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

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Abstract

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 analyzed to which extent these new vehicles can replace diesel technology on a large variation of regional railway lines. Our approach is based on two databases that we build: One for the announced emission-free vehicles, and one for existing lines, taking the German state of Bavaria as an example. 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 its limited performance. On the other hand, the Siemens Mireo Plus H series has higher performance and can operate 97% of the lines.

1 Introduction

During the recent years, governments became more aware of the climate change and hence are launching several programs to reduce emissions across all fields of 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 emissions in railway, adding up to 1.2 Mio. tons of CO_2-equivalent per year (Hecht and Culemann [2018]). There are several solutions to reduce this amount, mainly from these two categories.

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 et al. [2019b]). Although more kilometers were planned, they could not be completed on time due to limited planning capacities or funding (Isenhoefer and Zieger [2018]).

The second solution is to replace diesel technology with emission-free Battery Electric or Fuel Cell Electric Vehicles (BEVs or FCEVs). A number of established manufacturers pushed new vehicles into the market over the recent years: Alstom's iLint FCEV is already in operation (Verdict Media Ltd. [2018]), 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 has been done some work to compare 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]).

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

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

One solution that is not part of the introduced two common categories is the use of synthetic fuels. Their benefit would be that it is compatible with current vehicles and no infrastructure changes would be required. However, synthetic fuels are currently prohibitively expensive. A study by German think tanks lets us expect that synthetic fuels will remain significantly more expensive than today's fossil fuels until 2050 at least (Agora Verkehrswende et al. [2018]).

Pagenkopf and 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 operation is feasible on other lines was not investigated.

Next to axle load, an additional requirement that existing lines impose is the *range*. This is critical, as compared to diesel vehicles, the battery size is limiting the amount of energy BEVs can store on board. Pagenkopf et al. [2018] investigated range requirements and other properties for all 469 existing diesel lines in Germany. They expose that the line's properties vary in large 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 outline a number of lines with properties which recommend the use of BEVs and FCEVs, respectively. However, these recommendations were solely based on range considerations.

Ebrecht et al. [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 to be crucial: not keeping up schedules leads to increased journey times for customers first directly and second, even more, indirectly if connections to other trains cannot be made. 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 in case of the considered Bombardier Talent 3, but the assumption is not transferable to all novel vehicles. Some novel 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 and 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 feasibility of current vehicle 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 in terms of range, axle loads, and performance?"

We answer this question for the German region of Bavaria. Our approach is to create a database of the lines' requirements for axle loads, range, and schedules. Furthermore, we create a vehicle database to allow an assessment of the feasibility.

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

2 Approach

To answer the identified research questions, we follow a three-step approach described in the following three subsections: The first step is to take the three criteria identified in 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. The fourth step is described in the section "Results and Discussion". In this step, we map the vehicle database onto the line database using the defined criteria.

2.1 From literature criteria to quantifiable requirements

In the highly regulated business, there is a high number of criteria to 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 part of criteria. 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 operation of vehicles. As described in Section 1, this work relies on three criteria already proposed in literature. Two of them directly translate to quantifiable requirements. The third needs to be modified, we will translate the criterion into two requirements. The subsequent paragraphs further specify the four requirements used in this work.

First, a vehicle needs to be able to ride the line without recharging or refueling, i.e., it needs to have a sufficient range. This is the first requirement. In case of BEVs, the required range is the length of the non-electrified part of a line, in case of FCEVs it is the entire line length. On electrified parts, BEVs can operate independently from battery energy.

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

Third, compliance to 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 subrequirements are fulfilled:

- The vehicle has a maximum velocity which is at least as high as the currently operated maximum velocity of each line section. This is the third requirement.
- The vehicle has a specific power (power output divided by vehicle mass), that is at least as high as the one of the vehicle currently used. This is the fourth requirement. It constitutes a simplification of more complex physical relations: what actually determines the time a vehicle needs to accelerate to a certain velocity is acceleration, which is a function of velocity. 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 velocity, when power is limited. 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 at least. In the next two subsections, we describe how we determine these parameters.

