Issue 20(4), 2020, pp. 286-305
https://doi.org/10.18757/ejtir.2020.20.4.5439

TU Delft OPEN

EJTIR

ISSN: 1567-7141
http://ejtir.tudelft.nl/

Can regional railway become emission-free with recently announced vehicles? - A case study of Bavaria

Florian Mueller[1]
Technical University of Munich (TUM)

Markus Guerster[2]
System Architecture Lab, Massachusetts Institute of Technology (MIT)

Nikola Obrenović[3]
Faculty of Technical Sciences, University of Novi Sad (UNS)

Michel Bierlaire[4]
Transport and Mobility Laboratory, École Polytechnique Fédérale de Lausanne (EPFL)

Significant shares of regional passenger railway still rely on pollutive diesel vehicles. Alstom, Bombardier, Siemens, and Stadler have reacted and recently announced Battery Electric and Fuel Cell Electric Vehicles (BEVs and FCEVs). In this paper, we analyze to what extent these new vehicles can replace diesel technology on a large variety of regional railway lines in Bavaria, Germany. Our approach is based on two databases that we build: One for the announced emission-free vehicles and one for existing lines. We compare the lines and vehicles in terms of range, axle load, velocity, and specific power. The study reveals that 72 out of the 73 lines can be operated with an emission-free vehicle. The main driver for BEVs is their range and maximum velocity. Depending on these characteristics, they can operate between 53% and 82% of all lines. The main driver for FCEVs is their specific power and maximum velocity. One vehicle, the Alstom iLint, can only operate 18% of all lines due to its limited performance. The Siemens Mireo Plus H series has higher performance and can operate 97% of the lines.

Keywords: *Battery Vehicles, Emission Reduction, Fuel Cell, Regional Rail, Vehicle Technology.*

---

[1] A: Dachauer Strasse 25, 80335 Munich, Germany T: +49 179 41 97 800 E: flo.mueller@tum.de
[2] E: guerster@alum.mit.edu
[3] E: nikola.obrenovic@uns.ac.rs
[4] E: michel.bierlaire@epfl.ch

1. Introduction

In recent years, governments became more aware of climate change, and hence, they are launching several programs to reduce emissions across all industries. Although railway is amongst the less pollutive modes of transport, there is still a significant number of vehicles running on diesel. Focusing on Germany, diesel rail operation from regional passenger traffic causes 64% of all railway emissions, adding up to 1.2 Mio. tons of CO_2-equivalent per year (Hecht & Culemann, 2018).

The diesel operation only affects lines that are partly or not at all electrified, i.e., not equipped with an overhead catenary. As of 2018, 47% of the German network are not electrified (Federal Network Agency of Germany, 2019). Two emission-free vehicle technologies, Battery Electric Vehicles and Fuel Cell Electric Vehicles (BEVs or FCEVs), provide an opportunity to operate non-electrified lines without time-consuming and expensive line electrification.

Several established manufacturers are pushing new BEVs and FCEVs into the market in recent years. What remains unclear is to what extent these vehicles are ready to operate on the current grid. For example, these vehicles need to comply with infrastructure requirements, work with existing schedules, and store sufficient amounts of energy between recharging or refilling points. We answer this question for the German region of Bavaria.

In particular, we answer these questions: "Which vehicles can be operated on which lines?", "Does one of the technologies, BEVs or FCEVs, have an edge over the other?" and "Are emission-free vehicles, as of today, capable of enabling network-wide emission-free rail operation?"

In the remainder of this paper, we first provide further background on emission-free solutions, discuss our approach, and present the method. The subsequent section discusses the results for the regional tracks in Bavaria, Germany. In the final part, we elaborate on the conclusions and propose further research directions.

2. Emission-free rail vehicles in literature

As discussed in the introduction, there are two main categories of solutions to replace diesel operations:

The first solution is to increase efforts to electrify tracks. However, there are limitations: over the last two decades, an average of 35 kilometers out of 15 000 in total have been electrified per year in Germany (Mueller, Guerster, Schmidt, Obrenovic, & Bierlaire, 2019a). Although more kilometers were planned, they could not be completed on time due to limited planning capacities or funding (Isenhoefer & Zieger, 2018).

The second solution is to replace diesel technology with emission-free BEVs or FCEVs. Alstom's iLint FCEV is already in operation (Verdict Media Ltd., n.d.), Bombardier plans test operations of the Talent 3 Battery Electric Multiple Unit (BEMU) (Internationales Verkehrswesen, 2018), Stadler will commission 55 vehicles in 2022 and 2023 (Hebermehl, 2019), and Siemens already sold vehicles of its new modular platform Mireo, where eight different variants have been announced (Siemens Mobility GmbH, 2018).

There exists work that compares the two proposed solutions: A study by Verband der Elektrotechnik, Elektronik und Informationstechnik (VDE) investigated possible measures to allow for emission-free rail traffic (VDI/VDE Fachausschuss Wasserstoff und Brennstoffzellen, 2019). One solution that is not part of the introduced two common categories is the use of synthetic fuels. Their benefit would be that the compatibility with current vehicles and no infrastructure changes. However, synthetic fuels are currently prohibitively expensive. A study by German thinktanks lets us expect that synthetic fuels will remain significantly more expensive than today's fossil fuels until at least 2050 (Agora Verkehrswende, Agora Energiewende, & Economics Frontier, 2018).

Regarding the electrification of tracks, the VDE found that it plays an important role in emission-free traffic. However, first, they claimed that it is not economically feasible for all lines, and second, the planning and construction phase takes several years or even decades. Therefore, we conclude that electrification does not allow us to operate a large share of traffic emission-free within a reasonable time.

Concerning emission-free vehicles, the VDE found them to be a favorable option as the technology is expected to be cost-competitive and is available as of the time of the study. However, the study leaves the question open which new vehicles can replace which existing ones.

3. Approach

To answer the identified research questions, we follow a four-step approach described in the following four subsections: The first step is to take the three criteria identified in the literature and translate them into four requirements that we will use throughout the paper. Second, lines are assessed for their requirements one by one. Third, we set up a database of vehicles and their capabilities. Fourth, we map the vehicle database onto the line database using the defined criteria. This step is described in the "Results" section.

3.1 Literature criteria for vehicles' requirements

Pagenkopf & Kaimer (2014) investigated the technological feasibility specifically of BEV and FCEV vehicles. As both vehicle types' drivetrains tend to be heavier than the ones of current vehicles, they found axle loads to be an important constraint to allow for operation on existing tracks. They analyzed BEVs and FCEVs for one existing rail line and concluded that both concepts are technologically feasible. Whether the operation is feasible on other lines was not investigated.

Next to axle load, an additional requirement that existing lines impose is the range. Range is critical, as, compared to diesel vehicles, the battery size is limiting the amount of energy BEVs can store on-board. Pagenkopf, Böhm, Haas, & Friedrich (2018) investigated range requirements and other properties for all 469 diesel lines in Germany. They exposed that the line's properties vary in broad ranges, e. g. distances range from 5 to more than 400 kilometers, and average velocities from 23 to 95 km/h. In the same work, they outlined a number of lines with properties that recommend using BEVs and FCEVs, respectively. However, these recommendations are solely based on range considerations.

Ebrecht, Walter, Zedlitz, & Zimmermann (2019) took the novel BEV "Bombardier Talent 3 BEMU" and investigated the feasibility of operation on five lines in Germany. One of their criteria is that existing schedules on the lines need to be maintained. We agree and consider this crucial: not keeping up schedules leads to increased journey times for customers first directly and second, indirectly if connections to other trains are missed. Ebrecht et al. state the criterion on maintained schedules, especially addressing the time lost while charging. The authors assume that the novel vehicle has sufficient performance on the line without further justification. Feasibility might be given for the considered Bombardier Talent 3, but the assumption is not transferable to all vehicles. Some emission-free vehicles' performance might not be sufficient to maintain current schedules.

To summarize, we find that in the literature three criteria are used to determine feasibility: *axle loads* (Pagenkopf & Kaimer, 2014), *range* (Pagenkopf et al., 2018), and *maintaining the schedule* (Ebrecht et al., 2019). None of the studies used all three criteria to assess the feasibility of current vehicles with the new BEVs and FCEVs. This work aims to fill the literature gap and answers the question "Can new emission-free vehicles replace current diesel vehicles?"

