Development of a dynamic driving simulation model for automated design of regional trains' hybrid propulsion architecture

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Abstract. With this paper, we describe the driving dynamic model (DDM) as a key component of the collaborative research project TORPA (Toolbox for Optimal Railway Propulsion Architectures). As part of this project, we aim to find the optimal propulsion architecture for any given track. The newly developed DDM is key to provide a set of constraints for the optimization. This is achieved by a modular design approach, allowing the DDM to be specified for all kind of propulsion systems, consisting of electrical, combustion, and/or fuel cell engines as well as battery, supercapacitor, and/or flywheel energy storage options. In this paper, we first provide a literature background on existing DDMs. Second, we describe the overall methodology and optimization approach. The developed DDM and train mass models are shown after. We quickly introduce the track generation and finally, some preliminary results are shown, and the paper is concluded.

Nomenclature

ADC	Automatic Drive Control	GA	Genetic Algorithm
BBS	Backup Braking System	IPS	Internal Power Supply
DDM	Dynamic Driving Model	LCC	Life-Cycle-Cost
DES	Diesel Engine System	OPM	Object Process Methodology
DMU	Diesel Multiple Unit	PU	Propulsion Unit
EES	Electrical Energy Storage	SCS	Supercapacitor Storage System
EM	Energy Manager	SysML	Systems Modeling Language
EPS	External Power Supply	TBS	Traction Battery System
FCS	Fuel Cell System	TORPA	Toolbox for Optimal Railway Propulsion Architectures
FWS	Flywheel System		

1. Introduction

Traditional methods in classical design often consider only a few point-designs and therefore do not explore the architectural space extensively. This is particularly true for innovative systems on the horizon with a vast architectural space. To explore these spaces exhaustively, model-based tools are needed. In the context of this paper, we use the phrase "model-based" to describe a model which is implemented as a piece of executable code. Compared to SysML or OPM representation, this allows us to optimize the system within given constraints. For example, in our previous study [1], we optimized the sizing of the different propulsion system architectures with respect to mass and volume constraints for a specific track. We have shown that a model-based optimization reveals insights into solutions that otherwise might have been undiscovered.

In this paper, we describe the next developmental results within the collaborative research project TORPA (Toolbox for Optimal Railway Propulsion Architectures) between in-tech GmbH, MIT, and TUM. The high-level objective of TORPA is the development of a model-based toolbox to gather insights into the future of railway vehicles' propulsion architectures.

The initial trigger for this project is the paradigm change in the railway industry over the past years. In the past, railway vehicles were either developed as vehicle platforms that met a wide range of customers' requirements, or they were developed with tight specifications. The platform approach let to non-optimal designs for the majority of use cases, whereas, on the other side, often expensive customizations had to be made to meet very specific customer requirements. These approaches result in a customized vehicle with high investment costs or platforms with non-optimal variable costs. Furthermore, these methods are inflexible in adapting the design to changing requirements, such as changing environmental constraints or new technology. Our work aims to contribute the first step in finding automatically and systemically an optimal propulsion architecture for a specific use case and track. We want to support the paradigm shift towards a flexible design of use-case optimized vehicles with optimal life-cycle-costs (LCC).

In our earlier paper [1], we implemented the track constraints as a required energy equally distributed over equidistant stops together with a needed power requirement. These two data points were extracted from Pagenkopf's study [2]. Going forward, the objective of the tool described in this paper is to find the optimal propulsion architecture for any given track. With this software tool, we can support the automated design as well as the retrofit of existing diesel multiple units. Furthermore, we can assess the robustness of the optimal design for different tracks and train sizes. To achieve this, we started two parallel research thrusts: the first one is developing a dynamic driving model (DDM) given the track data and the second one is generating this track data from publicly available sources. The primary objective of this paper is to describe our first effort regarding the DDM and its fit within our existing toolbox.

In the following section 2, a review of the relevant literature is performed to provide the reader with context. The main section 3 first gives an overview of the methodology as well as optimization approach. It further describes the dynamic driving model, the mass model, and introduces the track generation approach. Preliminary results from the DDM are presented in section 4. Section 5 concludes our paper and gives an outlook.

