fuel cell power. The max traction power (Figure 101) occurs in the acceleration phase and reflects the maximal vehicle drivetrain configuration.

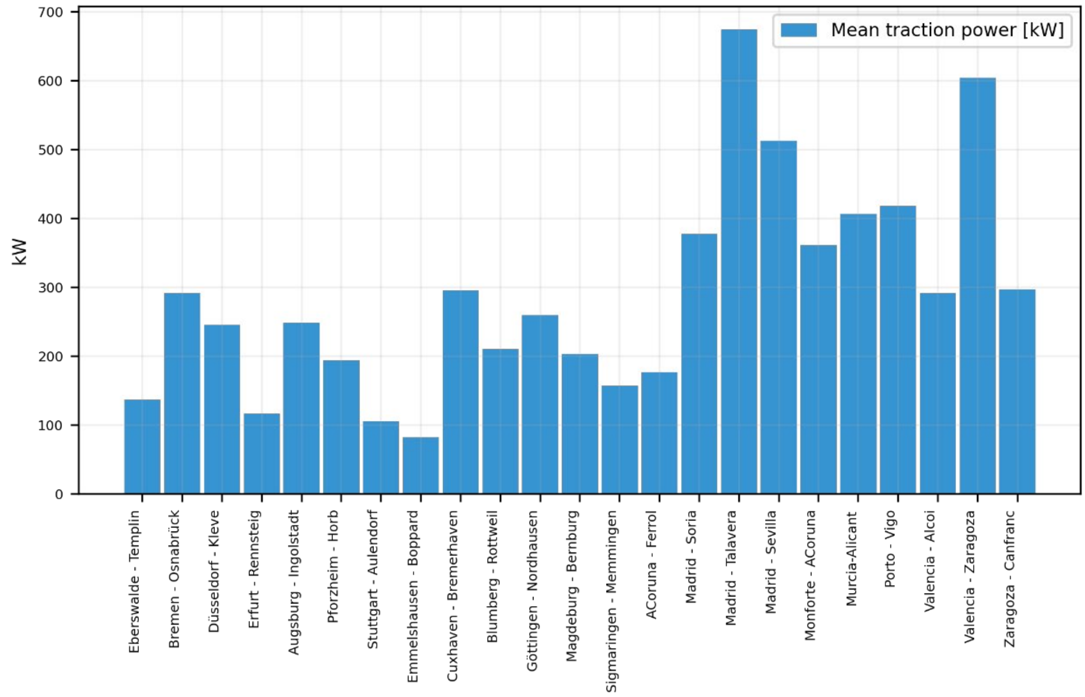

Figure 100: Average traction power for catenary-free sections.

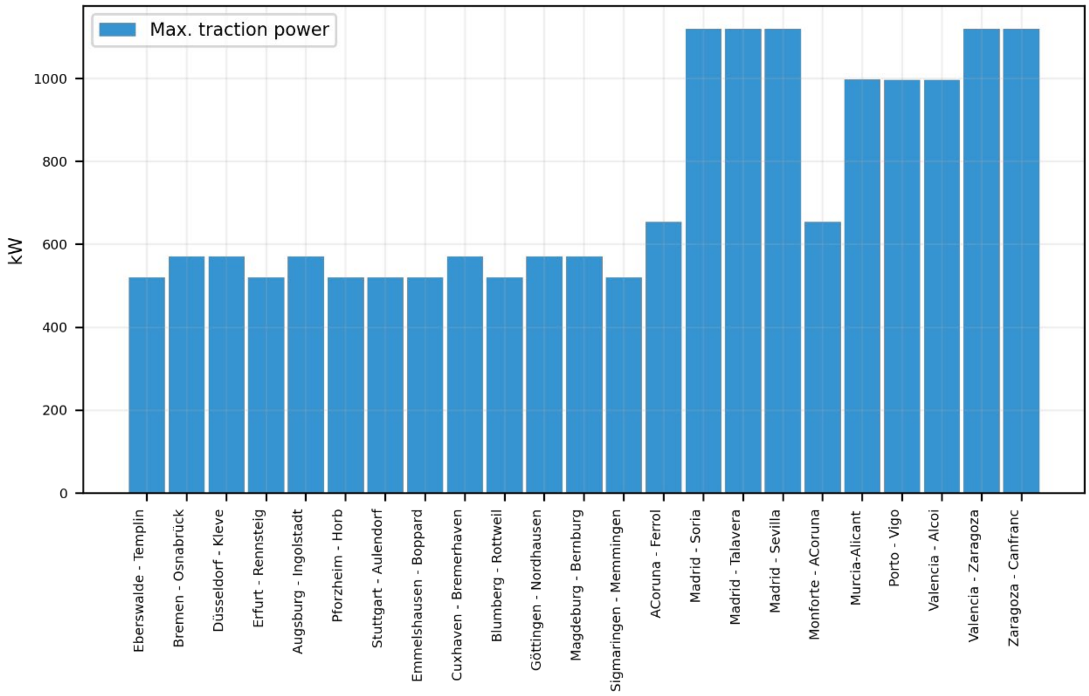

Figure 101: Peak traction power at wheel for catenary-free sections.