2.2 Line database

The line database includes 73 lines in the region of Bavaria as they are operated in 2019. A table of all lines is shown in the results section (Table 2). 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 2019. As sources, we used openrailwaymap.org (OpenStreetMap Contributors [2019]) and Deutsche Bahn's interactive map (Deutsche Bahn AG [2019]).

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

First, only lines in Bavaria are considered. For lines crossing states, we only take into account lines which are at least 70% in Bavaria. There are four lines in the database which 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. As an effect, some currently diesel-operated lines do not appear in the database, whereas others have shorter non-electrified sections compared to today. 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]).

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 itinerary for the database. With the three named assumptions, we defined what lines are considered.

How each line's requirements are derived 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 manufacturer's data. In case of multiple vehicle types operated on one line, we consider the most common one. For the requirement of maximum velocity we need to consider both the physical track's limitations and the current vehicle's limits. The overall maximum velocity of a line is whichever of the two values is lower.

Having gathered the lines' requirements, we are able to quantitatively analyze the them. We plot three histograms shown Figure 1, where the lines' requirements for range, maximum velocity (v_{max}), and specific power are shown.

The plot on the left displays that more than half of the lines have a range requirement less 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

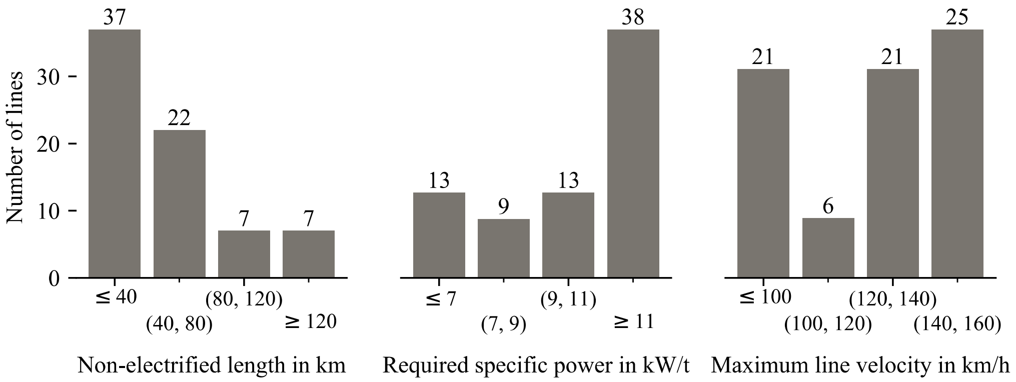


Figure 1: Distributions of requirements for range, specific power, and maximum velocity

maximum is 170 km. The upper and lower range boundaries are chosen roughly accordingly 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. 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 velocity. About a third of lines have 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 velocity. Partly electrified lines have two maximum velocities specified, one for the electrified part and one for the non-electrified part. Displayed in Figure 1 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. 40 lines permit loads up to 22.5 tons, corresponding to a category "D" in EN 15528 (European Committee for Standardization [2015]). 31 lines permit an axle load of 20 tons (Category C), only 2 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 mostly less than 120 km/h. Specific power requirements range from 6 kW/t to 13 kW/t. The majority of lines requires between 9 and 13 kW/t. Considering axle loads, 71 out of 73 lines can be operated with at least 18 tons of axle load.

2.3 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. Corresponding to the line database, every vehicle is assessed based on range, axle load, maximum velocity, 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 technological reasons: drawing high power from batteries, when 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. Estimated or calculated values are denoted with an asterisk ($*$) in the table. 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 good 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.

More generally, the vehicles in the database have the following characteristics:

- Range: BEVs have a range from 80 to 120 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 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.

3 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 considered line requirements (for 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.

Table 2 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. 7) 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 “Lightweight” configuration.

Apart from two lines (Nr. 7 and Nr. 52), 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 will be investigated more in depth subsequently.