2. Literature and background

The evaluation of J. Pagenkopf and S. Kaimer [2] was basis for our own study aiming to a more generic evaluation framework with a larger set of hybrid propulsion systems for railway vehicles, which are optimized for any given track. The authors demonstrated the economic benefit of environmental propulsion units (PU's) with a battery or fuel cell system compared to the base vehicle with a diesel engine operated on a dedicated track. We are working on a model-based framework enabling us to evaluate a vaster set of propulsion systems for vehicles on different tracks. The used genetic algorithm (GA) will find for each application the optimum of a propulsion system either for economic or environmental metrics.

S. Kurz, et al. [3] developed a model-based simulation of a Diesel Multiple Units (DMUs) with three transmission options (4-speed hydromechanic, a 6-speed hydromechanic, and electric transmission) and a set of different electrical energy storage systems. The authors compared different drive strategies of these different propulsion architectures for a given track. Compared to their approach, we consider a larger set of hybrid architectures which can be optimized for any given track. This increased design space will make it more likely to find a better optimal design. Our focus lies on developing a more generic tool.

3. Description of the model-based optimization tool

This is the main section of the paper where we will describe the tool that is under development. We first provide an overview of the optimization loops and then describe the main two interfaces of the driving dynamic model DDM, followed by an in-detail description of its building blocks.

A high-level view of the software architecture is shown in Figure 1. It shows the GA and the fitness function which itself decomposes into the inner optimization loop and the metric function.

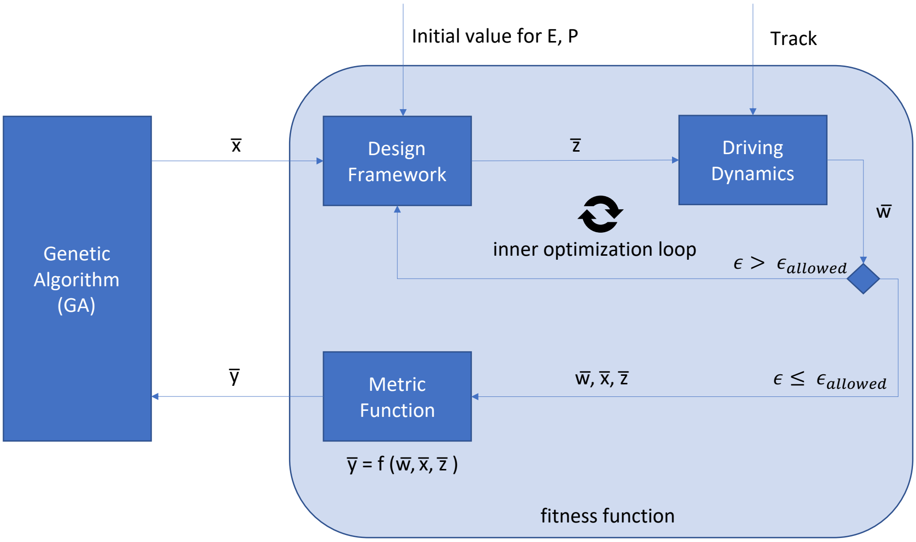

Figure 1: Overview of our software tool architecture consisting of a Genetic Algorithm multi-objective optimizer, an inner optimization loop for the design framework and the driving dynamic model, as well as a metric function.

The GA optimizes each propulsion architecture by its specific set of design variables ($\overline{x}$) (refer to our paper [1] for more details). With these design variables, the design framework calculates the values needed for the DDM simulation, which are masses, power, and energy components ($\overline{z}$). With this train design and a given track, the DDM simulates the track and obtains new power and energy results based on the mass of the train ($\overline{w}$). A decision point evaluates the convergences of the loop by comparing the initial guess of the required total energy (in $\bar{z}$) with the newly calculated total energy of the DDM (in $\bar{w}$). If this value is below a defined threshold, the inner optimization loop has converged for the given set of design variables ($\bar{x}$) and a metric function transforms all the available variables into an objective of interest ($\bar{y}$). These metrics are then the multi-objectives and the fitness evaluation criteria of the GA. The metric function is an ongoing field of research within the project (in our previous work [1] we used the CO2 emission, energy costs, mass and volume).

The DDM has its main two input interfaces with the track generation and the design framework:

Interface to track data

Before the first run of the DDM, the track data is imported and converted to a track data set. As stated in section 3.3 Track generation, the file is of xml type and consists of section data (station to station) like distance, altitude difference and inclination, time to drive, stationary time, availability and nominal power of stationary power supply, availability, type and power rating for wayside power supply (third rail or overhead line), and maximum permissible track speed. The limited resolution to sections - station to station - of this parameter does not reflect the reality with varying speed limits on tracks but is necessary for a reasonable runtime of the optimization. If a set of optimal design is found, the model run can be repeated with a track considering track data on a subsegment basis.