5.2 Use-cases mainline locomotives

In this chapter use-cases for mainline locomotives are shown. As described in section 4, mainline locomotives cover most of the long-distance services. Furthermore, as the broad usage of multiple units was only adopted at a later stage for the Spanish railway network, locomotives are deployed for high-speed services as well. [3] As they carry higher masses than multiple unit-services and through their operational scenarios, henceforth mainline locomotives represent challenging lines with the necessity to provide significant higher traction power. Therefore, two services with long distances were chosen, both currently covered with a configuration of ten coaches and one locomotive for the use-case Madrid – Algeciras or respectively ten coaches and two locomotives for the use-case San Sebastian – Lisboa. Both configurations could benefit greatly from bi-mode hydrogen propulsion. Both use-cases have been considered in simulations in subsequent Deliverable D1.4. [4] Additionally, deviations between the real and theoretical parameters for the simulation are already discussed in D1.4 inducing a potential overestimation.

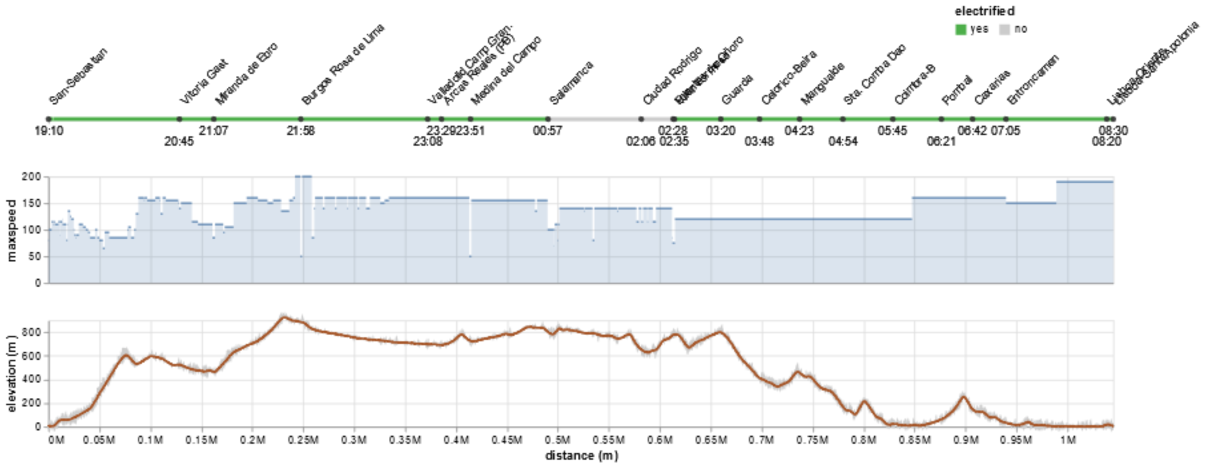

Figure 102: Operational profile for San Sebastian – Lisboa.

Table 81: Line-based requirements for San Sebastian – Lisboa.

Use-case attribute	Value	Unit
Route length	1045	km
Electrification degree	88	%
Start-end elevation gain	4	m
Start-end slope	0	‰
Travel time	13.35	h
Average stop distance	49.76	km
Average velocity	78.3	Km/h
Longest autonomy	123	Km
Traction energy*	1509.3	kWh
Recuperative braking energy*	154.7	kWh
Specific traction energy (without recuperative braking energy)*	0.031	[kWh/km*t]
Average traction power*	1385.7	kW
Peak traction power*	3289.9	kW

* At wheel on catenary-free sections.