The number of vehicles which are feasible on a line generally increases with decreasing range requirement, allowing for more of the BEVs. Some lines, e. g. Miltenberg-Wertheim 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 placed at these line intersections and thus 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 (Table 2), we make two major observations:

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

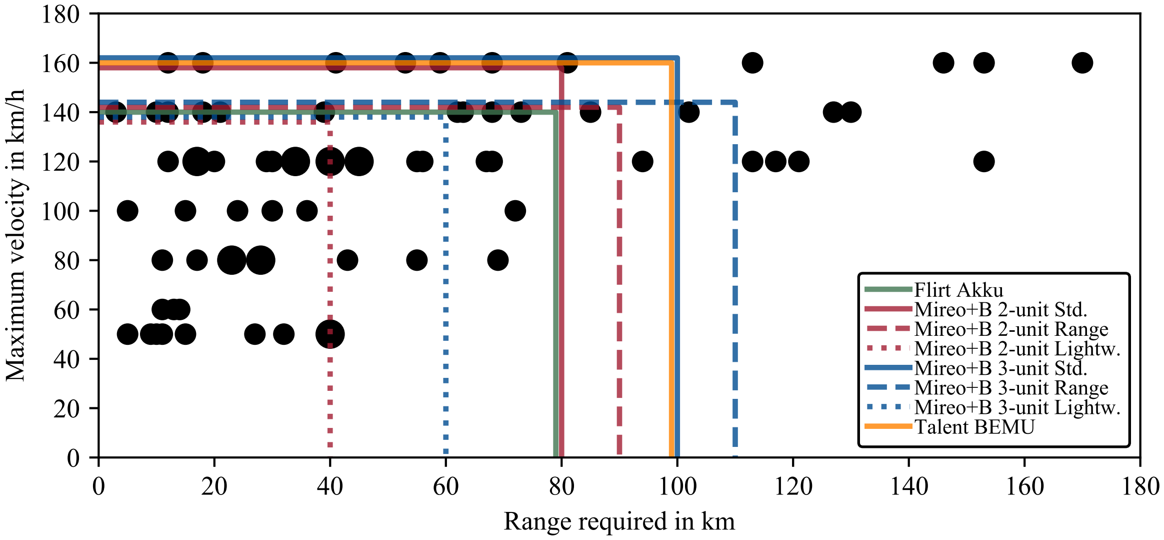
In other words, putting axle loads aside, BEVs are only limited by range and v_{max}, FCEVs are only limited in specific power and v_{max}. Making use of this observation, we plot the respective limiting parameters of each vehicle along with the lines' requirements (Figures 2 and 3). The combination of limiting parameters for a vehicle are referred to by their *performance envelope*. The term is commonly used for aircraft, but adapted for limitations of rail vehicles here.

3.1 BEV performance envelopes

Figure 2 shows the overall maximum line velocity and the range requirement of all lines, along with all BEVs' performance envelopes. The horizontal axis shows range in km, the vertical shows overall maximum velocity. As stated in the previous paragraphs, specific power requirements do not pose limitations to BEVs and axle load requirements only pose limitations in two cases, therefore these two dimensions are not shown. Each BEVs' performance envelope is displayed as 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. Overlapping performance envelopes, having the same v_{max} or range, are shifted a little 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.

Figure 2: Lines' requirements for maximum velocity and specific power with BEVs' performance envelopes



The vehicle with the shortest range, the Mireo+B 2-unit Lightweight, can operate on about every second. All vehicles have overall maximum velocities 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 velocity are sufficient.

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, can not be operated.