Interface to design framework

The interface between the *Design Framework* and the *Driving Dynamics* is a parameter set as vector $\bar{z}$, which includes all relevant parameters for the submodules. The *Design Framework* determines also design parameters of the complete propulsion system and vehicle parameters like number of drive axles, vehicle mass, etc. After a complete run of *DDM,* the calling function returns the result as variable $\bar{w}$ with energy or power required for driving the selected track.

3.1. Dynamic driving model (DDM)

Part of the complete framework is a modular model implemented in Matlab and Simulink representing a vehicle/multiple unit embedded in the environment. The model shown in Figure 2 is made of several submodules, with two main models: vehicle and environment. The environment represents the track and the dynamic forces acting on the vehicle and carriages that might be coupled.

The vehicle in our case is restricted to a modular drive train system including energy supply, propulsion unit, backup braking system and energy storages. The vehicle/multiple unit runs on a dedicated track driven by a virtual driver, who is represented by the Automatic Drive Control (ADC). Not only the power consumption of the propulsion unit must be considered but also the power consumption for auxiliary systems including DC power for the battery system. The metric energy consumption is defined by the consumed fuel, electric energy from external and the energy difference of the storages from start to finish.

The core of the dynamic system is the block *Driving Dynamics* feed by the traction/brake force from *Propulsion Unit* and *Railway Carriage* model (optional). The design parameters like train mass, drag coefficient, etc. determine together with track parameters (track inclination) the resulting acceleration/deceleration force, and therefore the train speed and traveled distance over the time.

The optional *Railway Carriage* model considers the impact of additional dynamic forces from pulled carriages. The optional brake force from the carriages shall also be controlled by the ADC.

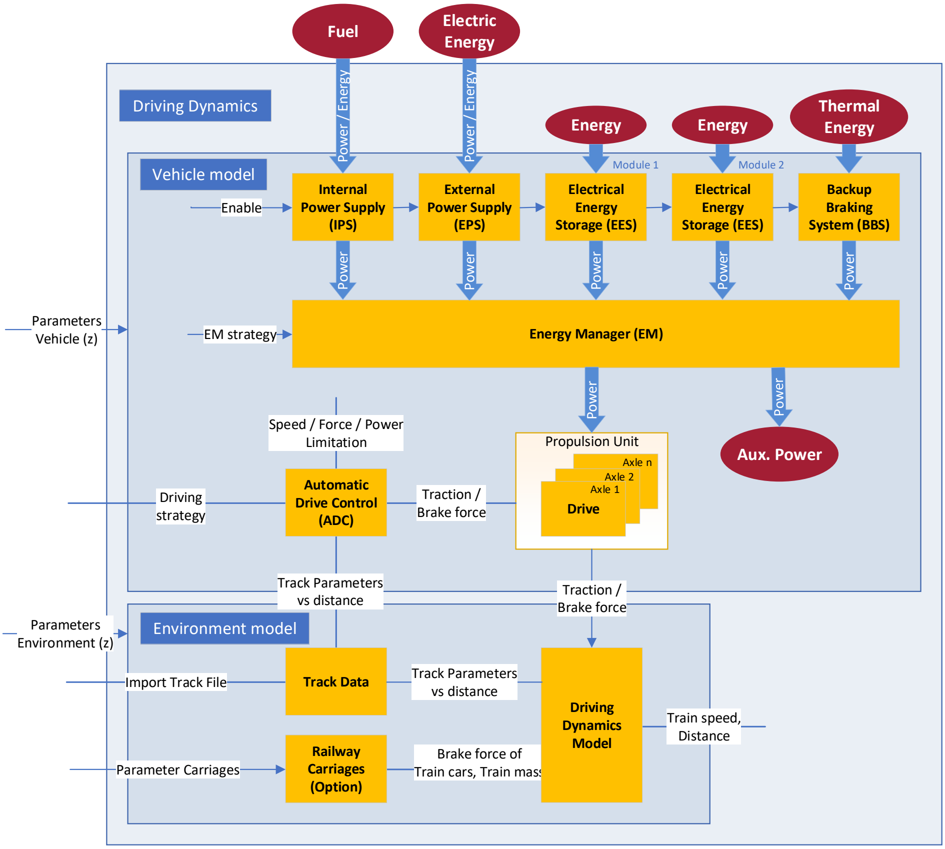

Figure 2: Block diagram of the complete Dynamic Driving Model

3.1.1. Environmental Module

The environmental module takes into account the physical laws of driving dynamics under constraints [4, 5]. On a moving vehicle forces act in all three directions. We assume that all forces not in driving direction have a minor influence on our objectives and we therefore only model the following components in the driving direction based on Peter Spiess [4] (see Figure 3 for an overview):

