Holistic cost assessment of innovative vehicle drivetrains and infrastructure measures to reduce emissions in regional railway

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Germany has committed itself to reduce emission from 1990 to 2030 by 55 %. Although four of five emission sectors are in their target corridor, emission in the transportation sector today are even higher than 1990 [8]. Although railway is amongst the energy efficient modes of transportation, regional passenger rail often runs on unelectrified tracks with polluting diesel engines [3]. There are two possible directions to decrease emissions: electrify a track and use a hybrid vehicle. It is conceivable that both track infrastructure and the vehicle are changed for an optimal solution. No work has been done to consider both options as intertwined and possibly contending options. For vehicles, there are numerous possible combinations of on-board power generation, storing, and driving components to compose a drivetrain [3]. Only a few possible drivetrain combinations have been evaluated in their performance and cost, and optimization of specific drivetrains has not happened yet [6][7]. Not only emissions are an important criterion for choosing propulsion systems, but also costs. As in most technical system design there will be a trade-off - here between costs and emission reduction. Past studies have focused on one of the dimensions while neglecting the other [1][5][7]. Performance of vehicle variants depends on multiple parameters, e. g. cost parameters, track parameters, and operational assumptions. To thoroughly understand dependencies of the vehicles performances, novel software tools need to be developed.
In this paper we propose a system to define distinct propulsion architectures with all their vehicle component and track equipment decisions. A software tool will be built that Incorporates all previously defined vehicle configurations,

Can handle arbitrary tracks including their electrification infrastructure, Optimizes component scalings of every vehicle architecture with regard to the chosen test case, and Allows to easily investigate the impact of each input parameter. Within this tool, we develop a model to quantitatively determine the fitness of every architecture for any chosen parameter input. Doing this for various tracks, we can state a more general performance of every architecture, therefore assessing which technology should be invested in and which not.
The described research objective is approached as follows: First, vehicle architectures are defined with a morphological decision matrix. In particular, there are three decisions: on-board energy production and transmission, on-board energy storage, and pantograph system to contact to an overhead wire. In each case, not having a component for the category is an option. So far, seven propulsion and six storage options have been defined.

Table 1: Morphological Decision Matrix defining a distinct VIA with every set of choices. Simplified to two options in each category.

Decision	Option 1	Option 2		
Power production and transmission	Diesel-Electric-Serial (DE)	Electric (_E)	2	*Vehicle Decision 1*
Storing of electric energy on board	Battery (b)	None (_)	2	*Vehicle Decision 2*
Pantograph + Trafonsformer	1 (P)	0 (_)	2	*Vehicle Decision 3*
Build external energy supply (catenary) in track section	yes	no	2	*Infrastructure Decision*
			16	

We combine all possible vehicle compositions in a vehicle architecture matrix and exclude non-feasible options. 58 vehicle architectures remain to be investigated. All operating or recently proposed drivetrain concepts in regional railway are included in this matrix. Pantograph vehicles require overhead wires to be set up in order to draw energy. Therefore, we expand the vehicle decisions with a fourth decision for infrastructure. The options are having a catenary already set up, setting up one if it is not existing yet, and leaving an unelectrified track as it is. This infrastructure decision is made for every track section (from station to station) while vehicle architecture does not change over one track. The conflation of all four involved choices for a track and vehicle leads to what we call combined Vehicle and Infrastructure Architecture (VIA). We evaluate the VIAs in two dimensions with an iso-performance approach. The first metric is the Life Cycle Cost (LCC). These costs include Drivetrain component procure-

