Coupled Vehicle-Guideway Dynamics Simulations of the Transrapid with Discretized Levitation Magnet Forces

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Summary. Magnetic levitation (maglev) is a promising technology for high-speed transportation systems, as shown by the Transrapid line in Shanghai operating successfully for nearly 20 years. Currently, a new high-speed train based on this technology is being developed, driven by China's Ministry of Science and Technology. Magnets are one of the key components of a maglev vehicle's suspension system. Attractive magnet forces ensure the contactless coupling of the vehicle to the guideway. Electromagnets are usually described using finite element (FE) models, electromagnetic circuit models, or simple analytical models for simulation purposes. However, FE magnet models are computationally often overwhelming, especially for transient studies, and thus too slow to use them in large vehicle models for vehicle dynamics simulations. Moreover, the parameterization of FE models often is non-trivial. Therefore, less detailed but fast-computable models are used in such simulations, often providing only a coarse discrete distribution of magnet forces along the vehicle. In this contribution, the coupled vehicle-guideway dynamics is investigated regarding different discretizations of levitation magnet forces. A two-dimensional model of the maglev vehicle Transrapid moving along an infinite elastic guideway is used, considering the heave-pitch motion of the vehicle and the vertical guideway bending. Simulations are performed using either a coarse distribution with two magnet forces per magnet or a fine distribution with twelve magnet forces per magnet, i.e., one magnet force at each magnet pole. It is shown that the simplification of two magnet forces per levitation magnet is valid for vehicle dynamics simulations. The model is parameterized with data from the Transrapid TR08 and uses a self-developed model predictive control (MPC) scheme to control the magnets.

Introduction

In Shanghai, the only commercial high-speed magnetic levitation (maglev) train based on electromagnetic suspension (EMS) technology is in operation at the Shanghai Maglev Transportation (SMT) line between Pudong International Airport and Longyang Road Station. It is operating with a maximum speed of 430 km/h. A new high-speed maglev train with a designed top speed of more than 600 km/h is developed at the Chinese rolling stock manufacturer CRRC Qingdao Sifang Co., Ltd. A prototype of the vehicle has already been presented to the public [1]. In Japan, at the same time the SCMaglev, a high-speed maglev train based on the electrodynamic suspension (EDS) technology using superconducting magnets, is developed [2]. High-speed maglev trains can close the gap between current high-speed railway technology with top speeds of 300 to 350 km/h and aircraft traveling at around 900 km/h. To investigate the dynamic behavior of the coupled system of guideway, vehicle, magnet, and controller, simulations and analyses with suitable models are essential tools in the development process regarding, e.g., the general design or safety and ride comfort aspects.

Magnets are key components of a maglev vehicle's suspension system. Hence, mathematical magnet models sufficiently describing the magnet statics and dynamics are essential for reliably predicting the behavior of a single magnet and eventually of the complete coupled system of vehicle and guideway by means of computer simulations. Depending on the issue to be investigated, the complex electromagnetic field needs to be modeled in different levels of detail. On the one hand, simple magnet models usually neglect effects like magnetic saturation and eddy currents, which become relevant for high loads, failure scenarios, and high velocities. Detailed magnet models taking these effects into account, on the other hand, are often computationally intensive and therefore unsuitable for application in large vehicle models for dynamics simulations. Basically, three ways to simplify physically detailed but computationally intensive magnet models exist. Firstly, simplification by neglecting highly nonlinear physical effects like saturation, see [3], secondly, model reduction procedures still considering these physical effects and at the same time reducing the computational effort, as elaborated in [4], and, thirdly, simplifications concerning the distribution of magnet forces along the vehicle. In literature, various maglev vehicle models are described with different levels of detail regarding the distribution of levitation magnet forces along the vehicle. In [5], a very coarse distribution is applied with four levitation magnet forces per vehicle section in the most complex model variant. The models from [6, 7] use one or two magnet forces per magnet, respectively. In [8], a model of the controlled magnets is presented, providing two magnet forces per magnet, combining both the magnet model and the control law in a PID-T1 system. Another approach is used in [9], where two torques are applied in addition to two forces per magnet. Both are multiplied with position-dependent factors mapping the discrete force application points (FAPs) to the continuous magnet force distribution of the real magnet. A fine distribution with one force per pole is implemented in [3], but the corresponding magnet model is simple with limited valid operational range. In [10], a magnet model with two forces per magnet from [4] is used to analyze the coupled dynamics of a vehicle consisting of three sections with 48 levitation magnet forces in total, moving along an infinite series of elastic guideway elements. While the influence of nonlinear physical effects like saturation and eddy currents has been investigated in detail in [4], the influence of magnet force distribution has not yet been investigated systematically. Therefore, the question arises whether it is a valid simplification in simulations of coupled vehicle-guideway dynamics to summarize the magnet force, which is actually distributed continuously along the magnet, in a single concentrated substitute magnet force per magnet or half magnet, respectively, or if a finer distribution is required with forces acting, e.g., at each pole.

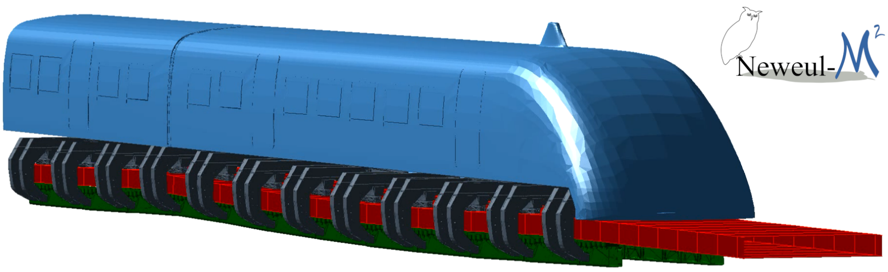


Figure 1: Coupled system of a rigid multibody maglev vehicle and an elastic guideway modeled and visualized with Neweul-M^2.