- Gradient force caused by the slope

- Rolling resistance
- Bearing resistance
- Drag force
- Traction / braking force from the drive with the optional braking force of the towed carriages
- Resulting acceleration or deceleration force

Due to their minor influence, we neglect the following resistance forces in our model:

- Curve resistance
- Switch resistance
- Transmission resistance
- Start-up force
- Dynamic resistance

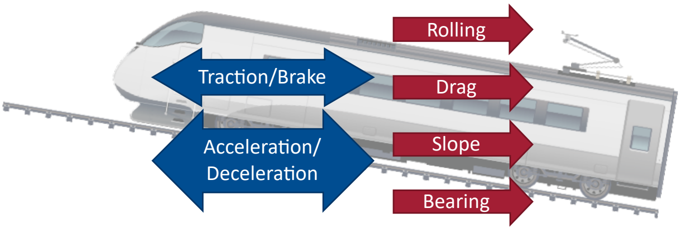

Figure 3: Overview of the acting forces on the train, which are modeled by our driving dynamic model

The sum of all traction, braking and resistance forces in the train results in an equation of the acceleration (Eq. (1)) or deceleration (Eq. (2)) [4]:

$$\mathrm{M} \cdot \rho \cdot \frac{\mathrm{dv}}{\mathrm{dt}} = -W(s, v) + F_Z - F_B \qquad (1)$$

with

M:	Total mass of train
ρ:	Mass factor for rotational mass
W:	Sum of resistance forces
F_Z:	Traction force
F_B:	Braking force

$$\mathrm{M} \cdot \rho \cdot \frac{\mathrm{dv}}{\mathrm{dt}} = F_N - W_{Roll} - W_{Bearing} - W_{Drag} + F_Z - F_B \qquad (2)$$

with

F_N	Gradient force
W_{Roll}	Rolling resistance
$W_{Bearing}$	Bearing resistance
W_{Drag}	Drag force

3.1.2. Vehicle Model

The block *Vehicle Model* is built of various power modules. The virtual driver (we call this block *Automatic Drive Control* (ADC)) can call up various driving strategies via a parameter (for example time-optimized or energy-optimized according to a timetable).

Depending on the strategy and controlled by the track data, it determines the acceleration and required train / braking force for the PU (and optional the brake force for pulled train carriages). The forces are within the limiting tractive/brake force diagram. The power supply modules including the optional *Backup Braking System* (BBS) are dimensioned in the architectural framework so that the required speed values, as well as acceleration and deceleration, can be achieved. Connected power modules can be easily replaced due to a harmonized interface to the *Energy Manager* (EM).

As part of the architecture optimization from the design framework, not only the parameters can be varied, but modules can also be activated or deactivated by an enable flag. Furthermore, the design framework considers limitations in terms of mass and volume of the individual modules. If limits are violated, the model will terminate.

Automatic Driving Control (ADC)

The ADC sets the traction force according to a given driving regime. At the same time, it defines the driving dynamic condition of the vehicle: standstill, acceleration, braking, or rolling. A jerk limitation is not implemented here.

We define 3 different possible driving modes of the ADC (see Figure 4 for an overview)

1. *Minimum time (without a timetable):* I - Acceleration with max tractive force but limited by P_{max}, II - Driving with v_{max}, III - Braking with max. braking force but limited by P_{max}
2. *Timed (timetable):* I - Acceleration with defined traction but limited by P_{max}, II - Driving at a constant speed at v_{target} (calculated from time table), III - Braking with defined braking force but limited by P_{max}
3. *Timed (timetable):* I - Acceleration with defined traction but limited by P_{max} to v_{max}, II - Coasting, III Constant speed at v_{cruise}, V - Braking with defined braking force but limited by P_{max}