3.2 Deriving quantifiable requirements from literature

The railway sector is highly regulated, and a number of criteria must be fulfilled for a vehicle to operate on the network. Train protection systems or platform heights are two examples. A number of these criteria differ from line to line. In this work, we focus on the drivetrain-specific aspects. As all vehicles assessed in this work are announced for the German market, we assume that there are no other drivetrain-independent requirements that restrict the operation of vehicles. As described before, this work relies on three criteria already proposed in the literature. Two of them directly translate to quantifiable requirements. The third, maintaining the schedule, needs to be modified, and we will translate the criterion into two separate requirements. The subsequent paragraphs then further specify the four requirements used in this work.

First, a vehicle needs to operate a line without recharging or refueling, i.e., it needs to have a sufficient range. This is the first requirement. In the case of BEVs, the required range is the length of the non-electrified part of a line; in the case of FCEVs, it is the entire line length. It is assumed that BEVs can operate independently from battery energy on electrified line sections.

Second, vehicles must comply with the track's specific maximum axle loads for the entire line. We define the term line to relate to routing from a start point to an endpoint. Different from that, we use the term "track" to describe physical infrastructure, e.g., "track electrification" or "track speed limit". In the case of axle loads, the vehicle must comply with the limits of all track sections that a line comprises. This is the second requirement.

Third, compliance with current time-tables needs to be sustained. Major contributors are the maximum speed, acceleration, deceleration, and tilting technology. As a simplification, we assume that journey times are sustained if two sub-requirements are fulfilled:

- The vehicle has a maximum speed that is at least as high as the currently operated maximum speed of each line section. This is the third requirement.
- The vehicle has a specific power that is at least as high as the specific power of the currently used vehicle. This is the fourth requirement. It constitutes a simplification of more complex physical relations: what determines the time a vehicle needs to accelerate to a certain speed is acceleration, which is a function of speed. Some manufacturers publish data of their vehicle's maximum accelerations; however, this is of little value without knowing the velocities to which they relate. Generally, acceleration decreases with increasing speed. Thus, we use specific power as a more accurate way to estimate acceleration performance.

Having defined the four relevant requirements for feasibility, it is clear that each line and vehicle needs to be specified with the four corresponding parameters. In the next two subsections, we describe how we determine these parameters.

3.3 Line database

The line database includes 73 lines in the region of Bavaria. Figure 1 shows a map of all lines, numbered from northwest to southeast. Next to the diesel lines in red, the electrified network is shown in green, and lines that are planned to be electrified in blue. Where diesel lines overlap with current or future electrification, the lines are highlighted in orange and purple, respectively. The map shows that most major cities are connected by electrified lines. The diesel-operated lines connect smaller cities with the electrified network. A number of lines overlap with electrification. The data-table of the lines is included in Appendix A.

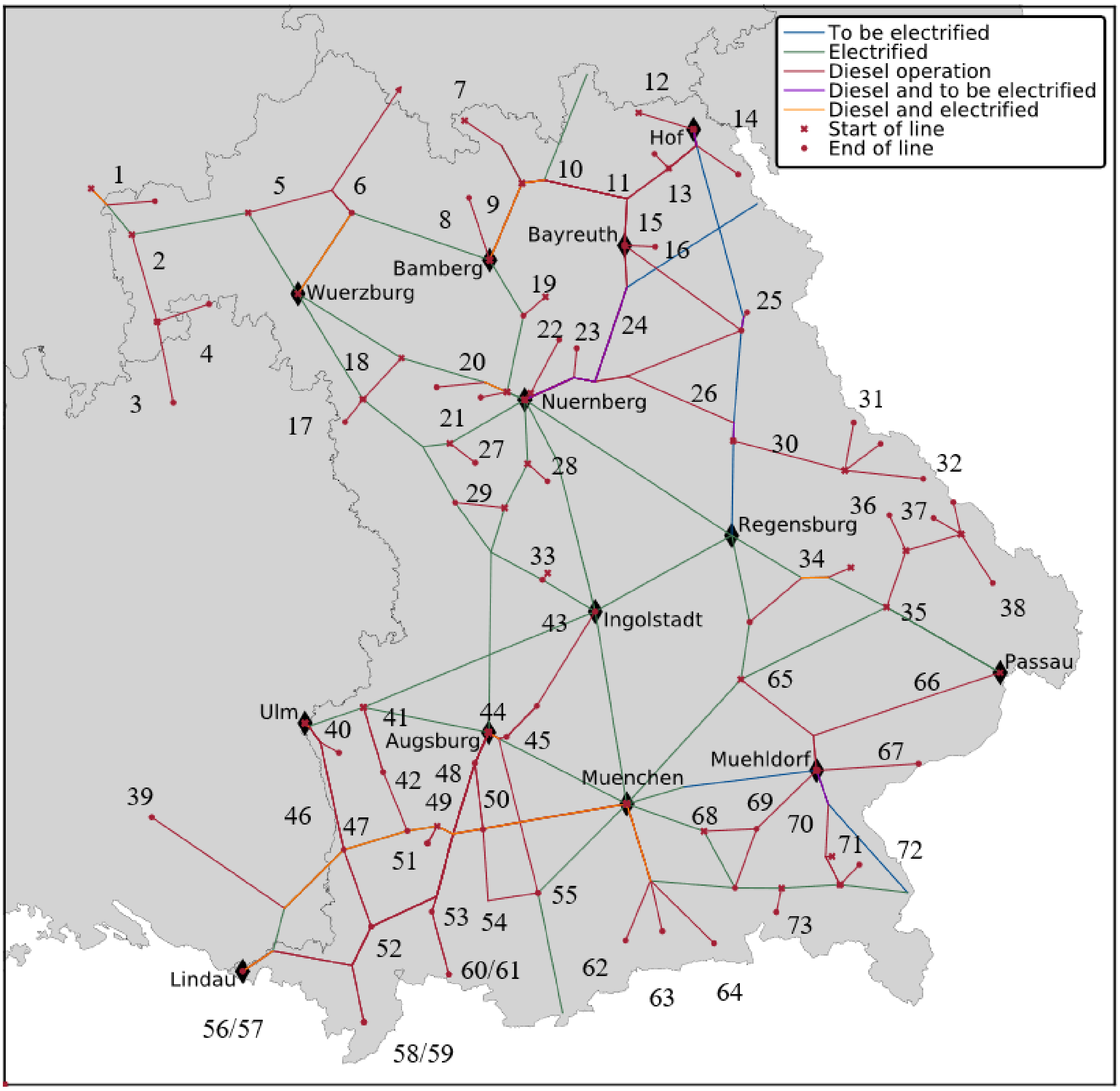

Figure 1. Map of diesel operated lines and overlap with current and future electrification

Lines are defined by state-owned and -funded companies. Since lines are subject to changes, our database draws on the publicly available calls and represents lines as they are operated in 2020. As sources, we used openrailwaymap.org (OpenStreetMap Contributors, n.d.) and Deutsche Bahn's interactive map (DB Netz AG, 2020).

To set up the line database, we use three assumptions:

First, only lines in Bavaria are considered. For lines that cross states, we only consider lines that are at least 70% in Bavaria. Eight lines in the database are not entirely in Bavaria.

Second, tracks that were in the highest priority category of the Federal Government's plan for electrification ("Vordringlicher Bedarf" in the "Bundesverkehrswegeplan") as of 2018 are assumed as electrified. These lines are Munich-Mühldorf-Freilassing, Mühldorf-Burghausen, Hof-Regensburg, and Nürnberg-Marktredwitz-Schirnding. The track of Nürnberg-Schwandorf-Furth is not considered electrified, despite the fact that it was moved to the highest category in the Government's plan in 2018, as realization still seems questionable (Henzler, 2019). Furthermore, the line between Munich and Lindau will start electrified operations in 2020 and is assumed as electrified. As an effect of future electrifications, some currently diesel-operated lines do not appear in the database, whereas others have shorter non-electrified sections compared to today.

Third, lines occasionally run shortened or extended itineraries, e.g., the last train in the evening may terminate at an otherwise intermediate stop. We apply the most common line itineraries for the database. With the three named assumptions, we define which lines are considered.

