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Development of a New Vertical Dynamic Model of a Rail Vehicle for the Analysis of Ride Comfort

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Abstract: The rail vehicle industry wants to produce vehicles with higher speeds, to maintain and increase its market share. However, when the speed of the vehicle increases, it may have an undesirable effect on ride comfort, in terms of ride dynamics. Recent developments towards lighter and faster vehicles make the problem of ride comfort at higher speeds increasingly important. Focusing on the behavior of flexible rather than rigid body behavior should not be neglected when designing long and light car bodies. There are several approaches to incorporate body flexibility in multibody simulations and they have some superiorities and weaknesses. In this study, an efficient and accurate vertical dynamic model for the ride comfort analysis is developed and implemented in a commercial object-oriented modeling (OOM) software DYMOLA (2015 FD01) which uses the open-source code MODELICA. This model includes car body flexibility with the assembling of a rigid body approach. The developed model is compared to a three-dimensional vehicle model in the commercial VAMPIRE software (Pro V5.50) at different velocities. For the vertical ride comfort analysis, the ISO 2631-1 standard was used for both the developed model and the three-dimensional model. The results are presented as acceleration history and a^{wrms}—weighted r.m.s (root mean square) of accelerations—as required by the standard. The developed model has shown its feasibility in terms of its efficiency and accuracy for the vertical ride comfort analysis. The accuracy of the model is evidenced by the fact that the car body vibration level at high speeds shows minor differences compared to the results of the VAMPIRE, which is a validated commercial software in the area of rail vehicle dynamics. The approach involving the assembly of rigid bodies is applied for the first time for high-speed trains in dynamical modelling, with flexible car bodies for ride comfort analysis. Furthermore, it can be used for parametrical studies focusing on ride comfort, thereby offering a quite beneficial framework for addressing the challenges of ride comfort analysis in high-speed rail vehicles. Improvements for and analyses of other aspects are also possible, since the optimization and other useful libraries are readily available in DYMOLA/MODELICA.

Keywords: rail vehicle; dynamic model; high speed; ride comfort; object-oriented modeling

Citation: Çati, Y.; Düzgün, M.; Kracht, F.E. Development of a New Vertical Dynamic Model of a Rail Vehicle for the Analysis of Ride Comfort. *Appl. Sci.* **2024**, *14*, 3848. https://doi.org/10.3390/app14093848

Academic Editors: Peter Gaspar and Junnian Wang

Received: 27 March 2024
Revised: 22 April 2024
Accepted: 25 April 2024
Published: 30 April 2024

1. Introduction

Transportation by railway has seen a continuous increase due to its safe, comfortable and high-speed service. The travel speed of rail vehicles has risen with the improvements in new technologies. The need to remain competitive and be competitive in the future is also a driver for these improvements. However, while traveling at high speeds, a significant issue arises, namely the increase in vibrations that affect the rail car body and passengers due to track irregularities. Therefore, comfortable and safe transportation at higher speeds has become an important engineering problem to be solved [1–4].

Ride comfort needs to be considered both in the design and evaluation phases of a rail vehicle to overcome the above problems. This is because the vibration behavior of a rail vehicle, and thus the ride comfort, is affected by track irregularities (as excitations) and dynamic characteristics of the rail vehicle. The dynamic characteristics of rail vehicles, at this stage, are significantly important, with the increasing use of advanced materials in the design of light rail vehicles. Structural stiffness—which changes with lightweight construction—accounts for a large part of the vibration level [4].

Most rail vehicles have a body-bending frequency close to 10 Hz, and, unfortunately, the human body is very sensitive to the frequency range of 4 to 10 Hz [5–7]. This means that, in addition to the rigid car body vibrations, the flexural vibrations of the car body must be also considered in the analysis of ride comfort.

There are two methods to evaluate the dynamic behavior and ride comfort of a rail vehicle: measurements and simulations. Measurements are not always possible during the design phase of a new vehicle and are usually very expensive to perform. Therefore, simulations based on dynamic models of rail vehicles provide a good way to predict rail vehicle behavior. Apart from that, dynamic models of rail vehicles form the basis for comfort optimizations and for many other areas, such as train traction systems [8–10]. Finally, they can reduce the workload and costs of experiments by providing valuable insights into rail vehicle behavior.