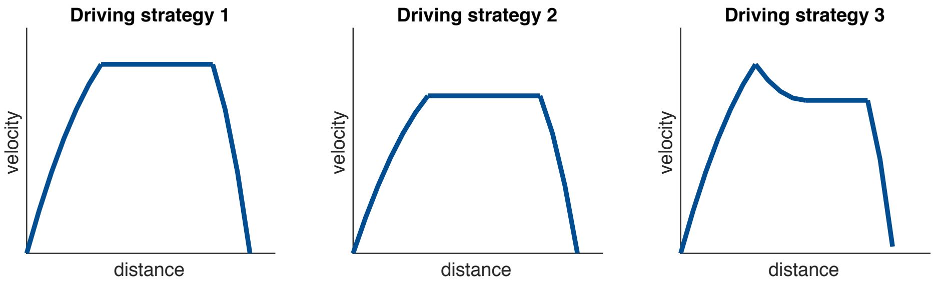

Figure 4: Overview of the different driving strategies: (1) Minimum time (without a timetable); (2), and (3) timed with a timetable

Propulsion Unit (PU)

The *Propulsion Unit* converts the requested tractive/brake force into individual forces per driven or braked axles. Several axle drives can be involved in acceleration and deceleration on the train. The model does not consider a friction brake (pneumatic or magnetic brake system).

The module is regarding the maximum permissible wheel-rail adhesion and calculating the requested power considering the system efficiency from the EM. In the case of a recuperation (regeneration of dynamic energy) the power supply from EM is negative.

An alternative PU for a mechanical gear or hydrodynamic gear can be implemented. In this case, the interface to the diesel engine is also the requested power for the EM which is provided from a diesel engine.

External Power Supply (EPS) or Internal Power Supply (IPS):

An *Internal Power Supply* is a system without energy transfer on the track. The opposite *External Power Supply* has an interface for trackside or stationary energy transmission. The electric overhead line or third rail supply and the stationary feeding of electrical energy belong to the second type. Different systems can be used and combined in our vehicle model.

Diesel Engine System (DES)

The efficiency of the diesel engine depends on the operating point of the combustion engine. The efficiency is determined by the engine characteristics. Since this is a two-dimensional characteristic field with engine speed vs torque and the speed is decoupled from the drive unit, we assume a motor controller that always operates at the optimal consumption point. Thus, the consumption can be determined by the requested power. The total efficiency is determined by the complete system diesel engine & generator and an AC/DC converter.

External Power Supply (EPS)

The EPS can be realized as an AC version or a DC version of the power supply. In both variants, the supply voltage is switched on via the main switch. As soon as the external supply is available according to the track model, the corresponding power from the EPS is available for sourcing and regenerating. We do not consider the variant with a three-phase feed from a stationary wall-box here, as it is not practical for our simulation with feeding at a station.

Fuel Cell System (FCS)

The Fuel Cell is an alternative option for internal power supply. It can be standalone or in a combination with a diesel combustion engine. In contrast to the battery and the capacitor, the FCS cannot be simply described through a characteristic curve, as it has a reaction time on dynamic power requests. This type always needs to be combined with an EES and a modified EM which balances the power request from EM between FCS and EES. FCS is switched off at power demands below the minimum. The power of the FCS is controlled according to the state-of-charge (SOC) of the used EES.

Electrical Energy Storage (EES)

The energy storage device is responsible for on-demand power supply (short time or permanent) and intermediate storage of dynamic energy (provided during braking). The system provides or stores energy if requested by the EM, from the PU, and from the auxiliary power system, respectively. The following systems can be used as EES:

Supercapacitor Storage System (SCS)

An SCS consists of a DC/DC converter which will charge or discharge the storage device. The complete storage module is a combination of serial and parallel connected capacitors. We consider the storage as one capacitor with parasitic insulation resistance - R_{Isol} and a serial resistor such as connecting wires, contact resistors - R_{ESR}. The serial inductance X_C has no influence for our rather static model. The system block diagram shows the input as a power request from the EM (see Figure 5).