The derivation of each line's requirements is explained subsequently. In general, we rely on multiple sources. Range and axle loads are taken from the track databases Openrailwaymap and DB's interactive track map. The requirement for specific power directly relates to the vehicle currently in use on the line. Thus we rely on manufacturers' data. In the case of multiple vehicle types operated on one line, we consider the most common one. For the requirement of maximum speed, we need to consider both the tracks' limitations and the current vehicles' limits. The overall maximum speed of a line is whichever of the two values is lower.

Having gathered the lines' requirements, we analyze them quantitatively. We plot three histograms, shown in Figure 1, with the lines' requirements for range, maximum velocity (v_{max}), and specific power. Additionally, the requirements are visualized on the three maps in Appendix B.

The plot on the left displays that more than half of the lines have a range requirement greater than 40 km. Another 18 lines have a requirement between 40 and 80 km. Only 14 lines have a range requirement of more than 80 km; the maximum is 170 km. The upper and lower range boundaries are chosen roughly according to the BEVs' ranges in this work.

The center plot displays the specific power of the considered lines. Approximately half of the lines have a specific power requirement between 11 and 13 kW/t. Ca. 10 lines have specific power requirements smaller than 7, between 7 and 9, and between 9 and 11 kW/t, respectively. No line has a specific power requirement greater than 13 kW/t; the minimum in the database is 6 kW/t.

The right plot displays the maximum operational speed. About a third of lines are operated at 100 km/h or less. Only 11 lines require to be operated with more than 140 km/h. No line exceeds 160 km/h of maximum speed. Partly electrified lines have two maximum velocities specified, one for the electrified part and one for the non-electrified part. Displayed in (Internationales Verkehswesen, 2019) is the higher velocity of the two, which is the v_{max} under electrification for all lines. We explain the reasons for this distinction in the subsequent section. Although there is a number of lines with a v_{max} of 100 km/h or less, we do not distinguish them in this figure as we expect any vehicle to reach a v_{max} of 100 km/h.

Axle load requirements in the database are investigated as well. Forty lines permit loads up to 22.5 tons, corresponding to a category "D" in EN 15528 (European Committee for Standardization, 2015). Thirty-one lines permit an axle load of 20 tons (Category C). Only two lines are limited to 18 tons (Category B).

From the 73 lines, we find that the majority has a range requirement of less than 80 km. Maximum velocities range up to 160 km/h but are often less than 120 km/h. Specific power requirements range from 6 kW/t to 13 kW/t. The majority of lines require between 9 and 13 kW/t. Considering axle loads, 71 out of 73 lines can be operated with 20 tons of axle load or more.

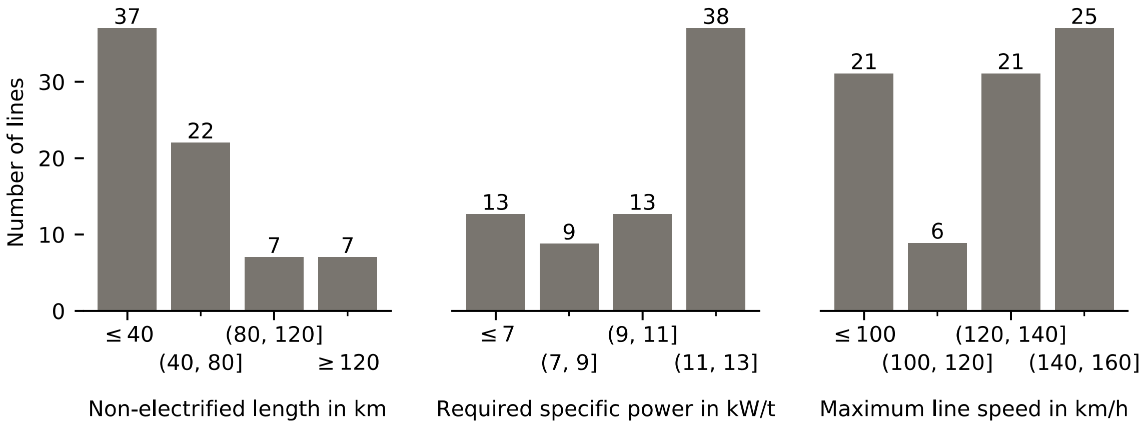

Figure 2. Distributions of requirements for range, specific power, and maximum speed

3.4 Vehicle database

Having gathered the line-requirements, we set up a corresponding database with vehicles' capabilities. The database contains all emission-free passenger vehicles available on the market or announced to be available by 2023 in Germany to the best of our knowledge and based on public information available as of summer 2020. Corresponding to the line database, every vehicle is assessed based on range, axle load, maximum speed, and specific power. The vehicle database is given in Table 1.

BEVs tend to have lower performance when operated on battery power instead of catenary power, affecting both v_{max} and specific power. This is due to technical reasons: drawing high power from batteries when a catenary is not available comes at higher costs. The battery's size directly corresponds to the maximum power demand, incurring significant mass and cost increases. Therefore, it is not expedient to design for relatively rare peak power demands. Although observed for the Talent 3 BEMU in the database and a prototype (Railway Gazette, 2018), which is not listed, some BEVs seem to face no differing performance with and without catenary according to the manufacturers' information. This applies to the Flirt and Mireo+B variants as it can be seen in the database, and performance does not depend on electrification. The same is true for FCEVs, which do not use catenary power in general.

Not all parameters required for the database are available directly and unequivocally. Therefore, we make the following assumptions:

For range, the worst-case range is used in the database. In the case that specific power P is not directly given, the relation $\frac{P}{m} = \frac{F \cdot v}{m} = \frac{m \cdot a \cdot v}{m} = a \cdot v$ is used to calculate a value from a given acceleration a, velocity v, and mass m. F denotes the tractive force.

Siemens claims that their vehicles accelerate as well as an Electric Multiple Unit (EMU). Thus, we investigate all common EMUs on the German network (multiple types of Stadler Flirt, Bombardier Twindexx, Series 440, and Bombardier Talent 2 each) and find an average specific power of 20 kW/t. We assume that this is the specific power of all Mireo vehicles.

There are eight BEV and three FCEV models available. All vehicles are either two or three-car configurations. For Siemens' vehicles, we substitute the manufacturer spelling "Plus B/Plus H" with "+B/+H". Only one of the vehicles in the database, the Alstom iLint, is already in service, whereas all others are announced to be available until 2023 at the latest. Overall, there are 114 zero-emission regional railway vehicles on order in Germany.

Table 1. Emission-free vehicles and performance data

Type	Manu-facturer	Model	Specification	Number of cars per train	Range in km	V_{max} in km/h		Spec. Power in kW/t		Axle Load in tons	Status
						under catenary	without catenary	under catenary	without catenary		
BEV	Stadler	Flirt Akku	-	3	80	140*	140	14*	14	<20*	To be deployed from 2022
BEV	Siemens	Mireo+B	2-unit Std.	2	80	160	160	20*	20*	<20	Available from 2023
			2-unit Range	2	90	140	140	20*	20*	<20	
			2-unit Lightw.	2	40	140	140	13*	13*	<18	
			3-unit Std.	3	100	160	160	20*	20*	<20	To be deployed from 2023
			3-unit Range	3	110	140	140	20*	20*	<20	
			3-unit Lightw.	3	60	140	140	20*	20*	<18	
BEV	Bombardier	Talent 3 BEMU	-	3	100	160	120	14	14*	<20*	In test operation
FCEV	Alstom	Coradia iLint	-	2	600	140		6		<18	Operational
FCEV	Siemens	Mireo+H	2-unit	2	500	160		20*		<20	Available from 2021
			3-unit	3	800	160		20*		<20	

Generally, the vehicles in the database have the following characteristics.

- Range: BEVs have a range from 80 to 110 km. FCEVs have a range between 600 and 900 km.
- Maximum velocity: All four Siemens Mireo models have a v_{max} of 160 km/h. The Talent 3 BEV can operate at 160 km/h under catenary, but only 120 km/h without it. The Stadler Flirt and Alstom iLint operate at a maximum of 140 km/h, both with and without electrification infrastructure.
- Specific Power: The lowest value for specific power is observed for the iLint with 6 kW/t. Stadler Flirt and Bombardier Talent 3 BEV both have a specific power of ca. 14 kW/t. The four Siemens vehicles have the highest specific power of 20 kW/t.
- Axle load: Most vehicles have a maximum axle load of 20 tons. Three vehicles, the "Lightweight" variants of the Mireo+B and the iLint, have a smaller maximum axle load of 18 tons.