Simulation Model

In this contribution, the influence of levitation magnet force distribution on the dynamic behavior of the coupled vehicle-guideway system is investigated. A two-dimensional model of a maglev vehicle moving along an infinite elastic guideway based on [10] is used, mapping the heave-pitch motion of the vehicle and the vertical guideway bending. The infinite track is represented by a small number of identical single-span Euler-Bernoulli beams, which are used repeatedly, following the concept of moving system boundaries. The vehicle is modeled as a rigid multibody system with three sections, each one consisting of a car body, levitation chassis, and levitation magnets coupled by air springs and elastomer elements. The mechanical model has 76 degrees of freedom. Figure 1 shows the coupled system modeled and visualized with the in-house multibody simulation toolbox Neweul-M^2 [11]. The vehicle mechanics is parameterized with values from the Transrapid model called TR08, the predecessor of the SMT vehicle running in Shanghai. Parameters representing the first generation of concrete girders at the test facility in northern Germany (TVE) are taken for the guideway elements. The simulation model is basically the one described in [10], therefore, the interested reader is referred to this publication for a complete model description. Nevertheless, to provide a good understanding of the model, its most important aspects are summarized below, as well as the extensions and changes made for the work at hand.

Mechanical Vehicle Model

The vehicle model represents a detailed two-dimensional rigid multibody model of the maglev vehicle Transrapid mapping the heave-pitch motion in the x-z-plane. It represents a longitudinal section of the system. The left and right side of the system, that is the y-direction, are summed up. An overview of the mechanical vehicle components is given in Fig. 2.

The model comprises a rear end section, a mid section, and a front end section. Each section consists of rigid bodies for a car body, four levitation chassis, and seven or eight levitation magnets, respectively. Each section has the length of eight standard levitation magnets, but the magnets are arranged in such a way that a magnet connects the neighboring levitation chassis of two sections. At the front and rear end of the vehicle, bow levitation magnets are installed that are longer and have 14 poles, while standard levitation magnets have twelve poles. Thus, bow levitation magnets have a shifted center of gravity and higher mass and inertia compared to a standard levitation magnet. Each rigid body has two degrees of freedom (DOF): a translational one in z-direction and a rotational one about the y-axis, making up 76 DOF for the complete vehicle.

Stiff elastomer elements connect the car bodies. The support of the car bodies on the levitation chassis is realized by rather soft air springs, also called secondary suspension. The primary suspension, i.e., the connection of levitation magnets and levitation chassis, is realized by stiff elastomer elements again. All elastomer elements and air springs are implemented as linear spring-damper combinations in the model.

Furthermore, the magnets are attracted to the guideway by magnet forces computed by the magnet models described below. For the coupling with the magnet computation, the distances to the guideway reference plane are outputs of the mechanical system for calculating the air gaps, and the magnet forces are inputs to the mechanical system. As shown in Fig. 3, there are two or twelve such inputs and outputs for each standard magnet. For the longer bow magnets, there are

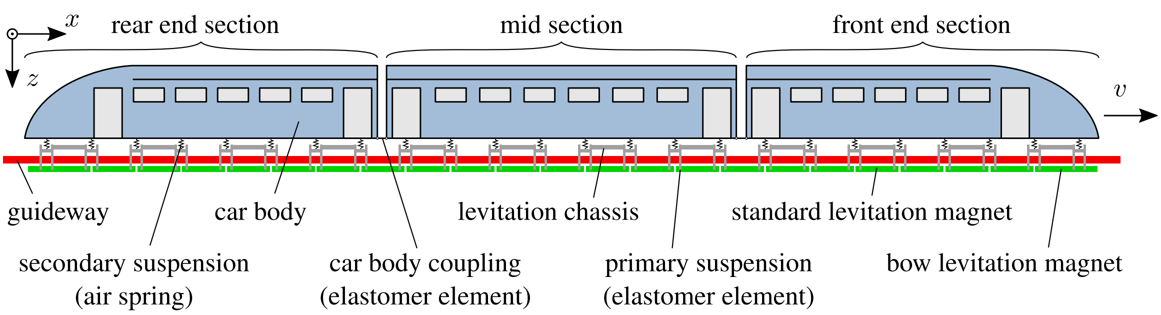
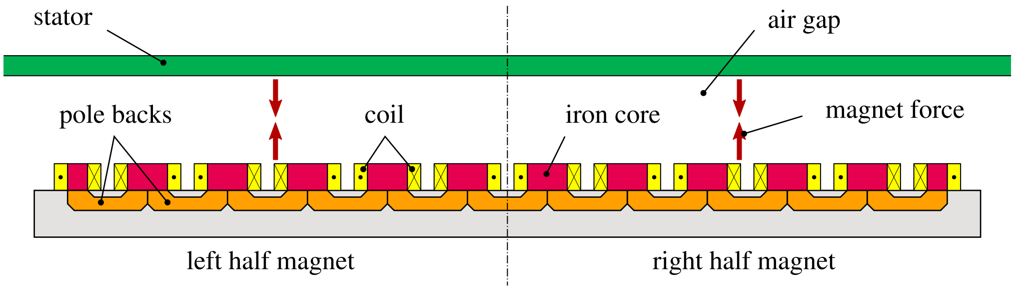


Figure 2: Components of the complete vehicle model on the guideway.