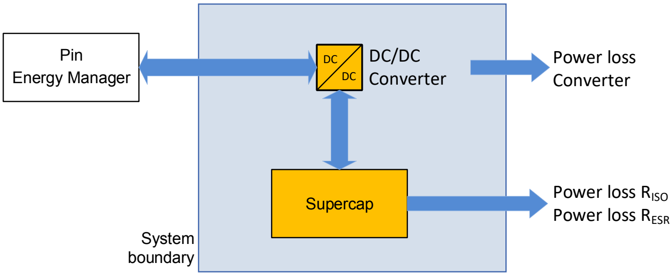

Figure 5: Supercapacitor storage system with system boundary and input and outputs as defined in the text

Traction Battery System (TBS)

The TBS consists of a DC/DC converter charging and discharging the battery. The Battery is abstracted to a single battery pack and the characteristics of the TBS are regarded in a characteristic curve and depend on the power draw/supply. While the SCS is a short time storage, storing roughly enough energy for one acceleration phase, the TBS can be used for both types - as intermediate EES with lower capacity or with larger capacity, allowing the vehicle long distances to be traveled solely by battery.

Flywheel System (FWS)

The flywheel is an alternative to the supercapacitor storage system and acts as a short-term energy storage. The model uses a DC/AC converter with a motor accelerating the flywheel to a higher speed. The system is fully charged when it has reached the maximum speed. In the opposite direction, the motor acts as a generator and is feeding the EM with power. We have static losses due to losses of the running gyrating mass, as well as charging and discharging losses, respectively.

3.2. Mass model

Within one train architecture, the high-level goal of our optimization is to find designs with low overall energy consumption. This energy consumption is an output from the DDM. In order to be able to calculate a required energy, the design variables generated by the GA ($\bar{x}$ vector from Figure 1) need to be transformed into values that can be used in the DDM's equations of motion ($\bar{z}$ vector). Therefore, for the fraction of the optimized mass, the design framework creates physical data like masses from the design variables. Input for the DDM is the overall vehicle mass, so the non-optimized part of mass needs to be added. The calculation of this mass from model inputs is described as a mass model in the following. We define this model for a regional train with two or more cars. It consists of the following components: passenger cabin structure mass, bogie mass, mass of driver's cab and crash structure, payload mass, and mass of the propulsion system including motors, drivetrain, fuel and energy storage (as seen in Figure 6).

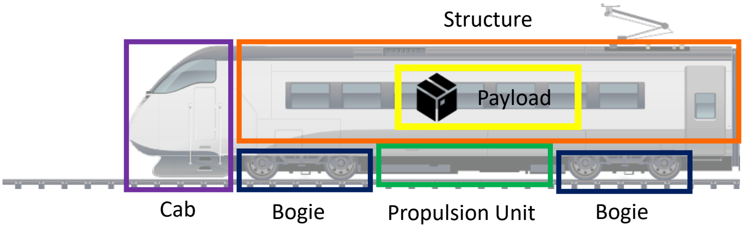

Figure 6: Overview of our structural decomposition of a regional railway vehicle. It consists of driver's cabs, bogies, the optimized propulsion unit, and from the passenger numbers depending components, the payload, and the structure.

The engine is considered part of the propulsion system which is optimized. Following up on a previous study [6], a constraint for the maximum mass of the propulsion unit is chosen to be 5000 kg for the model. This is primarily due to limited axle loads on railroad tracks.

The payload mass per seat is assumed to be 75 kg as defined by common industry standards [7].

Based on manufacturer data [8], we assume that a bogie for a regional train traveling slower than 160 km/h has a mass of 6 tons, under addition of 1 ton if the train is a tilting train. For most vehicles, the motor is integrated into the bogie but still accounts to the drivetrain mass and not the bogie mass.

The remaining structure mass is considered the passenger carrying structure, which is a function of the number of passengers. According to data of a set of state-of-the-art regional trains [9, 10] we calculated this variable mass to be 268 kg per passenger seat. With the same set of data, we derived a mass of 22 tons per driver's cab.

The validation of the mass model is shown in Table 1. The relative difference of our model to the reference case is between -6.8 % and +10.6 %. Weighting all reference cases equally, the average discrepancy amounts to 3.6 %. Overall, the mass model provides sufficient accuracy for further calculations.