However, simulations of complex models can take quite a long computation time, depending on the analysis. In some cases, modeling the system in a smarter way for a specific analysis, i.e., not the complex model with full characteristics, is a good approach for computational efficiency. After building an accurate model, it is usually necessary to conduct parametrical and optimization studies targeting the improvements in ride (vertical and/or lateral) dynamics through modifications of suspension parameters using the model. For modern rail vehicles, it is also important to implement the most suitable ride and suspension control algorithms. As an example, in a recent study [9], a dynamic model of a rail vehicle was built to improve the ride comfort level using secondary suspension control algorithms. These algorithms require fast and accurate dynamic models. As mentioned above, the speed of rail vehicles is increasing, leading to more complex ride conditions. Consequently, there is a need to address numerous configurations for examination.

In terms of modeling of a car body for vibration analysis, there are three approaches that consider flexural vibrations, as follows:

1. Modelling the entire car body frame with the finite element method (FEM).
2. Using the free-free beam method (partial differential equation).
3. Assembling rigid bodies with the torsional stiffness elements by distributing the mass of the car body frame (ordinary differential equations—ode).

Finite element method has a great accuracy in the calculation, but this method is too complex for computational efficiency. The method becomes especially complex when the full vehicle model with a large number of degrees of freedom (DoF) is included in the analysis [11,12].

The beam method was first used by Suzuki to analyze the car body flexibility of rail vehicles [13]. After that, this method was used in several studies, and it has been shown that the approach has a good agreement in the appropriate frequency range [7,14,15]. In this method, the car body is presented as a Euler–Bernoulli beam with a constant profile section, including mass, length, moment of inertia (pitch axis) and the bending modulus parameters. However, this method uses partial differential equations and the solution is more time-consuming than ordinary differential equations.

Assembling rigid bodies is used for practical reasons, such as analyzing ride quality and comfort in the frequency range of interest. The method has been used in several studies for long and heavy vehicles, to predict the responses of the car body [16,17]. Apart from that, the method is used for the dynamic behavior analysis of freight vehicle car bodies [18]. The assembling of rigid bodies is not as accurate a method as the finite element and beam methods in calculating the body dynamic displacements, but it enables engineers to analyze the car body dynamic responses in an easy and efficient way within a moderate accuracy range. This method is used in the current study to build a vertical dynamic model of a rail vehicle that incorporates car body flexibility for ride comfort analysis. The approach is novel and has the advantage of replacing a complex three-dimensional model with a simplified yet accurate model that specifically targets vertical dynamics behavior for a fast ride comfort analysis.

The main purpose of the study is to develop a high-speed rail vehicle model with flexible car body characteristics for ride comfort analysis, using the assembling of rigid bodies approach in an OOM environment, so that the model can be used for analysis in an efficient and accurate way with a low computational cost. A new methodology and the rail vehicle model can be useful, considering the challenges that modern high-speed rail vehicles need to face. This study consists of two phases (see Figure 1). Firstly, real track irregularity data and rigid car body models are created and simulated. After that, a flexible car body model is built with DYMOLA and compared to the flexible model of the same vehicle in VAMPIRE [19]. The validation process is realized using VAMPIRE. There are significant advantages to validating the object-oriented model using a model in VAMPIRE, which is validated using experiments. Also, the commercial software is specifically designed for rail vehicle dynamic analysis. Therefore, it can be used to generate a variety of test data to compare the results of DYMOLA. The simulations were performed in a time domain and different travel speeds were considered. The results suggest that the DYMOLA model has good agreement, compared to VAMPIRE, in terms of car body-related ride comfort analysis. In this study, it is shown that the assembling of rigid bodies, combined with OOM, can be beneficial in providing moderately accurate and efficient analysis in the design phase of high-speed rail vehicles, when the model is enhanced with a suitable mathematical approach, e.g., a flexible car body approach.