(a) Coarse distribution of magnet forces with one force per half magnet.

(b) Fine distribution of magnet forces with one force per pole.

Figure 3: Variants of magnet force distributions along a levitation magnet.

either three or fourteen inputs and outputs. Furthermore, the velocities of the poles or FAPs of concentrated substitute forces, respectively, are defined as outputs of the mechanical model. They are necessary to compute the time derivatives of the air gaps at each of the poles or FAPs of concentrated substitute forces, respectively, required by the magnet model to compute the magnet forces.

Mechanical Guideway Model

The track is implemented as a regularly pillared elastic guideway of infinite length. Applying the concept of moving system boundaries as proposed in [12], a small number of identical Euler-Bernoulli beams is used repeatedly, as shown in Fig. 4. In [10], the implementation of this concept to obtain an infinitely long track is described. In short, a guideway element is taken from behind the vehicle as soon as it is no longer required there, its states are reset, and it is placed in front of the vehicle again.

A detailed description of a single guideway element, a simply supported single-span elastic Euler-Bernoulli beam discretized by 24 finite beam elements and reduced to its first three eigenmodes, can be found in [13]. The application of moving magnet forces to the beam by means of equivalent nodal forces and torques at its nodes and the interpolation of nodal coordinates to get the deflections at arbitrary positions between the nodes using Hermite interpolation polynomials is explained there as well.

Compared to the guideway described in [10], additional static guideway disturbances are added to the model for the work at hand. According to the design principles for high-speed maglev systems from the German Federal Railway Authority,

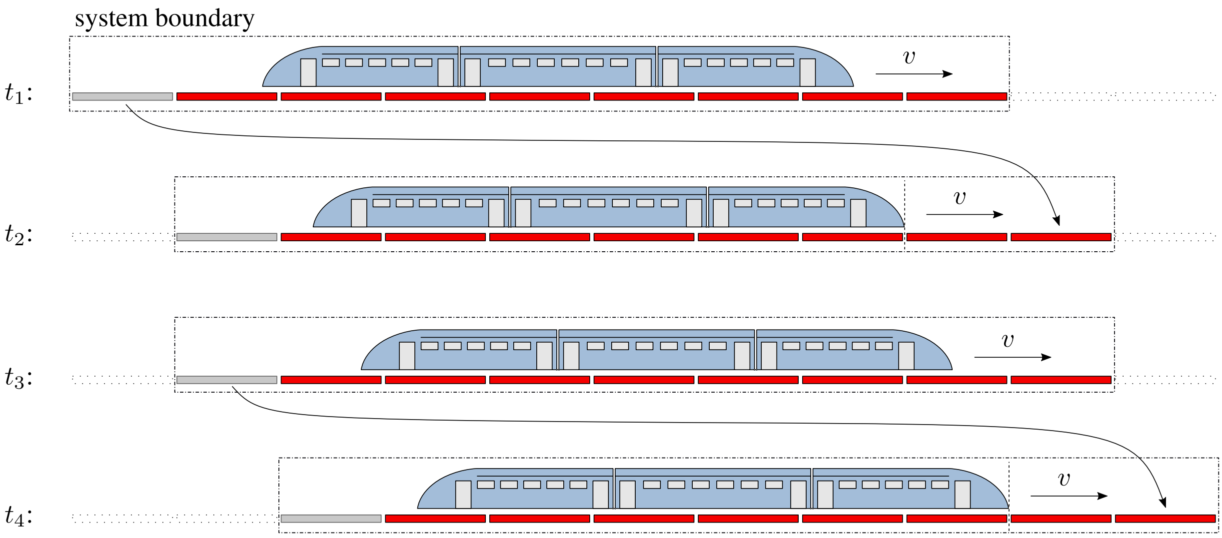


Figure 4: Concept of moving system boundaries: A small number of guideway elements is used repeatedly to realize an infinitely long elastic guideway in an efficient manner.

see [14], different types of guideway irregularities are to be considered. First, there is the bending of the girders when loaded with the vehicle. This effect is taken into account by modeling the guideway elements as elastic Euler-Bernoulli beams. Second, the pillars supporting the girders may have different heights resulting in not perfectly flat positions of the supported girders. And third, for the vertical position of the stator packs mounted to the girders, there are tolerances as well. The last two disturbances are applied to the guideway model in a statistical manner as presented in [15].

Magnet Model

Vehicle and guideway are coupled by the magnet forces of the levitation magnets. With the work at hand, the influence of magnet force distribution on vehicle and guideway dynamics is investigated. Actually, the magnetic field between the poles and the stator is distributed continuously along the magnet. To represent such a continuous distribution with a high degree of detail, a finite element model would be desirable, but this is unsuitable for vehicle dynamics simulations because of the tremendous computation time, enormous parameterization effort, or meshing difficulties. Therefore, the continuous force field must be discretized for computer simulations, and the question arises of how detailed this discretization must be. Therefore, two different discretization approaches are analyzed and compared here: a fine one with one magnet force per pole, and a coarse one with one magnet force per half magnet, i.e., two forces per standard levitation magnet. Both approaches are depicted in Fig. 3.