Table 1: Validation of the developed mass model of regional train architectures

Manu-facturer	**Model**	**DB AG Class**	**# of cars**	**Calculated mass [kg]**	**Source mass [kg]**	**Relative Difference**
Bombardier/ Adtranz	Regioswinger [11]	612	2	111.63	116	-3.91%
Bombardier	Talent 4-car [12]	4024 (ÖBB)	4	125.73	116	7.74%
Siemens	Desiro [13]	642	2	72.25	69	4.49%
Alstom	Coradia Cont. [14]	440-4	4	111.41	119	-6.81%
Alstom	Lint 54 [15]	622	3	108.21	98	9.43%
Alstom	Lint 81 [16]	620	4	154.35	138	10.59%

3.3. Track generation

Since all tracks are different, there is a benefit in optimizing the propulsion architecture for each track [17]. The optimal design that is computed by the DDM will differ for different rail tracks. To take this dependency into account, we collect data from open public accessible data portals which allows us to represent the track in a standard data collection format. In our first approach we concentrate on a database relying on German railway data, but we plan to include other international areas in the future. Figure 7 pictures an elevation model as one exemplary way of representing a track in its individual characteristics.

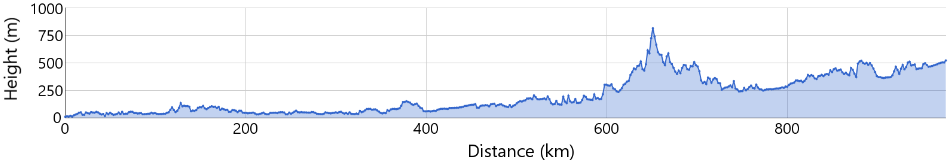

Figure 7: Elevation Model: A possible outcome of the track generation

The generated file format describes the railway trail separated in sections and subsections. Sections are way segments from one train station to another train station which include subsections. Subsections are segments themselves that split the same way segment into continuous segments. These subsegments are then grouped by a specific attribute, which is equal over all the subsections in order to compromise the size without loss and reduce the DDMs computation time.

Sections and subsections are defined by attributes like distance, speed, and electrification. We consider static values that characterize the enclosing environment of the track and have an impact on the driving behavior of a train. We define nine attributes (see Table 2) for either a section or subsection.

Table 2: Defined attributes and their impact on the train driving behavior

Section	
Stationary time	Time while staying in the start station of this section
Stationary power supply	Electronic feed power that is available during the stationary time. If none is available, the value is "N/A"
Track time	Time difference between the starting station departure time and the arrival time at the destination station.
Destination power supply	Electronic feed power that is available at the destination station
Subsection	
Distance	The spatial range between the starting point and end point of this subsection
Altitude difference and inclination	Differences in the elevation and slope of the track
Maximum driving speed	Allowed maximum velocity during this subsection.
Track power supply	If the subsection is electrified, the available power is given. If not electrified, this value is set as "N/A".
Type of track power supply	An integer describing the architecture of electronic feed. 0 for no feed at all, 1 defines overhead supply and 2 if there is a third rail.

Given these requirements, no single source was found that contains all of this information in an acceptable quality. Thus, we merge datasets of multiple sources by connecting them via keywords and -positions, e.g. names of train stations.

In future work, the outcome of the track generation will be validated with other sources. For datasets with limited access in their programming interfaces or sources which are not available in a digital format, the validation can be done manually for at least some tracks and special edge cases. Other services can be integrated into the program to collect the same types of data and generate homogeneous track files. The files themselves and their outcomes of the DDM (when feeding it with the found sections for a track) can be used to compare the results with actual recorded GPS data. Thereby, we can investigate which sources provide the best and most realistic input values for our use.

4. Results

As a first result and validation, we executed the *Dynamic Driving Model* with data from Pagenkopf [2] where a DMU of type VT612 drives on a roughly 130 km long track between Ulm and Oberstdorf with 13 intermediate stops (see Figure 8). Our model runs the simulation for each section of the track from one train station to the next (14 in total).

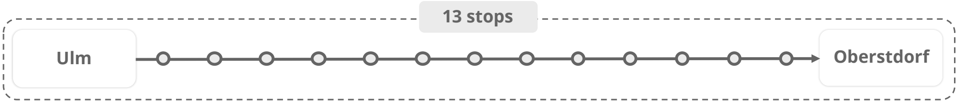

Figure 8: Overview of the test track with 13 intermediate stops between Ulm and Oberstdorf

Figure 9 shows the velocity profile and power consumption throughout the track. It can be seen that we use driving strategy 1 with maximum acceleration until the maximum allowed velocity and then cruise until we have to decelerate to stop at the station. Equally, the power demand of the engine reaches its maximum during acceleration and drops to around 40% during cruising.