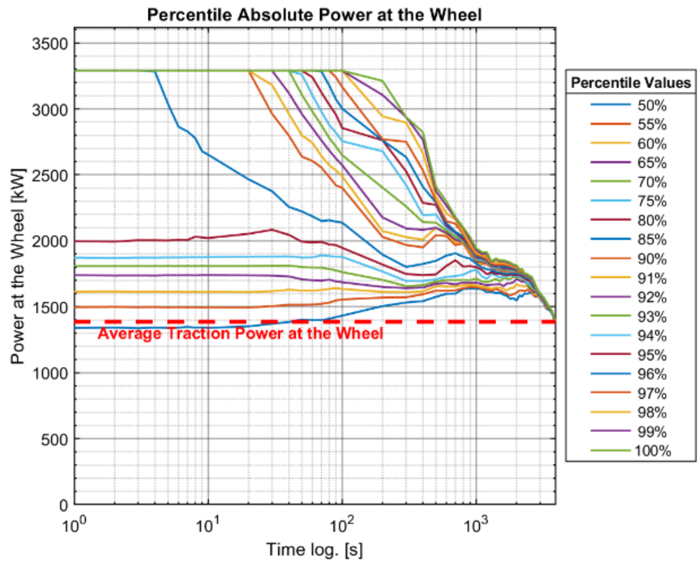

Figure 103 Time weighted load curves for San Sebastian - Lisboa.

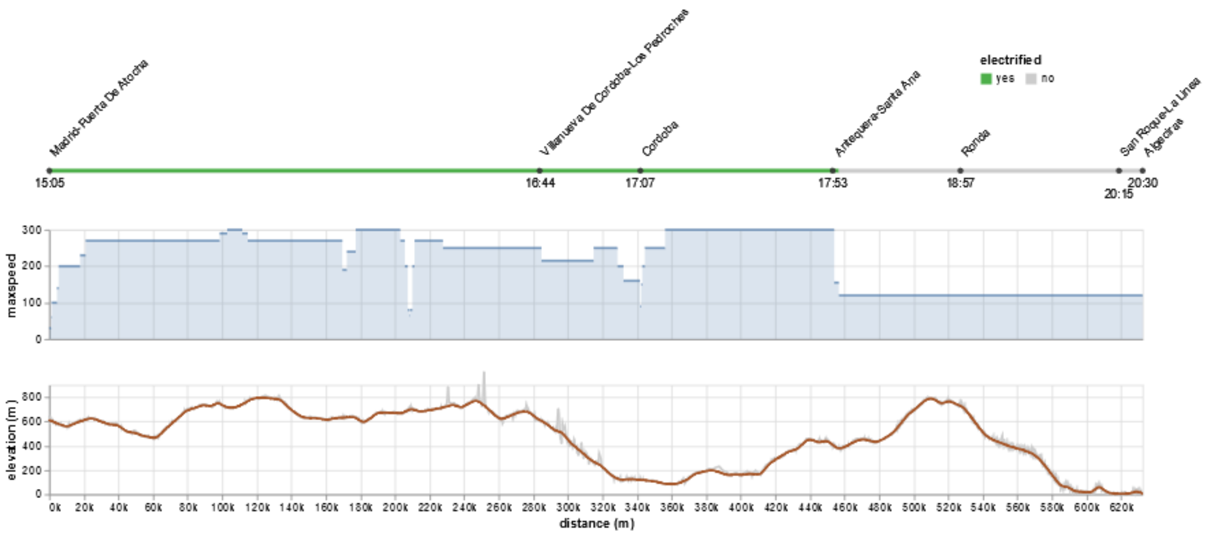

Figure 104: Operational profile for Madrid - Algeciras.

Table 82: Line-based requirements for Madrid - Algeciras

Use-case attribute	Value	Unit
Route length	632	km
Electrification degree	72	%

Start-end elevation gain	603	m
Start-end slope	0.95	‰
Travel time	5.9	h
Average stop distance	90.35	km
Average velocity	107.2	Km/h
Longest autonomy	176	Km
Traction energy*	3257	kWh
Recuperative braking energy*	285.4	kWh
Specific traction energy (without recuperative braking energy)*	0.031	[kWh/km*t]
Average traction power*	945.6	kW
Peak traction power*	2092	kW

* At wheel on catenary-free sections.