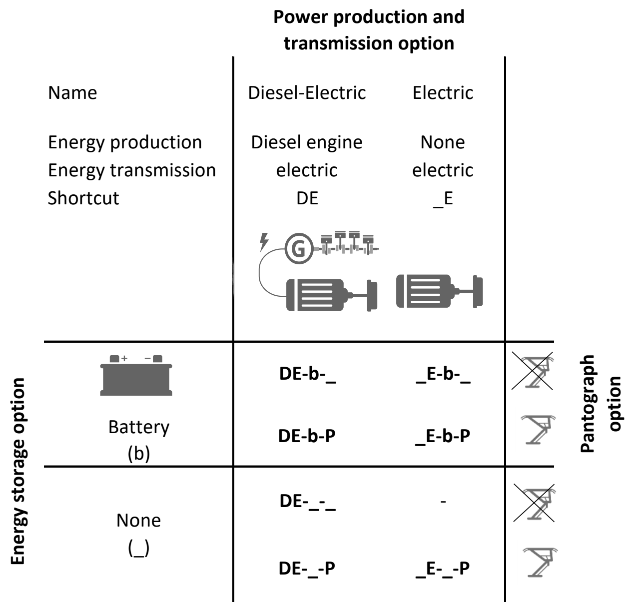

Figure 1: Reduced Vehicle Architecture Matrix, comprising 8 vehicle architectures that are derived from three vehicles decisions, where each decision is simplified to two options.

ment costs, depending on the components scaling, Vehicle maintenance cost, Infrastructure investment costs for electrification, or battery recharge stations, Infrastructure maintenance costs, for maintaining catenaries, recharge stations, and gas stations, and Energy costs. The second metric to evaluate a VIAs performance is CO_2 emissions. Only emissions directly caused during energy production are included in the model, as other contributors to life cycle emission have been found to have a minor importance. Axle loads have been found to be a crucial constraint for hybrid drivetrains, like in recent efforts of the Deutsche Bahn AG to equip existing diesel trains with batteries [9]. Therefore, we set a mass constraint for the train during optimizations, which will lead to non-feasibility of some VIAs or requirement to place additional components in a separate wagon, causing additional costs and increased vehicle mass. The evaluation of VIAs can be done on any chosen real track or with generic tracks. Different than in previous works, we are therefore able to test a large number of different tracks, rather than only one. A driving dynamic model simulates driving a specific vehicle on the track, precisely outputting energy and power demands for each component [2]. Doing so allows us to evaluate emissions and costs of every subvariant, with a distinct set of component scalings, of a VIA separately. Thus, we can determine optimal variants of every VIA, whereas the result is a Pareto frontier with the two above mentioned metrics. The Pareto

frontier comprises all variants where one metric performance can not be improved without worsening the other performance component. Optimization of some tested VIAs has been found to be computationally expensive. Therefore we apply a methodology called Hyperspace Exploriation (HSE) [5]. There, a surrogate model is built to approximate behaviour of the driving dynamic model. Thus, calculation can be accelerated significantly, allowing to probe larger sets of parameters in reasonable time. Eventually, we will carry out a sensitivity analysis for a large number of parameters, determining the most important ones. With metric performances of every VIA and sensitivity of every parameter, can expect which VIA will be optimal for any given set of input parameters.
Considering outputs we preliminary focus on 7 of the 58 defined vehicle architectures. The diesel-only and pantograph-only VIAs are already deployed in large scale. Multiple track electrification projects are realized, scheduled, and proposed all over Germany. Several other drivetrain concepts are in development or announced to enter service soon. Concluding, all these VIAs currently draw attention and should be compared. As a first test of the software framework, a VIA with a diesel engine and a battery has been optimized. It was revealed which subvariants of the VIA dominate over others. Especially one configuration has been found to be advantageous. It draws 80 % of maximum power from a battery, mostly used for accelerating, and 20 % of maximum power from a diesel engine, which is running relatively constantly. The costs, performances, and lifetimes of batteries are volatile. After a sensitivity analysis, it will be more clear which of the battery parameters are critical and should be given more attention. Further VIA optimization results are expected to be included in the final conference paper. In a second test of the model, the payoff of track electrification versus continued diesel operation has been investigated. It has been shown that the main cost contributor of diesel vehicle operation is energy. For the pantograph-only VIA, track electrification and its maintenance cause the highest costs. There are tracks operated with diesel vehicles that have a catenary set up on a large part due to intersection with other tracks. It was found that for typical regional railway operation electrification pays off when more than about a third of the track is already electrified. Furthermore, it was found that one parameter is especially important for the break-even: a reduction of stop distance from 10 to 3 km more than doubles energy consumption, leading to increased costs for diesel operation and making electrification pay-off more likely.