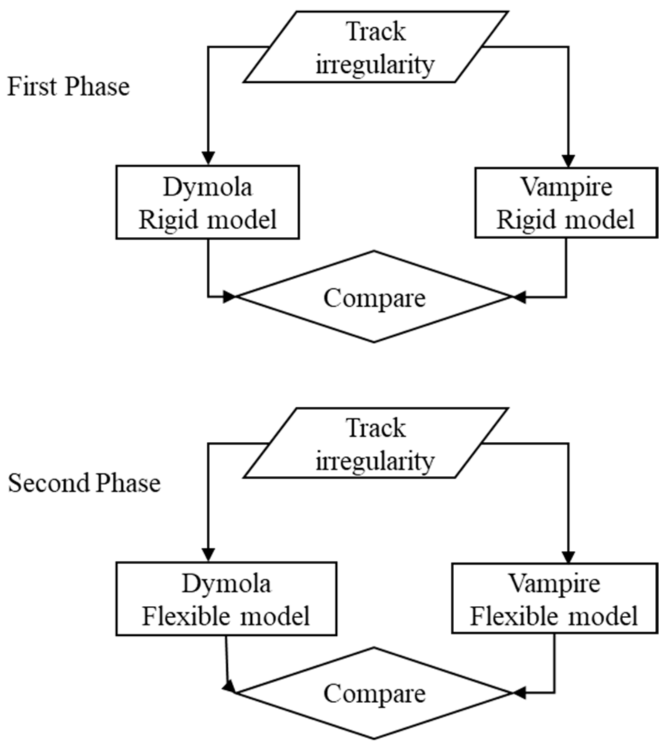

Figure 1. Methodology of the study.

2. Modeling of Rail Vehicles

DYMOLA and VAMPIRE models were built for the time domain analysis because the ride comfort analysis in ISO 2631-1 standard requires the time history of accelerations from the middle of the car body's floor [20]. Rail vehicle (from here on, this term will be used instead of high-speed rail vehicle) parameters and track irregularity data of the models were taken from the VAMPIRE library (see Table 1 for physical and geometrical parameters of the vehicle model). Measured track irregularity data, available in VAMPIRE, were used as an input in both models. Also, for both models, it was assumed that track and wheel stiffness had a negligible effect on the vertical ride comfort analysis in the frequency range of interest, as this had been demonstrated in previous studies [6,21]. The rigid DYMOLA model, in the first phase, had six rigid degrees of freedom. After comparing the results of the DYMOLA and VAMPIRE models, a DYMOLA model with eight rigid degrees of freedom (the flexibility of the car body was modelled using the assembling of rigid bodies method) was created and simulated. Also, the VAMPIRE model, with a flexible car body (the flexibility was modeled with a built-in software beam method) was simulated, for comparison in the second phase. Details of the assembling of the rigid body method, for building the flexible DYMOLA model, are described in Section 2.3. The resulting data are acceleration histories and filtered values of accelerations, using the ISO 2631 method, for the ride comfort analysis. Comparisons were undertaken in terms of these values.

Table 1. Geometrical and physical parameters of the rail vehicle.

Parameter	Value	Unit
m_c—car body mass	34,000	kg
I_c—car body moment of inertia	1.7×10^6	$kg{\cdot}m^2$
m_b—bogie mass	3000	kg
I_b—bogie moment of inertia	2000	$kg{\cdot}m^2$
k_θ—stiffness of the torsional spring	3.7×10^5	kN·m/rad
k_1—stiffness of the primary suspension	5000	kN/m
c_1—damping of the primary suspension	30,000	kN·s/m
k_2—stiffness of the secondary suspension	750	kN/m
c_2—damping of the secondary suspension	70	kN·s/m
$f_{bending}$—bending frequency of the car body	9.6	Hz
bs—bogie semi space	8.75	m
ws—wheel semi space	1.25	m
L—car body length	24	m

2.1. Modeling of Rail Vehicles in DYMOLA (Dynamic Modeling Laboratory)

Schematic representations of rigid and flexible vehicle models are shown in Figure 2. The DYMOLA software (dynamic modeling laboratory) was used for OOM of the rail vehicle. A feature of DYMOLA (and also of the OOM approach) is that the models in the user interface of the software explicitly represent the physical description of the system, rather than a mathematical description, i.e., the equations of the system (see Figure 3 for the rigid vehicle model and bogie model). The main components in the figure, such as the car body mass, suspension and track irregularities, can be seen explicitly, and quick modifications/improvements are possible within this approach. The other main feature of DYMOLA is that it is based on MODELICA, which is an open-source code for dynamical system modeling. MODELICA (and DYMOLA) has several libraries, such as multi-body dynamics, hydraulics, optimization, etc. Also, these libraries can be used in combination, for example with control and/or optimization algorithms focusing on various investigations related to the rail vehicle dynamics, whereas this is not possible in VAMPIRE. The individual objects are set-up with necessary variable assignments and then assembled to form a technical system [22]. The coordinate system was defined by the world component, and it is visible in top left of Figure 3. Gravity is in the direction of the negative y-axis. The x-axis is positive to the right presenting the longitudinal direction. Two bogies of the vehicle were named as front and rear bogies.