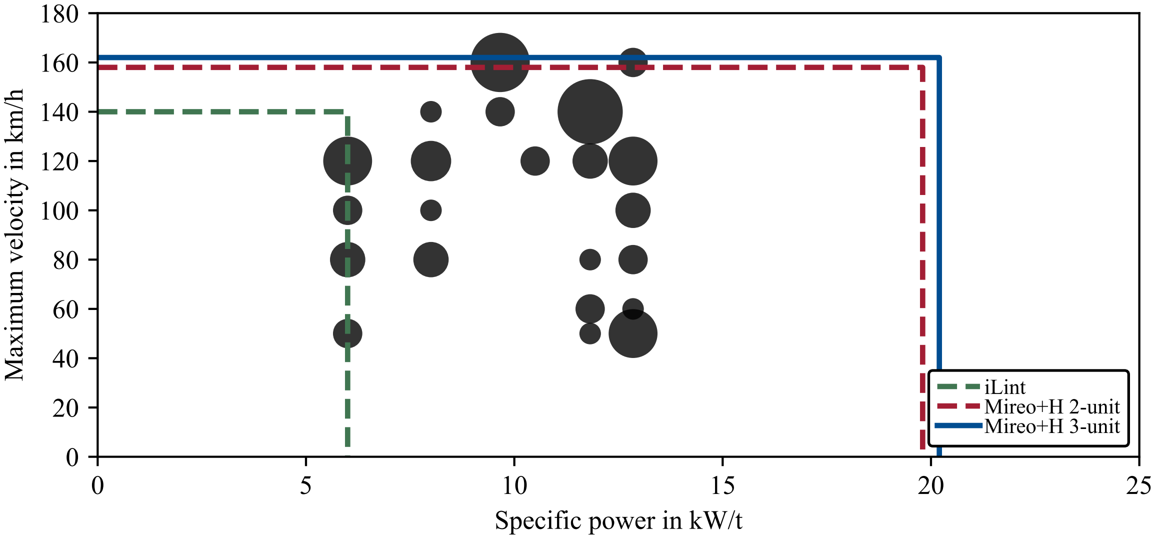
Considering the Mireo Lightweight variants, it gets visible that the number of lines within the performance envelope is decreased compared to the Standard variants. Evidently, the manufacturer trades a smaller axle load for increased range in the vehicle's design. Our analysis suggests a larger market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

The v_{max} shown in Figure 2 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. There is one vehicle to which this is relevant, the Talent 3 BEMU, as two different values for electrified and non-electrified sections are specified. The same is true for 10 of the lines in the line database. All other lines and vehicles do not differ in their v_{max} on electrified and non-electrified parts. In case we would not have 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. 27, 44, and 45) in the database.

3.2 FCEV performance envelopes

Corresponding to Figure 2 for BEVs, we plot the FCEVs' performance envelopes in Figure 3. As outlined in the previous section, specific power is here a relevant requirement and shown on the horizontal axis, but not range. The vertical axis shows overall maximum velocity. Other than for Figure 2, 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 a shifted slightly to make them visible.

Figure 3: Lines' requirements for maximum velocity and specific power with FCEVs' performance envelopes



The lines' requirements, preliminarily analyzed in Figure 1, 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 if its v_{max} was increased, no additional lines could be covered without increasing specific power.

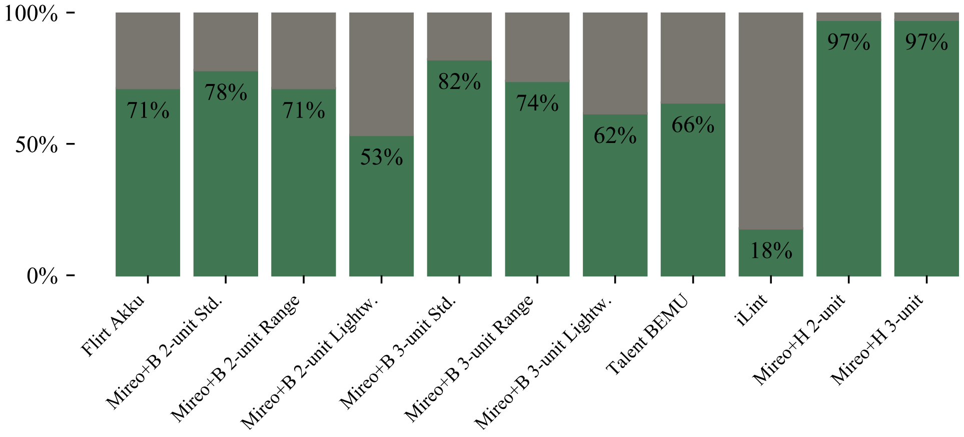
Contrary, all lines lie within the performance envelope of the Mireo 2-unit and 3-unit vehicles. The Mireos v_{max} of 160 km/h suffices all lines' requirements. The Mireo's specific power we estimate in our database is as well sufficient for all lines and provides additional margins. A benefit the iLint yet has over the Mireo Plus H is the lower axle load, required for two of the 73 lines as outlined in the line database analysis.

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

3.3 Number of feasible lines per vehicle

To address the question 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 recommendation for vehicle purchasers, as it gets visible how large the market is that each vehicle can address. The numbers can already be counted in Table 2 and are summed up in Figure 4 as proportion of all 73 analyzed lines.