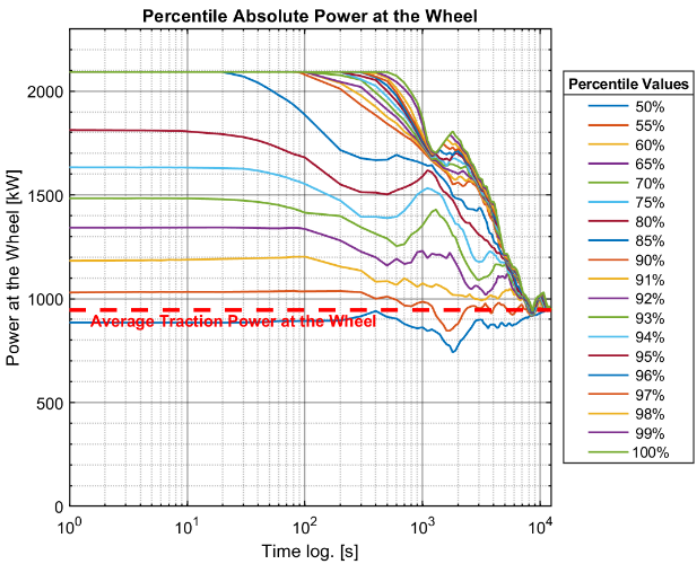

Figure 105 Time weighted load curves for Madrid Algeciras.

5.3 Shunting locomotives

Unlike trains in passenger services, shunting locomotives do not follow a recurrent scheduled operation. Shunting locomotives are mainly used for maintenance operation and manoeuvres. The mass changes according to the number of wagons the locomotive is towing. Operations of shunting locomotives are described in Deliverable 1.3 [3]. Pagenkopf et.al. (2022) [10] tracked operational profiles of shunting locomotives have been analysed. From this, generic shunting profiles have been developed. To derive FCHPP requirements for shunting locomotives a use-case was designed based on those generic shunting cycles. Figure 106 shows the representative load profile considered during the simulations.

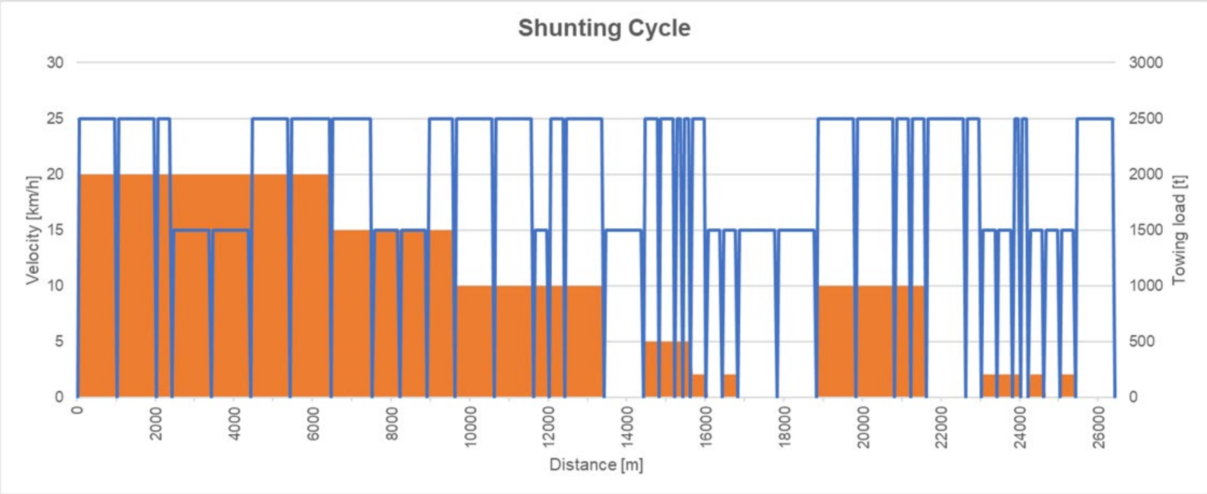

Figure 106: Towing load (orange) and velocity profile (blue) of generic shunting operation [10].

The vehicle used for simulation is a generic shunting locomotive based on the Alstom Prima H3 as it compares closely to the dominant types Class 310 and Class 311. Table 83 shows weight values for the generic shunter used in the simulations in subsequent deliverables D1.3 and D1.4.

Table 83: Weight values for the generic shunting locomotive simulation model

	Generic Shunting Locomotive
Locomotive (Tn)	67.5
Locomotive + maximum load during cycle Cargo (Tn)	2047.5
Rotative masses (Tn) (Locomotive)	1.35
Rotative masses (Tn) (Locomotive + max. load during cycle Cargo)	40.95

6. Conclusion

This chapter describes the general findings of this deliverable, discusses the achievable market potential of hydrogen trains and draws a final conclusion.

This document describes infrastructural and operational requirement on hydrogen trains. It does so by deriving attributes such as route length, autonomies, velocities and stop distances from public data sources for three countries. In comparison, Spanish railway passenger services are longer with fewer stops and few trips over a day while having rather challenging topologies. The topology demands are less well reflected in the net elevation gain from start-to-end in the line analysis but can better be understood by considering elevation profiles in use-case descriptions. In Portugal, only few lines operated with DMU are potentially FCHMU-services as extensive electrification plans are ongoing. For a selection of representative services use-cases are formed. For these use-cases, possible circulations are considered and mechanical energy simulations are performed. The mechanical energy simulation gives a first insight on requirements for a FCHPP, especially in terms of energy content and average power for catenary-free sections. This is also the foundation for more through energy analysis and component design in subsequent deliverables.