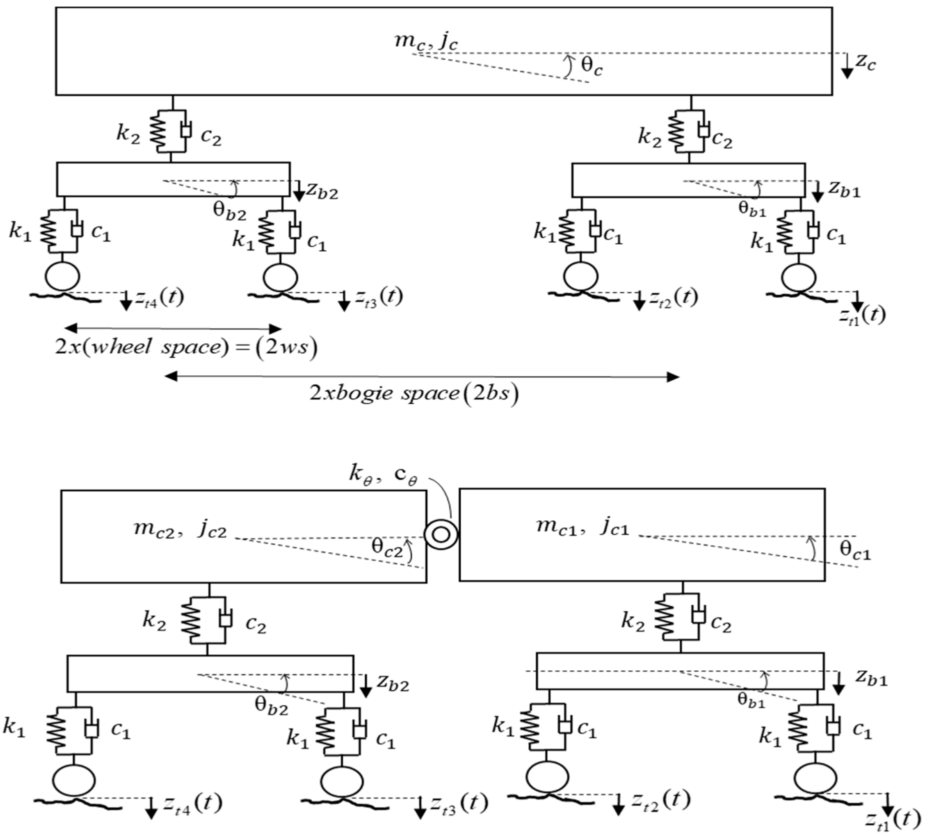

Figure 2. Schematic representations of models. Top: rigid DYMOLA model, bottom: flexible DYMOLA model.

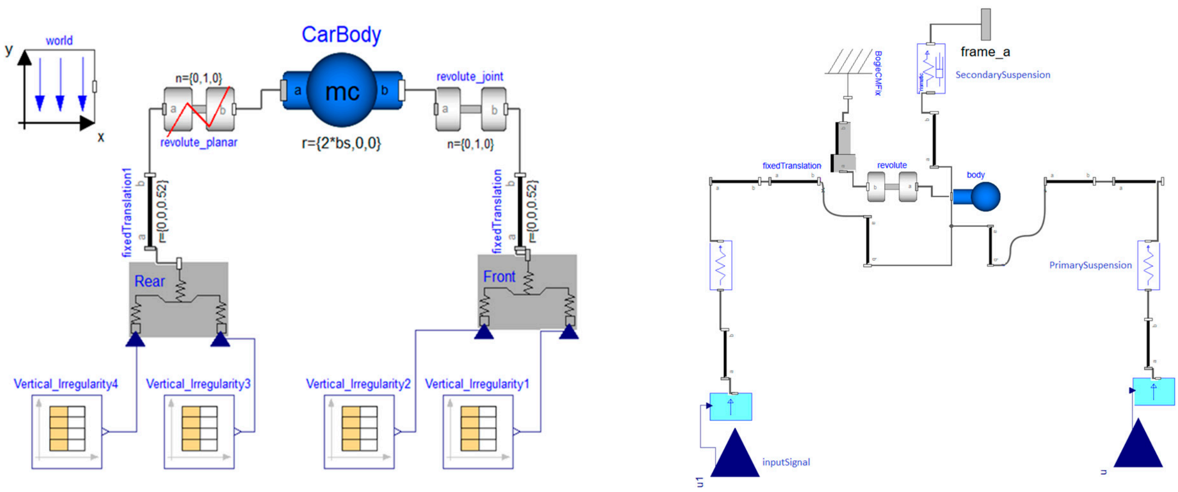

Figure 3. Components of rigid DYMOLA model and bogie component of the model.