In summary, we find 11 different emission-free vehicles, 8 BEVs and 3 FCEVs. BEVs have a range from 40 to 110 km; FCEVs have a largely higher range. Maximum speeds may depend on the presence of electrification infrastructure in the case of BEVs. In general, v_{max} varies between 120 and 160 km/h. We find a high variation in specific power among the database's vehicles. It ranges from 6 kW/t to 20 kW/t.

4. Results and Discussion

In this section, we match the line database with the vehicle database and determine *feasibility*, i.e., whether a specific vehicle can operate a specific line. A new vehicle is considered feasible on a line if all line requirements (range, axle load, v_{max}, and specific power) are fulfilled. We give the list of lines with vehicles feasible on each one, then analyze the number of lines possible to operate by type of propulsion system (BEV or FCEV) and individual vehicle.

Appendix A lists the lines in alphabetical order with a mark for every emission-free vehicle that can operate on it. The lines are named by the highest frequented stations.

We find that all lines but one (Nr. 43) can be operated by at least one vehicle. For this line specifically, a maximum axle load of less than 18 tons is the limiting parameter. It disqualifies all but three vehicles, namely the Mireo's Lightweight variants and the iLint. Among these vehicles, Mireos are infeasible due to a high range requirement, and the iLint is infeasible due to the lines' power requirement. The other line in the database with an 18-ton axle load limit can be operated by the Mireo+B vehicles in the "Lightweight" configuration.

Apart from two lines (Nr. 43 and Nr. 23), all other lines' axle load requirements allow for any vehicle in the database to operate. Thus, the lines are operable by at least the two Mireo+H FCEVs. Theoretically, the same would be true for the iLint FCEV if it was not limited in its performance. This limitation will be investigated in more depth subsequently.

The number of vehicles that are feasible on a line generally increases with decreasing range requirement, allowing for more of the BEVs. Some lines, e.g., Nr. 3 can even be operated with any vehicle in the database.

An additional observation of the table is that some stations appear more than once, e.g., 13 lines start in Augsburg, and 6 in Munich. Although outside the scope of this paper, it might offer operational or cost-benefit: e. g. hydrogen refueling stations can be used for multiple lines.

For a further investigation, we distinguish the vehicles by propulsion technology, i.e., BEVs and FCEVs. Based on the feasibility table (Appendix A), we make two major observations:

- All BEVs suffice all lines' specific power requirements.
- All FCEVs suffice all lines' range requirements.

In other words, and putting axle loads aside, BEVs are only limited by range and v_{max}, FCEVs are only limited in specific power and v_{max}. Using this observation, we plot the respective limiting parameters of each vehicle along with the lines' requirements (Figures 2 and 3). We refer to the combination of limiting parameters for a vehicle as the *performance envelope*.

4.1 BEV performance envelopes

Figure 3 shows the overall maximum line speed and the range requirement of all lines, along with all BEVs' performance envelopes.

The horizontal axis shows the range in km, the vertical axis shows the overall maximum speed. Each BEVs' performance envelope is displayed as a colored corner line in the plot. The Flirt Akku envelope is denoted with a green line, the Mireo+B 2-unit with a red line, the Mireo+B 3-unit with a blue line, and the Talent 3 BEMU with an orange line. The Mireo's Range and Lightweight variants are denoted with dashed and dotted lines in the corresponding variant's color, respectively. The dot size is proportional to the number of lines at this data point, with an indicator if the number is greater than one. Overlapping performance envelopes, having the same v_{max} or range, are offset to make all lines visible.

In general, most lines lie within the performance envelope of BEVs. Only a few lines are outside the performance envelope of the best performing vehicles. The vehicle with the shortest range, the Mireo+B 2-unit Lightweight, can operate on about half the lines.

All vehicles have overall maximum velocities of either 140 km/h or 160 km/h. Only 11 of the lines need to be operated with 160 km/h. For all others, vehicles with 140 km/h maximum speed are sufficient.

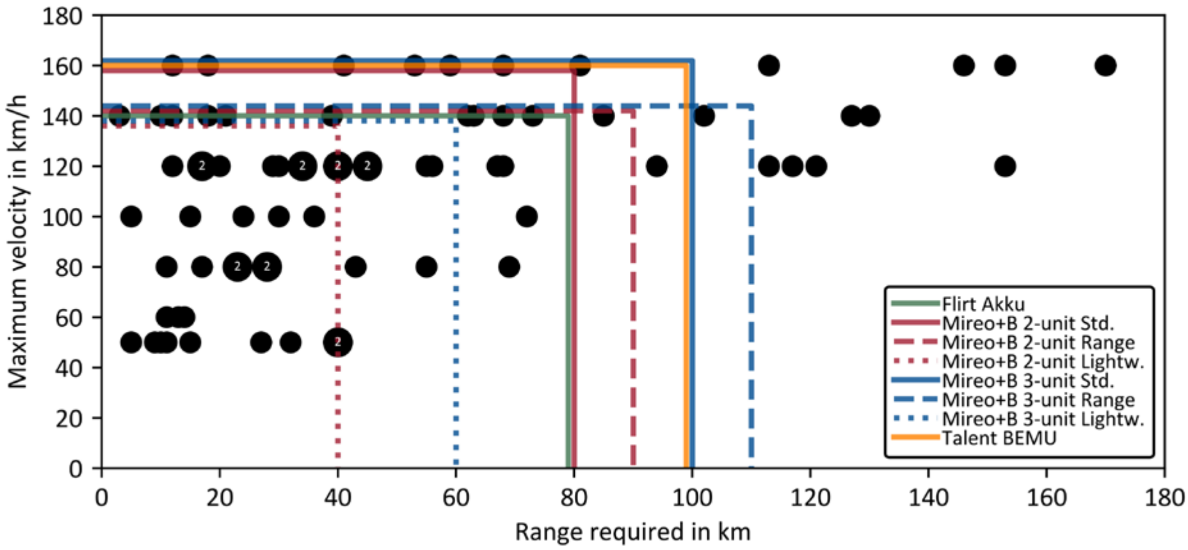

Figure 3. Lines' requirements for maximum speed and specific power with BEVs' performance envelopes. The size of the circle indicates the number of lines for each data point.

Between the Mireo+Bs' Standard and Range configurations, there is a trade-off of v_{max} vs. range. In both the 2-unit and 3-unit case, we find that the Range configuration can operate one additional line, but, on the other hand, 6 and 7 lines with a v_{max} of 160 km/h, respectively, cannot be operated.

Considering the Mireo Lightweight variants, it gets visible that the number of lines within the performance envelope decreases compared to the Standard variants. Evidently, the manufacturer trades a smaller axle load for increased range in the vehicle's design. Our analysis suggests a larger market for the Standard variants, although the decreased axle load is required for two lines.

The v_{max} shown in Figure 3 is the overall v_{max} of the line. As described under "Vehicle Database", there might be an additional, lower v_{max} requirement for non-electrified line sections. Ten of the lines and one vehicle, the Talent 3 BEMU, have differing maximum speeds for electrified and non-electrified line sections. All other lines and vehicles do not differ in their v_{max} on electrified and non-electrified parts. If we had not considered lower v_{max} requirements on non-electrified parts of lines, the Talent 3 BEMU would not have been considered feasible on three additional lines (Nr. 20, 61, and 64) in the database.

4.2 FCEV performance envelopes

Corresponding to Figure 3 for BEVs, we plot the FCEVs' performance envelopes in Figure 4. As previously outlined, specific power is the relevant requirement, and therefore, shown on the horizontal axis, but not range. The vertical axis shows the overall maximum speed. Other than for Figure 3, there are more lines with equal properties, apparent by larger dot sizes. The iLint performance envelope is denoted with a dashed red line, the Mireo+H 2-unit envelope with a dashed blue line, and the Mireo+H 3-unit with a continuous blue line. The Mireo's overlapping performance envelopes are shifted slightly to make them visible.

The lines' requirements, preliminarily analyzed in Figure 2, are visualized in more detail.

We notice that only 13 lines are within the performance envelope of the iLint. The limitation originates from the iLint's low specific power. Even with a higher v_{max}, no additional lines could be covered without increasing specific power.