In [4], a detailed magnet model is presented, considering the physical effects of magnetic reluctances, fringing and leakage flux, magnetic saturation, and eddy currents. It is validated for a standard levitation magnet of the maglev vehicle Transrapid and computes the magnet forces at each of the twelve poles. Additionally, a simplified magnet model is derived from the detailed one based on a reduction technique, providing just one concentrated substitute magnet force per half magnet. Concerning the magnetic and electric properties, it was shown in [4] that the difference with respect to the detailed model is negligible if the air gap is identical at all poles of one magnet. Its computation time is two orders of magnitude faster, making it usable for dynamics simulations of large vehicle models. In the contribution at hand, the influence of magnet force distribution is investigated by applying both magnet models from [4], the detailed magnet model providing one magnet force per pole and the simplified one providing one force per half magnet, to the model of the coupled vehicle-guideway system described above and comparing the results.

Controller

The reciprocal relation of the air gap and the attractive magnet forces – that pull the vehicle to the stator of the guideway from below – leads to an unstable system, which must be actively controlled to allow stable levitation. The air gap must be kept in a safe range to avoid physical contact between the vehicle and the guideway and simultaneously the acceleration has to be reduced to improve ride comfort. Each half magnet has its own gap measurement unit (GMU) and is controlled individually by its own magnet control unit, which provides the voltage for the magnet based on the gap, acceleration, and current measurements. As shown in [10], a self-developed offset-free model predictive control (MPC) scheme from [16] shows a promising performance even for higher speeds than the TR08 was designed for. Therefore, for both levels of detail of magnet force discretization, the magnets are controlled by this MPC controller instead of the actual control algorithm implemented for the TR08.

Coupled System

All subsystems, i.e., vehicle mechanics, guideway mechanics, magnets, and controllers are combined in a Simulink model representing the complete coupled system. The schematic setup of the Simulink model is shown in Fig. 5. For more details

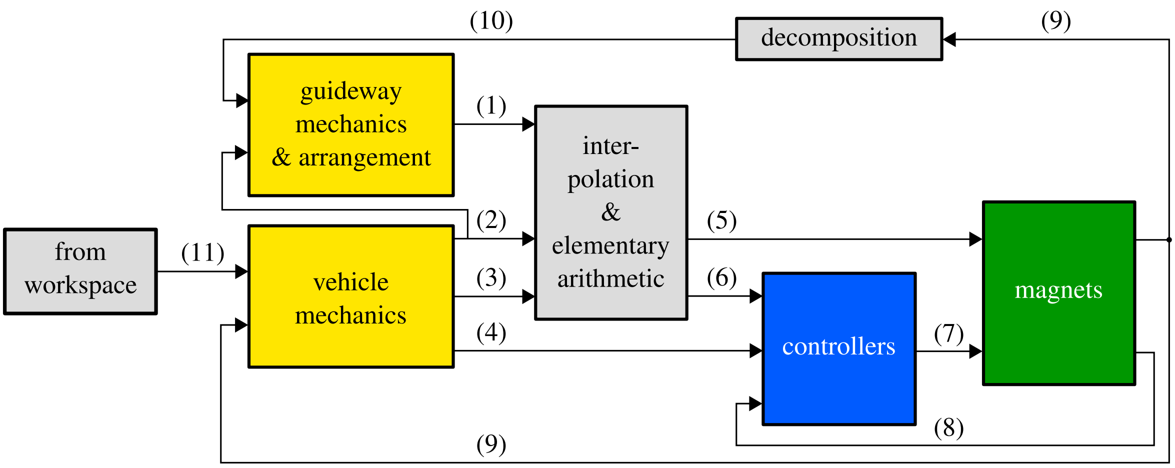


Figure 5: Schematic setup of the coupled model in Simulink. (1) nodal coordinates and velocities of beams, (2) x-positions of magnet forces, (3) magnet z-positions and velocities at magnet FAPs, x-positions of GMUs, magnet z-positions at GMUs, (4) magnet z-accelerations at GMUs, (5) air gaps and air gap velocities at magnet FAPs, (6) air gaps at GMUs, (7) magnet voltages, (8) magnet currents, (9) magnet forces, (10) nodal forces and torques, (11) x-position of front end car body. For more details see [10].

regarding the Simulink model and its signal flow, please refer to [10]. Due to the modular structure of the Simulink model, the individual components can be replaced with little effort. Thus, the simplified magnet model can be replaced easily with the detailed magnet model for the simulations described in the following.

Simulation Results

In the simulated scenario, the vehicle consisting of three sections is traveling on the infinite elastic guideway with a constant speed of 300 km/h. By comparing the two configurations with different force discretization, the necessary degree of detail is determined for vehicle and guideway dynamics analyses.

The simulation results plotted in Figs. 6-10 compare different dynamical quantities for both the detailed and the simplified magnet model. Figure 6 shows various quantities related to the magnet and the controller in the time domain, that is, the air gap s_{GMU} measured at the GMU normalized with the desired air gap s_{des}, the vertical magnet acceleration a_{GMU} measured at the GMU normalized with its maximum $a_{\max}$, the voltage U_{mag} applied to the magnet normalized with the nominal voltage U_{nom}, the current I_{mag} flowing through the magnet normalized with the nominal current I_{nom}, and the magnet force F_{mag} provided by the respective half magnet normalized with the nominal force F_{nom}. Each of them is shown for three positions along the vehicle: at the very rear end, at the center of the mid section, and at the transition from the mid to the front section. An exemplary time range of one second is shown. For the plot of F_{mag}, the forces in the detailed model belonging to the six poles of the respective half magnet are summed up to be compared to the force calculated by the simplified model. In Fig. 7, for the same quantities as in Fig. 6 the relative frequency of occurrence is plotted as bar plot on the left vertical axis together with the corresponding cumulative frequency of occurrence as line plot on the right vertical axis. Figures 8 and 9 show the motion of the levitation chassis and the car body, respectively. That is the vertical translations z_{LC} and z_{CB} and the rotations β_{LC} and β_{CB} about the y-axis. Again, the results obtained with the detailed model are compared to those obtained with the simplified magnet model. For the car body motion, exemplary time ranges of four seconds are plotted. In Fig. 10, the deflection w_{mid} of a single guideway element at mid span is plotted versus the position $x_{\mathrm{MF,front}}$ of the foremost magnet force of the simplified model for both the detailed and the simplified magnet model.