The flexible rail vehicle was also modeled in the same way as the rigid rail vehicle, but the car body was divided into two bodies with the revolute joint and torsional spring-damper components, so that the flexibility of the car body was included in the model. A virtual absolute acceleration sensor was placed in the center of the car body (see Figure 4).

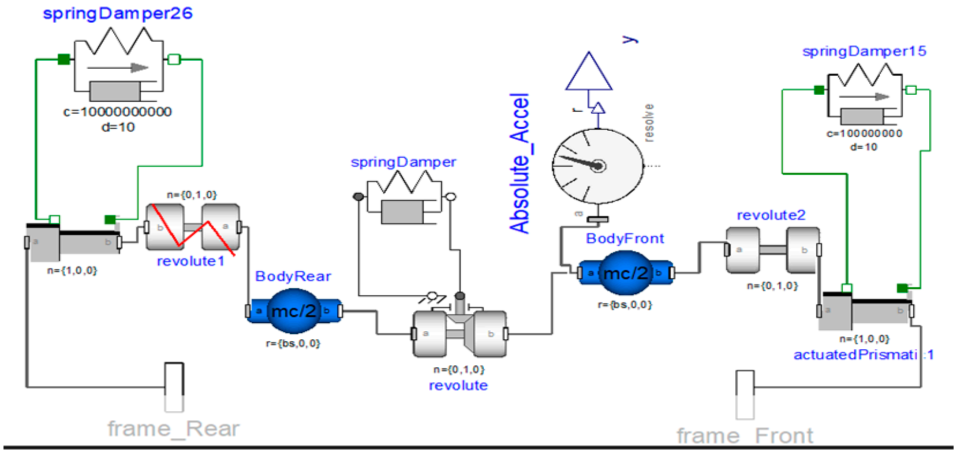

Figure 4. Detailed view of the car body of the flexible DYMOLA model.

The torsional spring and torsional damper coefficients connecting the half car bodies were calculated using the method explained in Section 2.3. Prismatic joints on both sides of the car body were used to limit movement in the horizontal direction.

2.2. Modeling of Rail Vehicles in VAMPIRE (Vehicle Analysis Modeling Package in the Railway Environment)

VAMPIRE software (vehicle analysis modeling package in the railway environment) was used for the three-dimensional multi-body modeling and simulation (MBS) of rail vehicles. For the validation of simulation results from the VAMPIRE software, different methods are used by special test facilities and equipment [18]. Therefore, this software was chosen for the software validation of the DYMOLA model.

A four-axle rail vehicle with a flexible body structure was available in the VAMPIRE library and was considered appropriate for the study. The three-dimensional model of the vehicle, with 47 DoF in VAMPIRE, is shown in Figure 5. The rail and wheel profiles in this model are UIC 60 and S1002, respectively. The track in the model has the standard gauge, which is 1435 mm (distance between inner faces of the left and right rail).

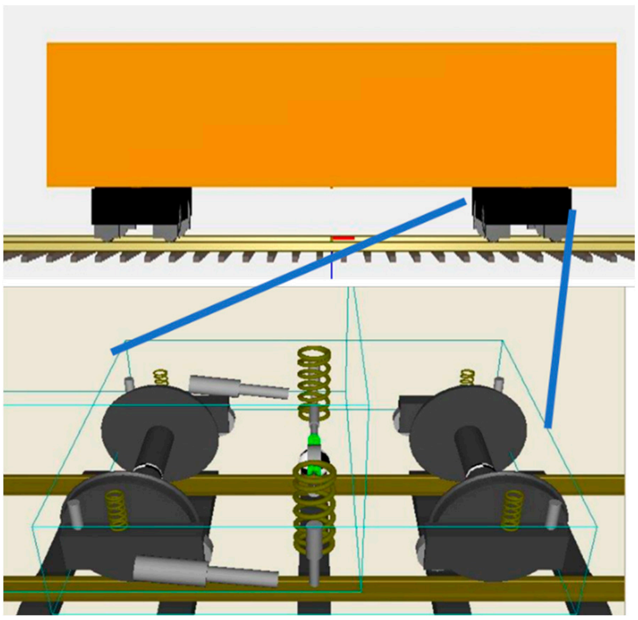

Figure 5. Four-axle passenger vehicle model built in VAMPIRE.