Figure 4: Proportion of lines that each vehicle can operate



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, presented in Table 2, 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.

3.4 Limitations of this work

The goal of this study is to investigate 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 presented approach and overall conclusions are not subject to these limitations.

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, it is possible that actual performance of vehicles will be worse than assumed. However, 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 completely. This has two effects: (1) the increased number of completely electrified lines will reduce the need for diesel vehicles as well as for BEVs and FCEVs, 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, accuracy of some numbers could be improved by a more detailed model. One aspect is that range of BEVs depends on more factors than just distance driven (Ebrecht et al. [2019]). In a previous study, we introduced a model to estimate energy consumption (Guerster et al. [2018]) and showed that velocity, acceleration, and elevation profile of the individual line have a significant impact on range (Mueller et al. [2019a]). Nevertheless, we expect our requirements for range and driving performance to be on the conservative side.

4 Conclusion

In this paper, we presented two databases. The first database comprises novel emission-free regional rail vehicles with battery-electric and fuel cell electric propulsion technology along with range, axle load, v_{max} and specific power for each. The second database includes regional rail lines in Bavaria and the requirements they impose on vehicles. We compared vehicle characteristic with line requirements 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.

We conclude that:

- 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. Range is the parameter that limits the number of feasible lines for most BEVs. Some BEVs can not operate lines due to limited $\mathrm{v}_{\mathrm{max}}$. 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) on all lines. The iLint is limited by its low specific power.
- Axle load was found to have a minor relevance, since most lines allow for all vehicles in terms of axle load.

In this study, we focused on feasibility and did not state preferences if multiple zero-emission vehicles are possible. Future work addresses the question which vehicle should be deployed when on each line. To do so, we plan to investigate three aspects: (1) operational implications of new technologies, (2) interaction of zero-emission technology with long-term line development, and (3) economic aspects. We describe the underlying drivers for each step subsequently. All three approaches suggest more in-depth investigations of individual lines.

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 have the potential to enable BEV operation on additional lines, decreasing required ranges, and obviate both BEVs and FCEVs on others in case lines are electrified entirely. 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.

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.

For specific vehicles, it can be estimated that the cheapest feasible vehicle will be deployed.

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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	13*	13*	<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	