In general, all results are in very good accordance for the simulations with the detailed and the simplified model. For the internal magnet dynamics small differences occur between the detailed model and the simplified model, as revealed by the plots for voltage, current, and magnet force in Figs. 6 and 7. These small differences can be explained by the differences and simplifications made in the simplified model with respect to the detailed model. While it was shown in [4] that the difference is negligible if the air gaps are identical at all poles of one half magnet, the air gaps and their change with time are individually computed here for each magnet pole. By summarizing the magnet forces of a half magnet in a single concentrated substitute magnet force, spatial balancing effects caused by different pole gaps occurring while traveling along an uneven guideway are neglected. However, as can be seen from Figs. 6-10, quantities describing the mechanical vehicle and guideway dynamics like air gap, magnet acceleration, levitation chassis motion, car body motion, and guideway motion are nearly identical for both magnet model variants. For the translation of the levitation chassis z_{LC}, the maximum difference between both model variants is less than 0.43 mm at all three considered positions, corresponding to less than 2.1 % of the maximum absolute amplitude. The mean deviation is below 0.1 mm at each of the three positions. The deviation of the car body translation z_{CB} remains smaller than 0.24 mm for all three sections. This is less than 1.5 % of the maximum absolute amplitude. On average it is even smaller than 0.06 mm for each section. For the guideway deflection at midspan w_{mid}, the difference is less than 0.07 mm between the detailed and the simplified model. That is only 1.2 % of the static guideway deflection when loaded with the vehicle. This means that for the analysis and prediction of vehicle and guideway dynamics, the simplified magnet model is here a sufficiently accurate approximation of the detailed magnet model.

This is a satisfying result, because the simulation time is about a factor of 100 faster with the simplified model than with the detailed model. It takes about 100 hours of real time for 62 seconds of simulation time with the detailed model, while for the same simulation time it takes just about one hour of real time with the simplified model. Additionally, the preprocessing time for creating the mechanical vehicle model takes some extra time if the detailed magnet model is to be used compared to when the simplified model shall be used.

With the results at hand, it can be concluded that a coarse spatial discretization of magnet forces along the maglev vehicle with one magnet force per half magnet is sufficient for vehicle dynamics simulations. Thus, neither finer magnet force discretizations nor FE models for detailed mapping of the magnetic field are necessary for determining the vehicle dynamics. Due to enormous simulation times, such models are unsuitable for application in vehicle dynamics simulations with large vehicle models and multiple magnets. Even with a view to the next few years, simulations with such high computational effort will not be reasonable. Therefore, it is all the more gratifying to see that the simplified model represents the detailed model so well regarding the resulting vehicle and guideway dynamics in a large vehicle model. However, for other simulations such as the elastic deformation of a magnet more complicated and spatially distributed magnet forces are required. As frequently in simulations, the simulation purpose determines the required level of detail in the modeling.