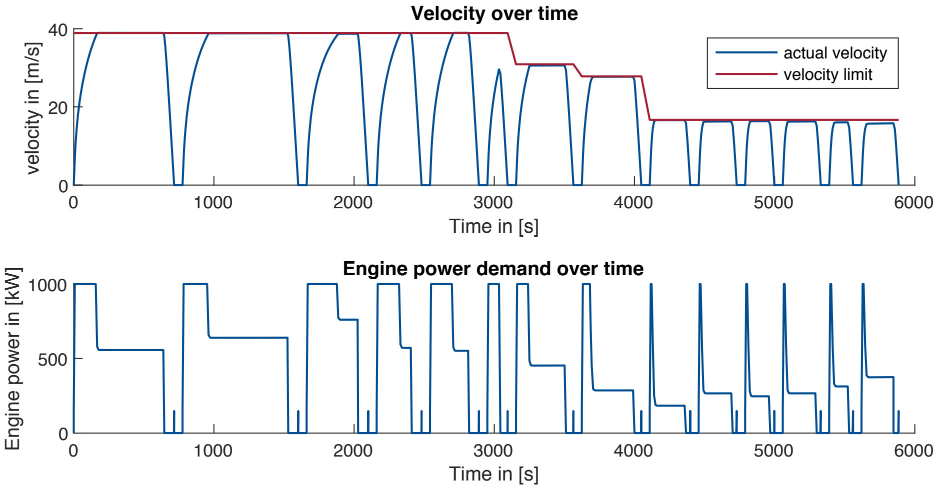

Figure 9: Velocity profile of the DDM with driving strategy 1 in the top subplot together with the speed limit. The bottom subplot shows the power demand on the DMU during acceleration and cruising

The total results of those 14 executions are shown in Table 3. The distance, the travel time as well as the energy consumption are sums of the individual executions. The model of the DLR paper simulated a train with a diesel-hydraulic system, where the hydraulic gearbox has an efficiency of 77.5%. We considered a diesel mechanical system. For better comparison, we lowered the efficiency of our generator to 77.5%. Otherwise, the total energy is approximately 20% lower than that of the DLR paper.

Table 3: Results of our model compared with the references data for the track between Ulm and Oberstdorf

	Our model	**DLR Model**	**Deviation**
Total distance	129.7 km	129.7 km	0.0 %
Total travel time	5896 s	5993 s	+1.6 %

Total propulsion energy	524 kWh	564.7 kWh	+7.7 %
Total energy	958 kWh	971.8 kWh	+1.5 %
Consumed fuel	270 l (≙ 2640 kWh)	248 l (≙ 2429.5 kWh)	-8.1 %

Our evaluation framework shows a close correlation with the data from the DLR paper. One aspect of the remaining deviation is that the DLR paper assumed an efficiency of 40% for the diesel engine, while our efficiency depends on a typical characteristic curve of a diesel engine, and therefore is a function of the workload of the engine. 40% is a value close to our mean efficiency over time. But our efficiency drops to 36% when accelerating and rises to 43% when cruising at high speeds. A large portion of the travel time is spent accelerating, which is also when most energy is consumed. This explains why our model has a slightly higher fuel consumption while having a lower total power consumption when compared to the DLR data.

Furthermore, the EM of our model uses the recuperation energy of the electrical brake for the auxiliary power of the train (lights, heating etc.), which was in both our and the DLR model assumed to be 138 kW on average. This additional factor plays a role when comparing both models, as the power output of our engine drops to zero during braking. We have implemented a start-stop auto control for the DES which is commonly used in hybrid vehicles to reduce fuel consumption [18].

5. Conclusion and outlook

First, we have described our model-based approach to find the optimal propulsion architecture for any given track. Second, an overview of the software architecture of the optimization tool was shown. We have focused on the description of the driving dynamic model and its modular architecture, and third, we presented some results.

We conclude that the development of the driving dynamic model is an important step towards a software tool which helps us size new railway vehicles and finds the optimal retrofit architectures for existing diesel multiple unit trains. One of the main challenges we faced was the development of an energy manager that can modularly accommodate all possible hybrid architectures. The results and validation of the driving dynamic model showed its meaningfulness.

As future steps, we will further enhance the software tool, specifically by developing (1) the track database in a format readable by the driving dynamic model, and (2) the metric function to optimize towards the objective of interests.

Once these capabilities are developed, we will be able to provide insights into the optimal design of a new vehicle as well as the optimal retrofit architecture for any given track. We will be able to explore solutions which are robust to different track requirements and flexible to adapt to changing requirements.

References

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