Considering the current market, alternative propulsion technologies are gaining ground in the field of regional passenger rail transport. With the Coradia iLint from Alstom, a hydrogen electric multiple unit has already reached market maturity. The model is already being used in regional railway operations. Mireo Plus H of manufacturer Siemens will enter passenger operation in 2024 in German Heidekrautbahn.

However, battery electric multiple units (BEMU) are playing an increasingly important role as a competing technology. Battery trains are more advantageous in terms of energy efficiency, as they incur lower energy conversion losses than fuel cell electric trains. This often makes them more cost-effective and more energy-efficient to operate. However, so far there is currently (02/2022) no battery-powered multiple unit that is operated in regular passenger service apart from temporary operational trial runs. Rolling stock manufacturers Alstom (Coradia Continental) and Stadler (Flirt Akku) both demonstrated BEMU-feasibility with prototype trains or will do shortly (Siemens Mireo Plus B). Tender contracts have been concluded for deliveries of BEMU to German networks (e.g. Pfalznetz and Nah.SH). Vehicles will start passenger services in 2023. In Niederrhein-Münsterland network in Germany Civity BEMU manufactured by CAF will enter passenger service on December 2025. A major disadvantage is the low range of battery trains. If battery trains are to be used on long non-electrified lines, as is particularly common in Spain, regular electrification islands or recharging stations along the route need to be installed. Hydrogen trains, on the other hand, can cover much longer autonomies. In Spain, autonomies in the range of 200 to 600 km per trip are common, often with rather few circulations. In Germany, the autonomies are significantly lower, but the routes are operated more frequently on average, which again leads to higher autonomies. In both cases, there are autonomies that can hardly be handled by battery-powered trains. Locomotive changes are particularly frequent on the longer routes that are operated with hauled locomotives. These time-consuming and expensive changes could be reduced by employing bi-mode trains. Through-connection options for trains have great potential to make daily train operations more flexible and offer customised connections, fitting to the transport demands. However, a precise assessment of through-connection options is a case-by-case consideration and cannot be carried out comprehensively across all countries.

In day-to-day operations, the cost of vehicle procurement plays a particularly important role when switching to a new technology. The average service life of multiple units in Germany is around 30 years. This also has an impact on the depreciation period. If major fleet renewals are carried out, this represents an obstacle to the introduction of new technologies. In Spain, 43.5 percent of vehicles are 25 years and older (Figure 107). In Germany, a major renewal along the vehicle stock took place between 2000 and 2005.

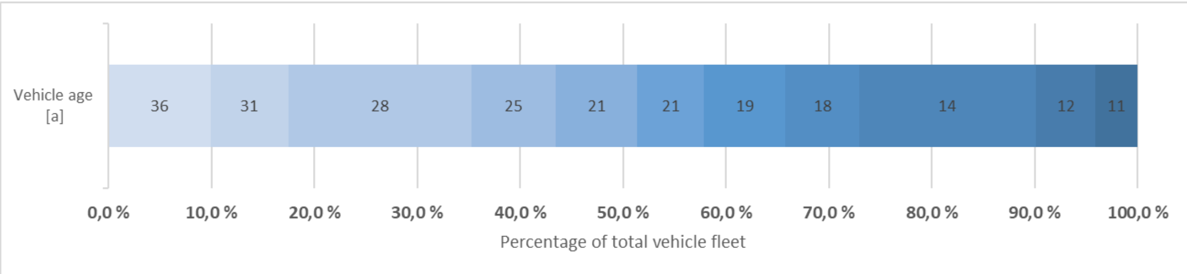

Figure 107: Percentage of vehicle ages of overall DMU fleet in Spain and Portugal.

It is unlikely that these younger vehicles will be phased out quickly and replaced with alternatively powered trains. For these vehicles, a retrofit solution to hybrid or all-electric powertrains could be an option, but being linked to a couple of technical, economical and approval related challenges. In all countries considered, however, there are a large number of vehicles whose age suggests that they will soon be phased out of service. In the current situation, where train manufacturers have to push ahead with technology development and ramp up production capacities, the market promises sufficient sales potential.

7. References

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A.1 List of Figures

A.2 List of Tables

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JOINT UNDERTAKING