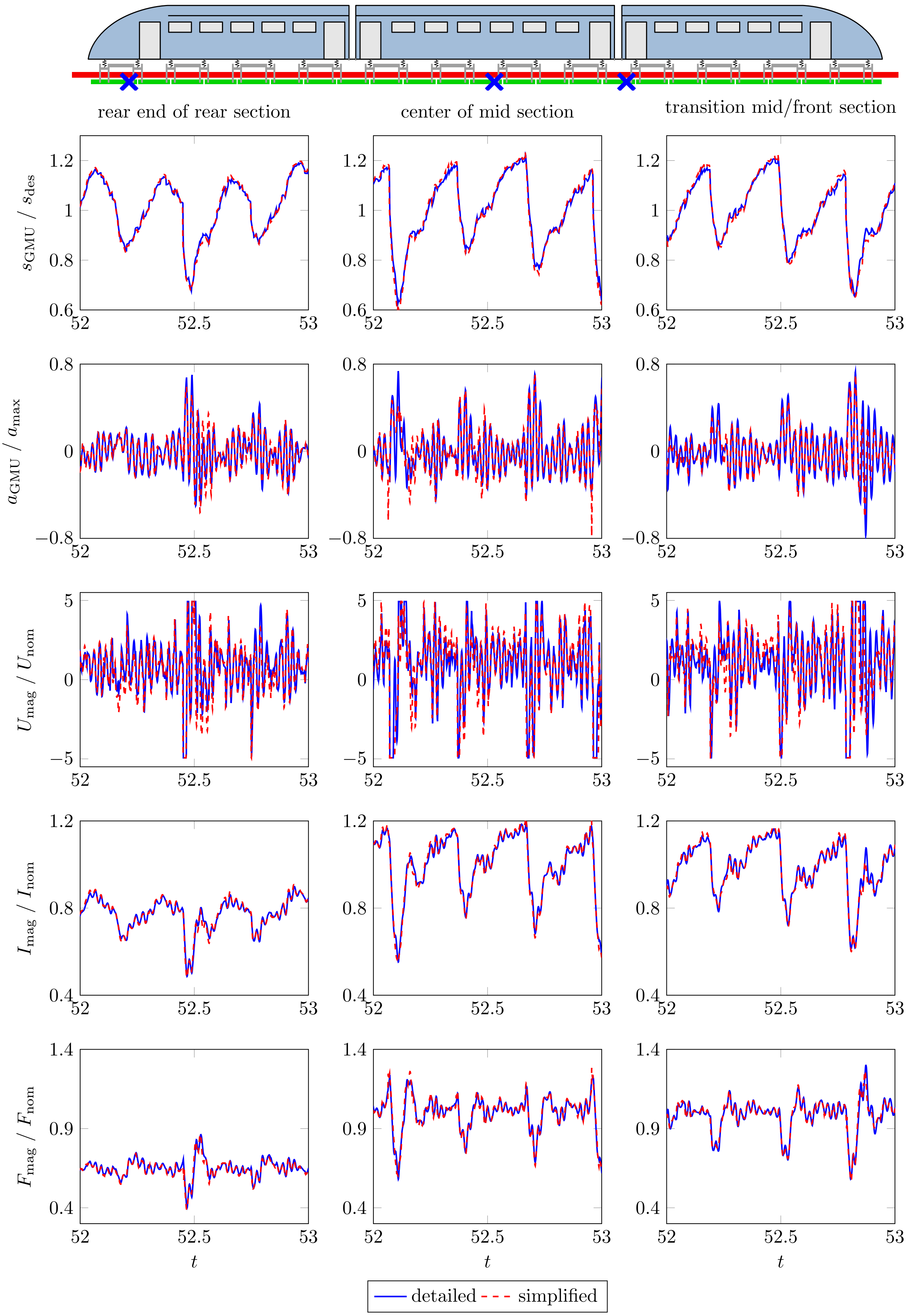


Figure 6: Comparison in the time domain of simulated quantities related to the magnet and the controller obtained with the detailed magnet model and the simplified magnet model at three positions along the vehicle: at the very rear end, at the center of the mid section, and at the transition from the mid to the front section.

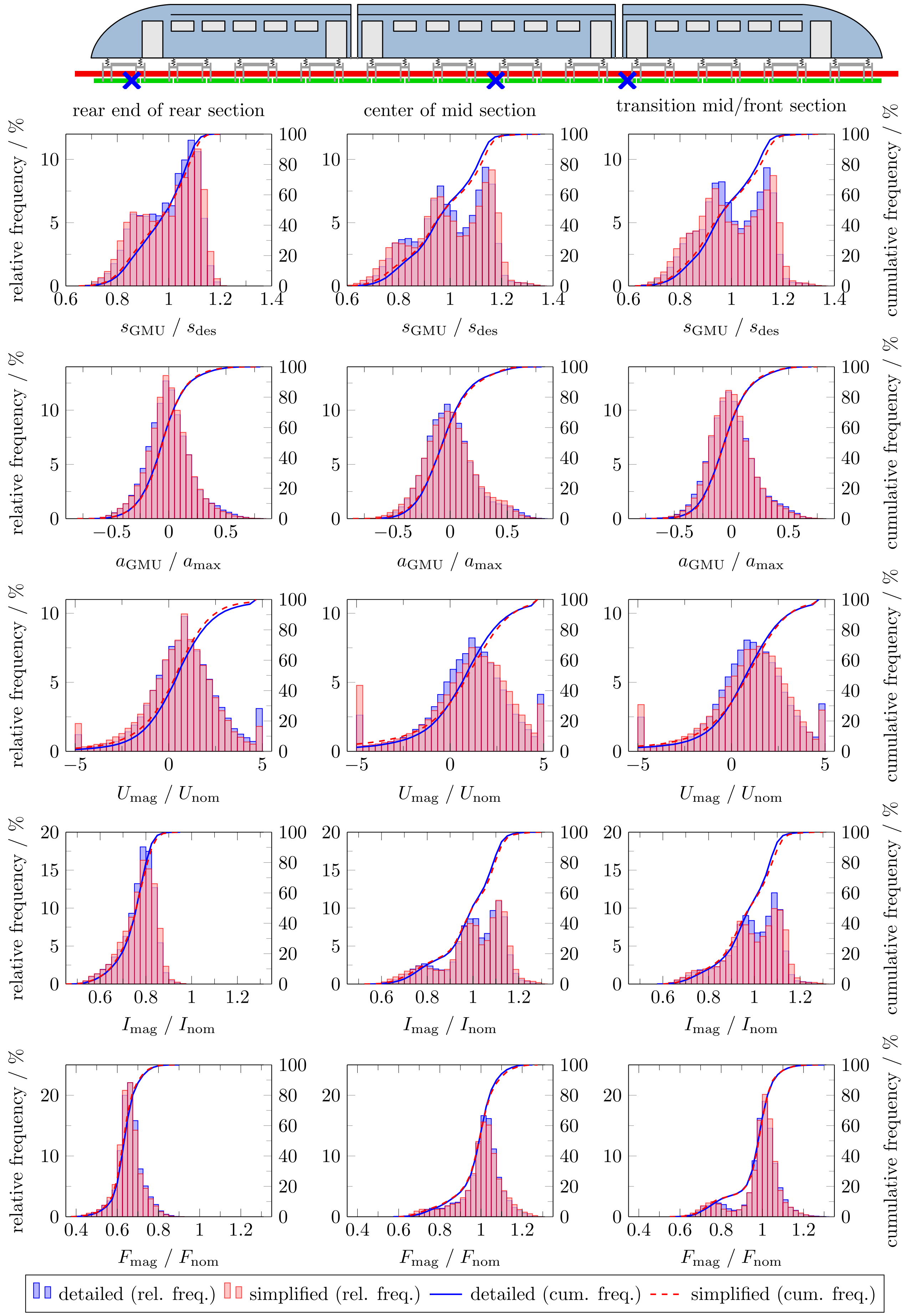


Figure 7: Relative (left vertical axis) and cumulative (right vertical axis) frequency of occurrence of the same quantities and at the same positions along the vehicle as in Fig. 6 obtained with the detailed magnet model and the simplified magnet model.