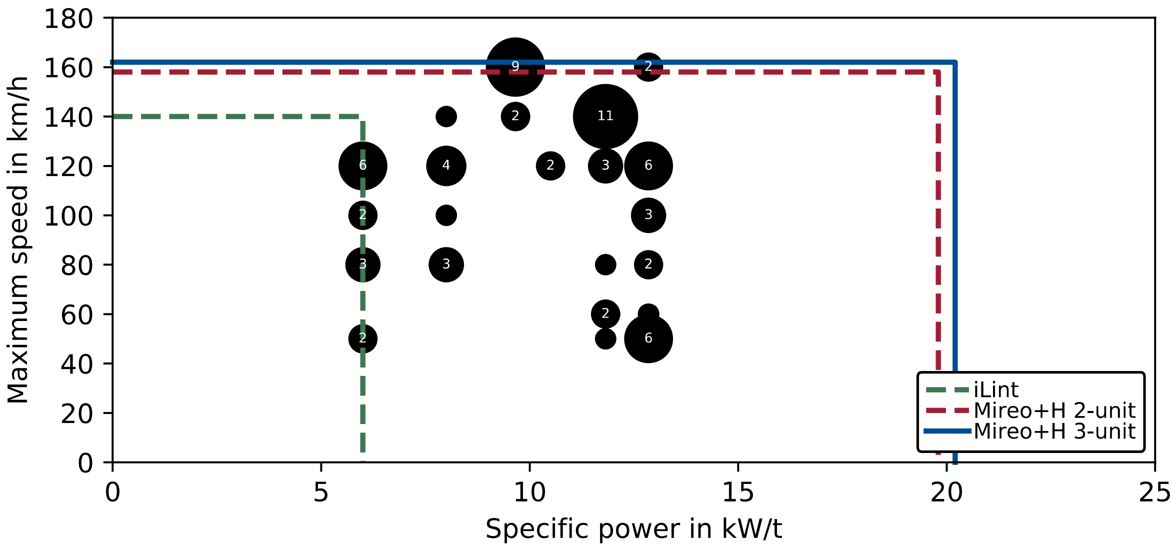

Figure 4. Lines' requirements for maximum speed and specific power with FCEVs' performance envelopes

On the contrary, all lines lie within the performance envelope of the Mireo 2-unit and 3-unit vehicles. The Mireos v_{max} of 160 km/h suffices all lines' requirements. The Mireo's specific power is sufficient for all lines and provides additional margins.

A benefit the iLint yet has over the Mireo+H is the lower axle load, which is required for two of the 73 lines as outlined in the line database analysis.

In general, FCEVs, can cover almost all the lines, but a good driving performance, as the Mireo+H variants have, is important to operate a larger share of lines.

4.3 *Number of feasible lines per vehicle*

To address the question of to what extent each vehicle can be operated on Bavaria's rail network, we count the number of possible lines for each vehicle. The data serves as a recommendation for vehicle purchasers, as it is an approximation of the addressable market. The numbers are summarized in Figure 5 as a proportion of all 73 analyzed lines.

BEVs can operate at least 53% of all lines. The highest proportion among BEVs is observed for the Mireo+B 3-unit Standard vehicle with 82%. Although the Mireo+B's Range and Lightweight variants have a lower proportion of lines to operate, our previous analysis showed that they might be the only option on some lines. However, the number of these lines is small.

The proportion of lines FCEVs can operate shows a two-sided picture: The iLint has the lowest proportion of lines possible of all vehicles (18%), where we outlined that this is mostly for its limited power. The Mireo+H in both versions can operate 97% of lines. Only two lines with low limits in axle load are not operable by the Mireo+H.

4.4 Limitations of this work

The goal of this study is to investigate the capabilities of currently announced vehicles on today's lines. Both vehicles and lines are subject to future changes. Following, we aim to provide limitations and expected trends of the precise numbers shown in this study. The overall conclusions are not subject to these limitations.

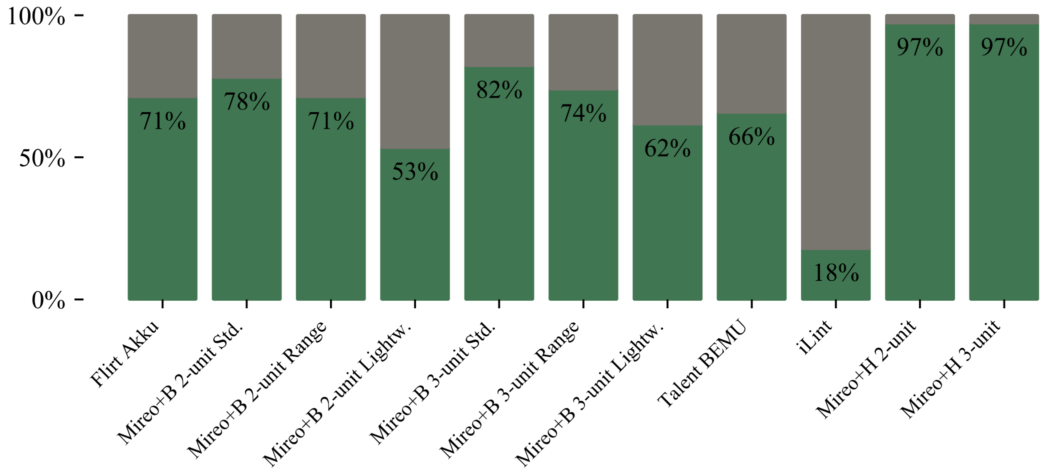

Figure 5. Proportion of lines that each vehicle can operate

The vehicle database is based on manufacturer information that was published not more than a few years, often only months ago, and therefore face uncertainties. As stated in the Section "Vehicle Database", maximum velocity and specific power needed to be estimated for some vehicles. Thus, the actual vehicle performance may be different than assumed. The trend for both BEVs and FCEVs lets us expect that more performant vehicles will enter the market in the long-term.

Line data is subject to change over time as well. More lines will be electrified partly or entirely. This has two effects: (1) the number of remaining diesel lines will decrease, and (2) range requirements for BEVs will decrease in case of partly electrification. For FCEVs, this means a shrinking market. For BEVs, we expect a stable market under the assumption that the two named effects compensate each other.

Although we do not expect the major trends outlined in this paper to change, we expect some numbers to change over time. Further details could allow for additional insights and conclusions. One aspect is that the range of BEVs depends on more factors than just the driven distance (Ebrecht et al., 2019). In a previous study, we introduced a model to estimate energy consumption (Guerster et al., 2018) and showed that an additional factor is vehicle capacity that is not considered in this study. Although this only affects a minority of lines, there are no direct replacements for current locomotive or single-car trains like the Stadler RS1. Instead, we assume that these vehicles can be replaced by one or more 2- or 3-unit trains, possibly at an economic disadvantage. Overall, the velocity, acceleration, and elevation profile of the individual line have a significant impact on range (Mueller, Guerster, Schmidt, Obrenovic, & Bierlaire, 2019b). We expect our requirements for range and driving performance to be on the conservative side.

4.5 Applicability of results to other regions

Given that the discussed rail vehicles are sold internationally, we suspect the requirements for maximum velocity, specific power, and axle load are in general similar to the investigated region.

The requirement on range depends on the individual lines' lengths and the extent to which they are partially electrified. We expect a structure of electrified main lines and non-electrified secondary lines in all countries with medium grades of electrification. Bavaria's electrification grade of 51% is close to the EU average of 54%. China, India, and Great Britain have between 30% and 70% of their network electrified. This indicates the applicability of our results there. As there is no information about line length, the applicability of range-limited BEVs has yet to be confirmed by future studies on an individual line level.

5. Conclusion and further research

In this paper, we built two databases. The first database comprises novel emission-free regional rail vehicles with battery-electric and fuel cell electric propulsion technology. The second database includes regional rail lines in Bavaria and the requirements they impose on vehicles. We compared the databases based on the criteria range, axle load, and performance (i.e., v_{max} and specific power) and, thus, determined which vehicle is feasible on which line. We furthermore assessed the share of lines that can be covered by BEVs and FCEVs, respectively.