References

[1] Guerster M., Moser C., Brueckmann A., and Grimm R., "Choosing the right architecture for the next generation of railway vehicles using aerospace methodologies", researchgate.net, 2017.

[2] Guerster M., Moser C., Moser K., Mueller F., Muehlbauer C., Brueckmann A., and Grimm R. "Development of a dynamic driving simulation model for automated design of regional trains hybrid propulsion architecture", EMEASEC and TdSE. 2018.

[3] Mueller F. "A dynamic techno-economic evaluation framework for hybrid regional train architectures", Bachelor thesis, Massachusetts Institute of Technology, 2018.

[4] Mueller F. "Towards a techno-economic evaluation framework for regional train propulsion architectures", Semester project report, Ecole Polytechnique Fdrale de Lausanne, 2019.

[5] Palm, H., Holzmann, J., "Hyper Space Exploration A Multicriterial Quantitative Trade-Off Analysis for System Design in Complex Environment", IEEE International Systems Engineering Symposium (ISSE) (pp. 1-6). 2018.

[6] Mueller, A., "Wissenschaftliche Bewertung von alternativen, emissionsarmen Antriebskonzepten für den bayerischen SPNV", elektrische Bahnen, 2017.

[7] J Pagenkopf and S Kaimer, "Potentials of alternative propulsion systems for railway vehiclesA techno-economic evaluation", ieeexplore.ieee.org, 2014.

[8] Umweltbundesamt, "Energiebedingte Emissionen — Umweltbundesamt", 2018.

[9] Claus S., "EcoTrain, the Erzgeirgsbahns New Hybrid Railway Vehicle, Now GmbH Dieselmechanischer Triebwagen wird bis zum intelligenten Mehrsystemfahrzeug weiterentwickelt", Presentation, 2017.

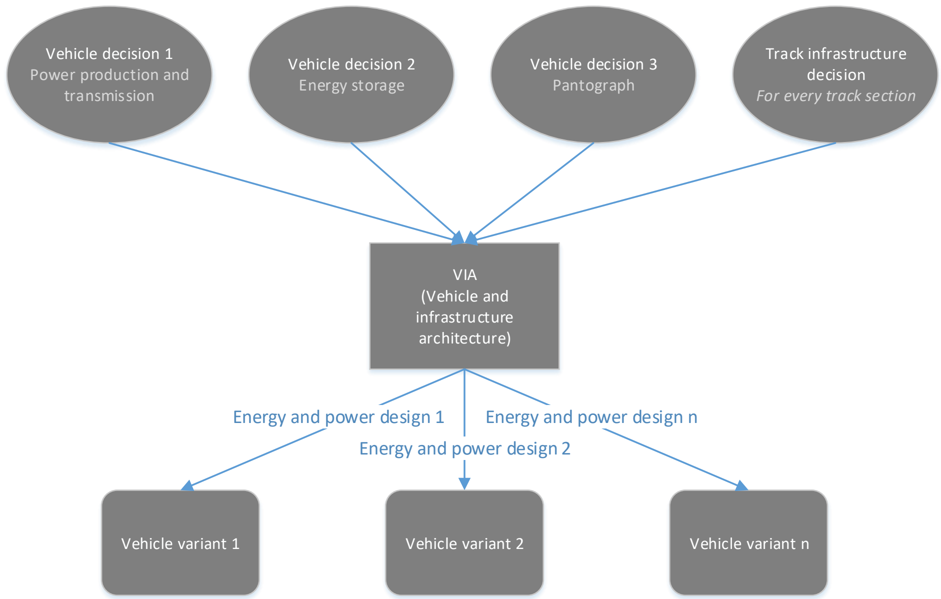

Figure 2: A set of design choices leads to one VIA, which has one or multiple variants