Table 2: Feasibility of zero-emission vehicles by line

Number	**Line**	**Rang req. in km**	**Max. axle load in t**	**Overall v_{max} in km/h**	**Spec. power req. in kW/t**	**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	20	120	6	◆	◆	◆		◆	◆		◆	◆	◆	◆
2	Augsburg-Aichach	21	20	140	12	◆	◆	◆	◆	◆	◆	◆			◆	◆
3	Augsburg-Bad Wörishofen	45	20	120	8	◆	◆	◆		◆	◆	◆	◆		◆	◆
4	Augsburg-Bobingen	12	20	140	12	◆	◆	◆	◆	◆	◆	◆			◆	◆
5	Augsburg-Friedberg	3	20	140	12	◆	◆	◆	◆	◆	◆	◆			◆	◆
6	Augsburg-Füssen	102	20	140	12						◆				◆	◆
7	Augsburg-Ingolstadt	62	18	140	12											
8	Augsburg-Landsberg	39	20	140	12	◆	◆	◆	◆	◆	◆	◆			◆	◆
9	Augsburg-Lindau	170	20	160	10										◆	◆
10	Augsburg-Marktoberdorf	73	20	140	12	◆	◆	◆		◆	◆				◆	◆
11	Augsburg-Memmingen	40	20	120	8	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
12	Augsburg-Oberstdorf	146	20	160	10										◆	◆
13	Augsburg-Schongau	68	20	140	12	◆	◆	◆		◆	◆				◆	◆
14	Augsburg-Weilheim	34	20	120	12	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
15	Bad Rodach-Weiden	153	20	120	13										◆	◆
16	Bad Streben-Münchberg	45	20	120	13	◆	◆	◆		◆	◆	◆	◆		◆	◆
17	Bamberg-Ebern	17	20	120	13	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
18	Bamberg-Hof	81	20	160	10					◆					◆	◆
19	Bamberg-Nürnberg	113	20	160	10										◆	◆
20	Bayreuth-Weidenberg	14	20	60	13	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
21	Bogen-Neufahrn	36	20	100	6	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
22	Cham-Lam	40	20	50	13	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
23	Cham-Waldmünchen	27	20	50	13	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
24	Ebermannstadt-Forchheim	15	20	100	13	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
25	Eichstätt Stadt-Bahnhof	5	20	50	12	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
26	Fürth-Cadolzburg	13	20	60	12	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
27	Fürth-Markt Erlbach	18	20	140	12	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
28	Gemünden-Schweinfurt	69	20	80	13	◆	◆	◆		◆	◆		◆		◆	◆
29	Gotteszell-Viechtach	40	20	50	13	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
30	Grafing-Wasserburg	23	20	80	6	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
31	Günzburg-Krumbach	28	20	80	8	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
32	Günzburg-Mindelheim	55	20	80	13	◆	◆	◆		◆	◆	◆	◆		◆	◆
33	Hanau-Schöllkrippen	23	20	80	8	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
34	Hof-Selb	24	20	100	13	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
35	Landshut-Mühldorf	55	20	120	6	◆	◆	◆		◆	◆	◆	◆	◆	◆	◆
36	Landshut-Rosenheim	117	20	120	6									◆	◆	◆
37	Lichtenfels-Bayreuth	56	20	120	11	◆	◆	◆		◆	◆	◆	◆		◆	◆
38	Lichtenfels-Hof	121	20	120	11										◆	◆
39	Miltenberg-Seckach	43	20	80	6	◆	◆	◆		◆	◆	◆	◆	◆	◆	◆
40	Miltenberg-Wertheim	30	20	100	6	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
41	Mühldorf-Simbach	40	20	120	6	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
42	Mühldorf-Traunstein	34	20	120	6	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
43	Münchberg-Helmbrechts	9	20	50	13	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
44	München-Bayrischzell	41	20	160	13		◆			◆			◆		◆	◆
45	München-Füssen	63	20	140	12	◆	◆	◆		◆	◆		◆		◆	◆
46	München-Kempten	68	20	160	10		◆			◆					◆	◆
47	München-Lenggries	30	20	120	13	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
48	München-Lindau	130	20	140	8										◆	◆
49	München-Tegernsee	12	20	160	13		◆			◆			◆		◆	◆
50	Neustadt (Aisch)-Steinach	29	20	120	12	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
51	Nürnberg-Bayreuth	18	20	160	10		◆			◆					◆	◆
52	Nürnberg-Gräfenberg	28	18	80	8				◆			◆				
53	Nürnberg-Neustadt (Naab)	59	20	160	10		◆			◆					◆	◆
54	Nürnberg-Schwandorf	53	20	160	10		◆			◆					◆	◆
55	Nürnberg-Simmelsdorf	10	20	140	12	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
56	Passau-Mühldorf	113	20	120	6									◆	◆	◆
57	Plattling-Bayer. Eisenstein	72	20	100	13	◆	◆	◆		◆	◆		◆		◆	◆
58	Pleinfeld-Gunzenhausen	17	20	120	8	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
59	Prien-Aschau	10	20	50	6	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
60	Roth-Hilpotstein	11	20	60	12	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
61	Schwandorf-Furth	67	20	120	13	◆	◆	◆		◆	◆		◆		◆	◆
62	Steinach-Rothenburg	11	20	80	12	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
63	Traunreut-Traunstein	17	20	80	6	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
64	Traunstein-Waging	11	20	50	6	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆
65	Türkheim-Bad Wörishofen	5	20	100	8	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
66	Ulm-Kempten	85	20	140	10			◆		◆	◆				◆	◆
67	Ulm-Oberstdorf	127	20	140	10										◆	◆
68	Ulm-Sigmaringen	94	20	120	13					◆	◆		◆		◆	◆
69	Ulm-Weißenhorn	20	20	120	8	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
70	Wicklesgreuth-Windsbach	12	20	120	12	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
71	Würzburg-Erfurt	153	20	160	10										◆	◆
72	Zwiesel-Bodenmais	15	20	50	13	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆
73	Zwiesel-Grafenau	32	20	50	13	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