The methodical contribution of this paper is the proposed approach that focuses on feasibility; and the practical contributions are these specific conclusions about the results for Bavaria, Germany:

- Diesel vehicles can be replaced by announced emission-free vehicles on 72 out of 73 lines in Bavaria.
- BEV models can operate between 53% and 82% of the lines. The range is the parameter that limits the number of feasible lines for most BEVs. Some BEVs cannot operate lines due to limited v_{max}. Specific power requirements do not pose limitations for any of the available BEVs.
- FCEV models can operate either 18% (Alstom iLint) or 97% (Siemens Mireo+H 2- and 3-unit) of all lines. The iLint is limited by its low specific power.
- Axle load is found to have a minor relevance since most lines allow for all vehicles in terms of axle load.

Future work can address the question of which vehicle should be deployed on each line. Three steps can be investigated: (1) operational implications of new technologies, (2) interaction of zero-emission technology with long-term line development, and (3) economic aspects. The following outlines why these three steps are important:

To investigate operational implications, future models need to consider charging time for electric vehicles. As (Ebrecht et al., 2019) outline, it is of interest whether BEV charging can be embedded in current schedules on a line or not. Although this does not impede the general feasibility investigated in this study, it is clear that operations are more complex in the latter case.

Long-term application studies are useful to ensure vehicles have a market for their entire lifetime. Ongoing electrification measures can enable BEV operation on additional lines and obviate both BEVs and FCEVs on others. Next to this, past electrification planning processes were merely focused on deciding between diesel operation and electrified operation. The interaction of electrification with BEVs and FCEVs needs to be investigated and considered for future electrification plans. The map in Appendix C displays the number of hourly trains per line segment. The highly frequented segments can be considered especially suitable for the entire or partly electrification of lines.

Economics might prove crucial for two aspects: (1) the point of time replacement of a diesel vehicle and (2) which emission-free vehicle is chosen if more than one is feasible. For the time of replacement, it can be assumed that vehicles will be replaced first on these lines where they offer the best economic benefits.

References

Agora Verkehrswende, Agora Energiewende, and Economics Frontier. (2018). The Future Cost of Electricity-Based Synthetic Fuels. Retrieved from https://www.agora-energiewende.de/en/publications/the-future-cost-of-electricity-based-synthetic-fuels-1/

DB Netz AG. (2020). Infrastrukturregister ISR Viewer. Retrieved from https://geovdbn.deutschebahn.com/isr

Ebrecht, B., Walter, D., Zedlitz, I., and Zimmermann, U. (2019). Methodik einer Machbarkeitsstudie zum Einsatz batterieelektrischer Triebwagen (BEMU) am Beispiel des VVO-Dieselnetzes. *Journal Für Mobilität Und Verkehr*, (3), 11–20.

European Committee for Standardization. EN 15528:2015: Railway applications. Line categories for managing the interface between load limits of vehicles and infrastructure (2015).

Federal Network Agency of Germany (2019). Railway Market Analysis 2019 Germany, 52.

Guerster, M., Moser, C., Moser, K., Mueller, F., Muehlbauer, C., Brueckmann, A., & Grimm, R. (2018). Development of a dynamic driving simulation model for automated design of regional trains' hybrid propulsion architecture. In *EMEASEC Proceedings*.

Hebermehl, G. (2019). Stadler Flirt Akku - 55 Batteriezüge für Schleswig-Holstein (2019) - auto motor und sport. Retrieved October 17, 2019, from https://www.auto-motor-und-sport.de/verkehr/stadler-flirt-akku-batteriezuege-schleswig-holstein-2019/

Hecht, M., & Culemann, C.-R. (2018). Klimaschutz als Chance für die Bahn. *Deine Bahn*, *12*, 14–17.

Henzler, C. (2019). Nürnberg - Sorge um 150 Kilometer - Bayern - Süddeutsche.de. Retrieved October 15, 2019, from https://www.sueddeutsche.de/bayern/nuernberg-sorge-um-150-kilometer-1.4280517

Isenhoefer, L., & Zieger, S. (2018). Analyse der Umsetzung von Aus- und Neubauvorhaben im Bundesverkehrswegeplan 2003. *Eisenbahntechnische Rundschau*, (7+8), 52–57.

Mueller, F., Guerster, M., Schmidt, K., Obrenovic, N., & Bierlaire, M. (2019a). Model-based economic analysis of electrification in railway - Conference Presentations. Retrieved October 17, 2019, from https://www.researchgate.net/project/TORPA-Toolbox-for-Optimal-Railway-Propulsion-Architectures/update/5da862ac3843b093838c934f

Mueller, F., Guerster, M., Schmidt, K., Obrenovic, N., & Bierlaire, M. (2019b). Model-based economic analysis of electrificationin railwayUnderstanding the impact of track, operations, and uncer-tainties. In *Swiss Transportation Research Conference 2019*. Retrieved from http://www.strc.ch/2019/Mueller_EtAl.pdf

OpenStreetMap Contributors. (n.d.). OpenRailwayMap. Retrieved October 15, 2020, from https://www.openrailwaymap.org/

Pagenkopf, J., Böhm, M., Haas, J. L., & Friedrich, H. (2018). Analysis of German diesel operated regional railway lines' patterns with regard to the application of battery and fuel cell electric trains. Retrieved from https://elib.dlr.de/121661/1/Railways 2018_E3.01_Pagenkopf %28DLR%29_Analysis of German diesel operated regional railway lines.pdf

Pagenkopf, J., & Kaimer, S. (2014). Potentials of alternative propulsion systems for railway vehicles— A techno-economic evaluation. *Ieeexplore.Ieee.Org*. Retrieved from https://ieeexplore.ieee.org/abstract/document/6843995/

Railway Gazette. (2018). Battery-powered Desiro ML Cityjet Eco unveiled - Railway Gazette. Retrieved January 13, 2019, from https://www.railwaygazette.com/news/traction-rolling-stock/single-view/view/battery-powered-desiro-ml-cityjet-eco-unveiled.html

Siemens Mobility GmbH. (2018). Moderne Antriebstechnik im Bahnbereich Anhand des Beispiels Cityjet eco.

Trialog Publishers Verlagsgesellschaft - Internationales Verkehrswesen. (2018). Bombardier und TU Berlin: Innovativer Batteriezug ab 2019 im Testbetrieb. Retrieved October 18, 2019, from https://www.internationales-verkehrswesen.de/batteriezug-ab-2019-im-testbetrieb/

VDI/VDE Fachausschuss Wasserstoff und Brennstoffzellen. (2019). Brennstoffzellen- und Batteriefahrzeuge - Bedeutung für die Elektromobilität. Retrieved from https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=2ahUKEwiF2JXCyZ7lAhVRuXEKHSidBXIQFjAAegQIBBAC&url=https%3A%2F%2Fwww.vde.com%2Fresource%2Fblob%2F1875246%2F3a4ac5081799af17650c62316c183eb4%2Fstudie-brennstoffzelle-data.pdf

Verdict Media Ltd. (n.d.). Alstom Coradia iLint Hydrogen-Powered Regional Train. Retrieved October 17, 2019, from https://www.railway-technology.com/projects/coradia-ilint-regional-train/