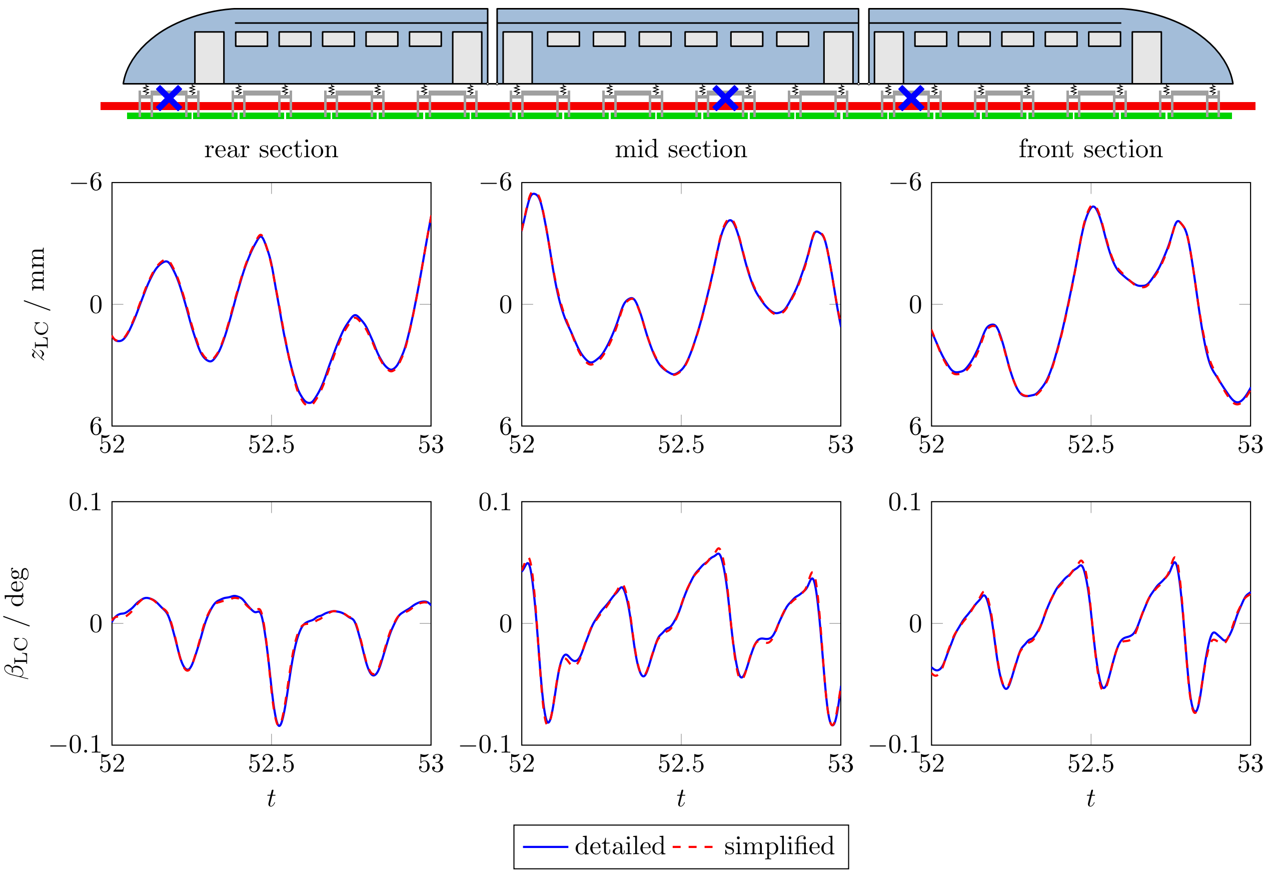


Figure 8: Comparison of simulated translations and rotations of the levitation chassis obtained with the detailed magnet model and the simplified magnet model at three positions along the vehicle: at the very rear end, at the center of the mid section, and at the transition from the mid to the front section.