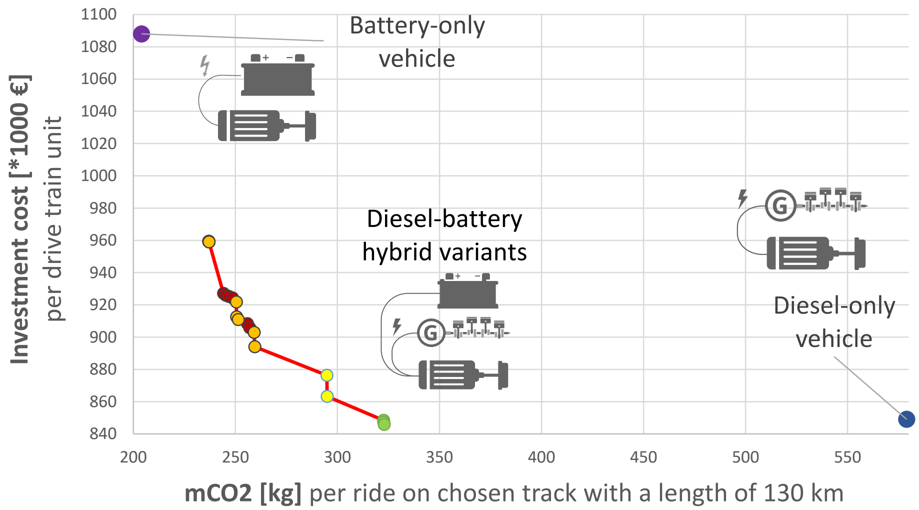

Figure 3: Evaluation of diesel-only, battery-only, and diesel hybrid vehicle variants in the metrics of CO_2 and vehicle drivetrain investment cost.

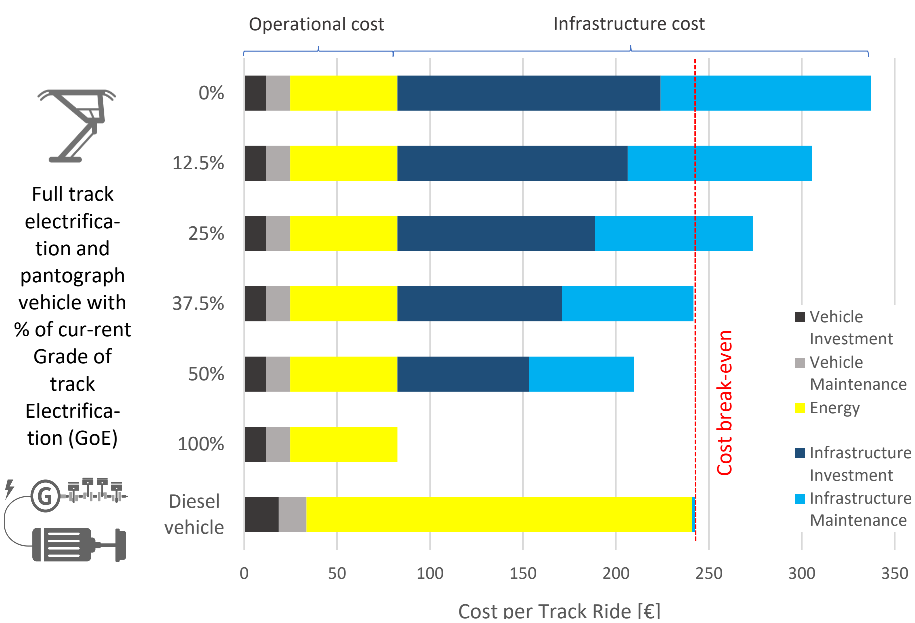

Figure 4: Cost calculation for a generic track of 80 km length and 10 km stop distance, with varying grades of current electrification.