Appendix A: Feasibility of zero-emission vehicles by line

Number	Line	Non-el. dist. in km	Overall v_{max} in km/h	Flirt Akku	Mireo+B 2-unit Standard	Mireo+B 2-unit Range	Mireo+B 2-unit Lightweight	Mireo+B 3-unit Standard	Mireo+B 3-unit Range	Mireo+B 3-unit Lightweight	Talent 3 BEMU	iLint	Mireo+H 2-unit	Mireo+H 3-unit
1	Aschaffenburg-Miltenberg	68	120	◆	◆	◆		◆	◆		◆	◆	◆	◆
2	Miltenberg-Seckach	43	80	◆	◆	◆		◆	◆	◆	◆	◆	◆	◆
3	Miltenberg-Wertheim	30	100	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
4	Hanau-Schöllkrippen	23	80	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
5	Würzburg-Erfurt	153	160										◆	◆
6	Gemünden-Schweinfurt	69	80	◆	◆	◆		◆	◆		◆		◆	◆
7	Bad Rodach-Weiden	153	120										◆	◆
8	Bamberg-Ebern	17	120	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
9	Bamberg-Hof	81	160					◆					◆	◆
10	Bamberg-Nürnberg	113	160										◆	◆
11	Lichtenfels-Hof	121	120										◆	◆
12	Bad Steben-Münchberg	45	120	◆	◆	◆		◆	◆	◆	◆		◆	◆
13	Münchberg-Helmbrechts	9	50	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
14	Hof-Selb	24	100	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
15	Lichtenfels-Bayreuth	56	120	◆	◆	◆		◆	◆	◆	◆		◆	◆
16	Bayreuth-Weidenberg	14	60	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
17	Steinach-Rothenburg	11	80	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
18	Eichstätt Stadt-Bahnhof	5	50	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
19	Fürth-Cadolzburg	13	60	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
20	Fürth-Markt Erlbach	18	140	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
21	Neustadt (Aisch)-Steinach	29	120	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
22	Nürnberg-Bayreuth	18	160		◆			◆					◆	◆
23	Nürnberg-Gräfenberg	28	80				◆			◆				
24	Nürnberg-Neustadt (Naab)	59	160		◆			◆					◆	◆
25	Nürnberg-Schwandorf	53	160		◆			◆					◆	◆
26	Nürnberg-Simmelsdorf	10	140	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
27	Pleinfeld-Gunzenhausen	17	120	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
28	Wicklesgreuth-Windsbach	12	120	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
29	Ebermannstadt-Forchheim	15	100	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
30	Roth-Hilpotstein	11	60	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
31	Schwandorf-Furth	67	120	◆	◆	◆		◆	◆		◆		◆	◆
32	Cham-Lam	40	50	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
33	Cham-Waldmünchen	27	50	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
34	Bogen-Neufahrn	36	100	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
35	Gotteszell-Viechtach	40	50	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
36	Plattling-Bayer. Eisenstein	72	100	◆	◆	◆		◆	◆		◆		◆	◆
37	Zwiesel-Bodenmais	15	50	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
38	Zwiesel-Grafenau	32	50	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
39	Ulm-Sigmaringen	94	120					◆	◆		◆		◆	◆
40	Ulm-Weißenhorn	20	120	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
41	Günzburg-Krumbach	28	80	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
42	Günzburg-Mindelheim	55	80	◆	◆	◆		◆	◆	◆	◆		◆	◆

43	Augsburg-Ingolstadt	62	140											
44	Augsburg-Aichach	21	140	◆	◆	◆	◆	◆	◆	◆			◆	◆
45	Augsburg-Friedberg	3	140	◆	◆	◆	◆	◆	◆	◆			◆	◆
46	Ulm-Kempten	85	140			◆		◆	◆				◆	◆
47	Augsburg-Memmingen	40	120	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
48	Augsburg-Bobingen	12	140	◆	◆	◆	◆	◆	◆	◆			◆	◆
49	Augsburg-Landsberg	39	140	◆	◆	◆	◆	◆	◆	◆			◆	◆
50	Augsburg-Bad Wörishofen	45	120	◆	◆	◆		◆	◆	◆	◆		◆	◆
51	Türkheim-Bad Wörishofen	5	100	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
52	München-Kempten	68	160		◆			◆					◆	◆
53	Augsburg-Marktoberdorf	73	140	◆	◆	◆		◆	◆				◆	◆
54	Augsburg-Schongau	68	140	◆	◆	◆		◆	◆				◆	◆
55	Augsburg-Weilheim	34	120	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
56	Augsburg-Lindau	170	160										◆	◆
57	München-Lindau	130	140										◆	◆
58	Augsburg-Oberstdorf	146	160										◆	◆
59	Ulm-Oberstdorf	127	140										◆	◆
60	Augsburg-Füssen	102	140						◆				◆	◆
61	München-Füssen	63	140	◆	◆	◆		◆	◆		◆		◆	◆
62	München-Lenggries	30	120	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
63	München-Tegernsee	12	160		◆			◆			◆		◆	◆
64	München-Bayrischzell	41	160		◆			◆			◆		◆	◆
65	Landshut-Mühldorf	55	120	◆	◆	◆		◆	◆	◆	◆	◆	◆	◆
66	Landshut-Rosenheim	117	120									◆	◆	◆
67	Mühldorf-Simbach	40	120	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
68	Mühldorf-Traunstein	34	120	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
69	Grafing-Wasserburg	23	80	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
70	Passau-Mühldorf	113	120									◆	◆	◆
71	Prien-Aschau	10	50	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
72	Traunreut-Traunstein	17	80	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
73	Traunstein-Waging	11	50	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆