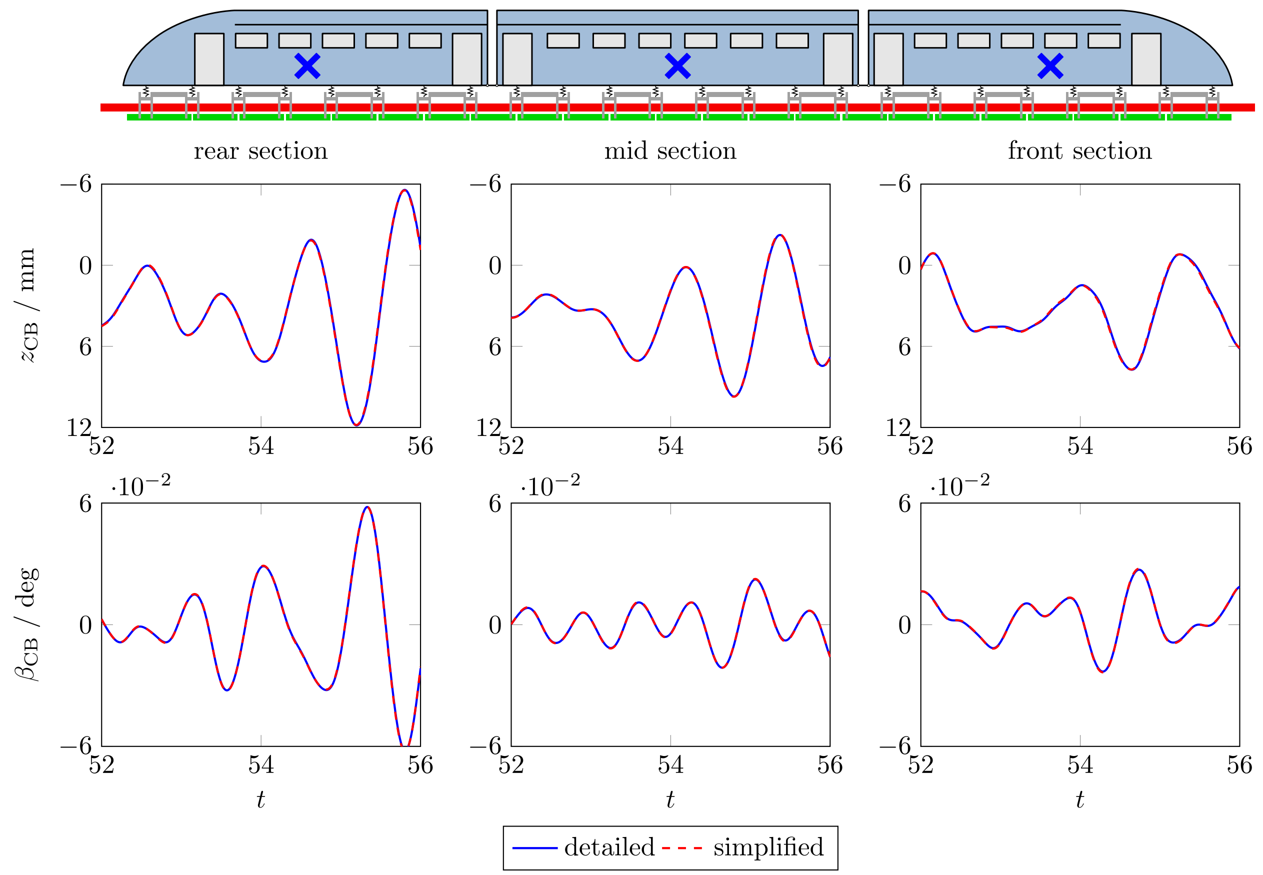


Figure 9: Comparison of simulated translations and rotations of the car bodies of rear, mid, and front section obtained with the detailed magnet model and the simplified magnet model.

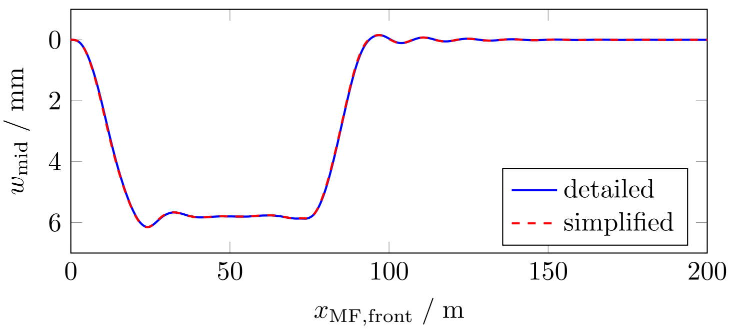


Figure 10: Deflection of a single guideway element at mid span versus position of the foremost simplified magnet force obtained with the detailed magnet model and the simplified magnet model.

Conclusions

This publication investigates the degree of detail of spatial magnet force discretization required for reliable analyses of maglev vehicle and guideway dynamics. Maglev vehicle dynamics simulation models often use fast-computable magnet models providing concentrated substitute magnet forces to approximate the actually continuously distributed magnetic field. However, to the best of the authors' knowledge, no analysis has been published yet showing that this simplification is a valid assumption. Therefore, the novelty of this contribution is the simulative investigation of the high-speed maglev train Transrapid TR08 regarding the influence of different magnet force distributions along the levitation magnets on the behavior of the coupled vehicle-guideway dynamics while the vehicle is traveling along the guideway.
For this purpose, two different magnet force discretizations are compared: a coarse one with one magnet force per half magnet, and a fine one with one magnet force per pole. It is shown that a coarse discretization with a single concentrated substitute magnet force per half magnet is a sufficient approximation when mechanical vehicle and guideway dynamics are in focus and if the magnet model computing this single force provides a sufficiently accurate representation of the magnet dynamics. The used magnet model from [4] proves to fulfill this requirement. There are minor differences in the internal magnet dynamics like voltage or current due to the simplifications of the simplified magnet model providing one force per half magnet with respect to the detailed model providing one force per pole. However, the mechanical vehicle and guideway dynamics turn out to be nearly identical for the simplified and the detailed model.
This is an important and relieving result, because the simplified magnet model providing forces with a coarse discretization has significantly shorter simulation times, about a factor of 100, than the detailed model with a fine discretization. Such detailed magnet models with fine magnet force distributions thus are unsuitable for application in large vehicle models for vehicle dynamics simulations. Instead, the fast-computable simplified magnet model with one force per pole can be used for this purpose, allowing much faster simulations with hardly any loss of quality in the relevant quantities. However, the simplified magnet model has to map the magnet physics sufficiently accurately, of course.

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