Appendix B: Mapped line requirements

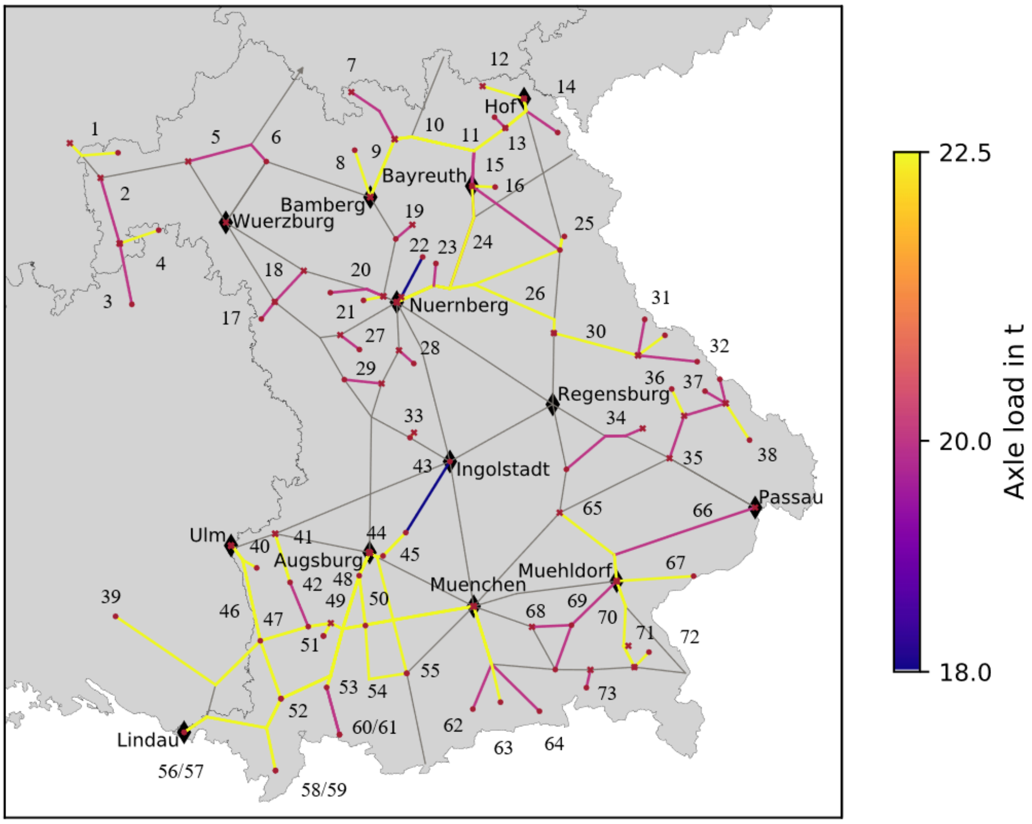

Figure 6. *Figure B1: Maximum axle loads on current diesel lines*

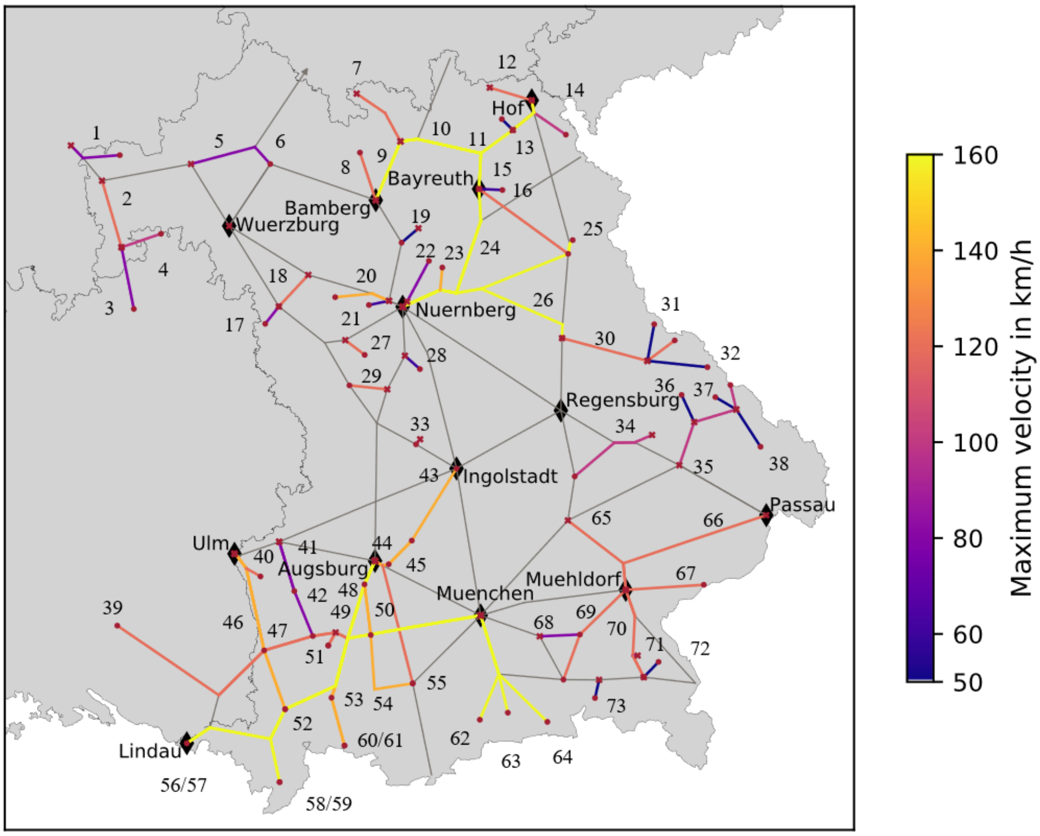

Figure 7. *Figure B2: Maximum velocity on current diesel lines*

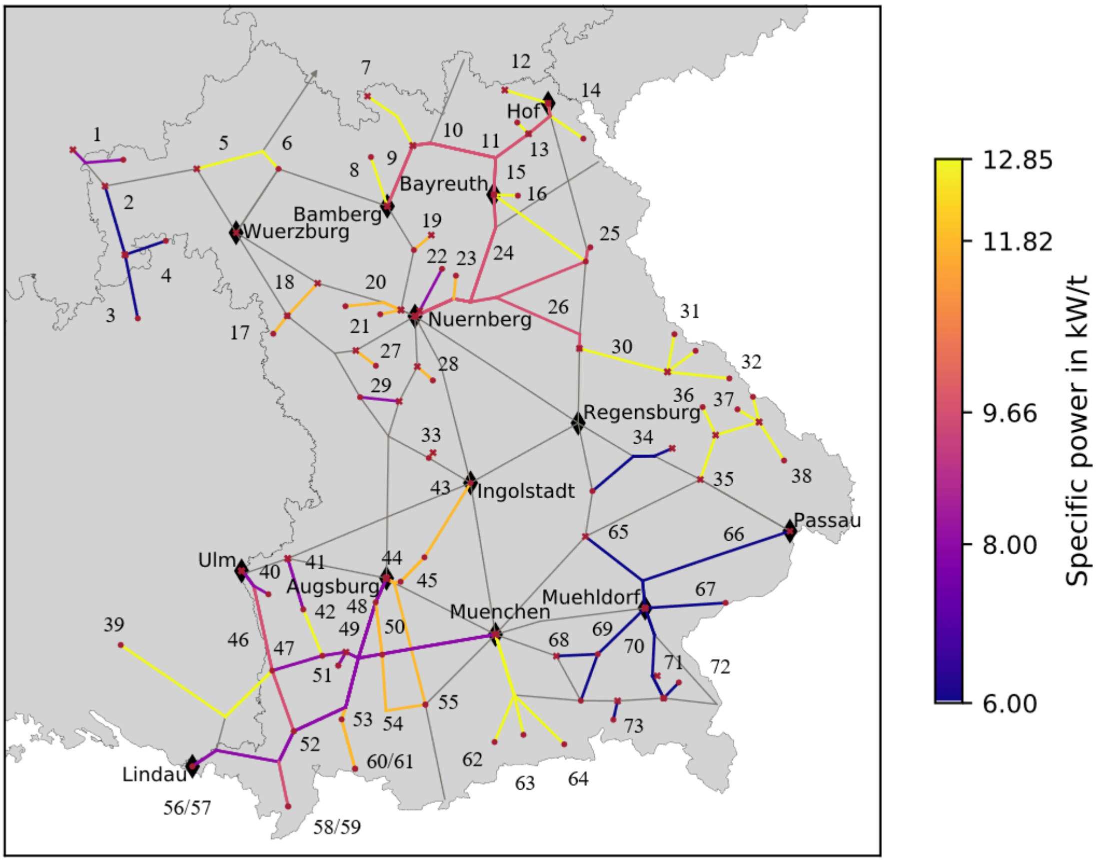

Figure 8. Figure B3: Minimum specific power requirements on current diesel lines

Appendix C: Trains per hour and line segment

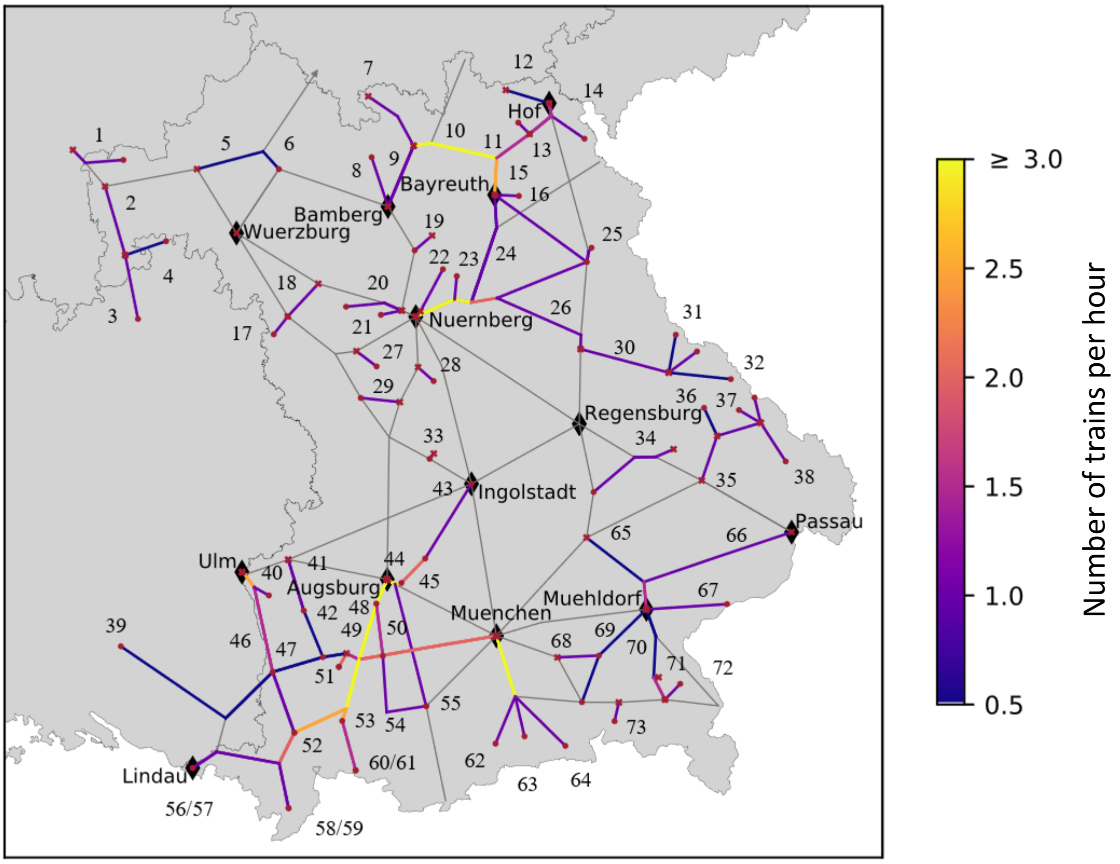

Figure 9. Figure C: Number of trains per hour on current diesel line segments