A bogie of this vehicle had two wheelsets and vertical, lateral and longitudinal suspension elements. The model of the bogie is also shown in Figure 5. Each element/component in the model had positional and physical parameters. The frequency of the first bending mode of the car body was 9.6 Hz, which was embedded in the VAMPIRE model. The flexible car body was modeled (embedded already in the software) using the beam method in VAMPIRE. The flexibility feature was enabled active for the flexible vehicle simulation and disabled for the rigid vehicle simulation. A virtual acceleration sensor was set on the center of the car body. The rigid body option was chosen for track, wheels and bogies. Measured track irregularities in VAMPIRE have a tabular structure that can be used directly in a time domain analysis.

2.3. Assembling of Rigid Bodies

In this study, two rigid bodies were connected by torsional spring to simulate the vertical bending motion of the car body (see Figure 6). The flexible model of the car body had two rigid masses (long and slender beam) with their moments of inertia. Also, one generalized coordinate, θ, was assumed because of the symmetry in the longitudinal direction. The equation of motion was derived using Lagrange's equation [23]. The position vectors of the front and rear car body halves were calculated as follows:

$$\begin{aligned}\vec{r}_F &= \tfrac{L_h}{2}\cos\theta\mathbf{i} + \tfrac{L_h}{2}\sin\theta\mathbf{j} \\ \vec{r}_R &= \tfrac{3L_h}{2}\cos\theta\mathbf{i} + \tfrac{L_h}{2}\sin\theta\mathbf{j}\end{aligned} \tag{1}$$

where $\vec{r}_i$ is the position vector for the center of the front and rear half of car body, the subindex h is used for the word "half" and L is the length of the car body. The kinetic energy and potential energy of the whole car body, using the position vectors (1) and the definition of the moment of inertia, is calculated as follows:

$$T = \frac{1}{3}m_{c,h}\,L_h^2\left(\dot{\theta}\right)^2 + \; m_{c,h}\,L_h^2\left(\dot{\theta}\right)^2\sin^2\theta, \quad I_h = \frac{m_{c,h}\,L_h^2}{12}$$

$$V = \frac{1}{2}k_\theta(2\theta)^2 = 2k_\theta\,\theta^2 \tag{2}$$

where T is the kinetic energy, V is the potential energy of the system, m_c is the mass of car body and I is the moment of inertia. Due to the symmetry, a rotation of θ caused a 2θ change in potential energy in total. This assumption was used in the potential energy equation.

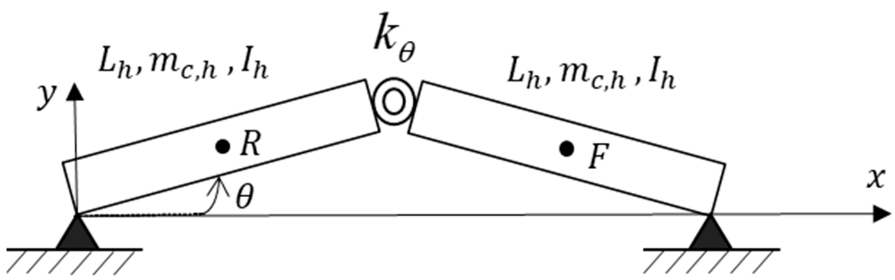

Figure 6. Schematic representation of the assembling of rigid bodies.

Substituting the energy terms into the Lagrangian formulation yields the following equation of motion:

$$\left(\frac{2m_{c,h}\,L_h^2}{3} + \; 2m_{c,h}\,L_h^2\;\;\sin^2\theta\right)\ddot{\theta} + \; 2m_{c,h}\,L_h^2\left(\dot{\theta}\right)^2\sin\theta\;\;\cos\theta + 4k_\theta\,\theta = 0 \tag{3}$$

where k_θ is the stiffness of the torsional spring connecting the car body halves. After linearization, the nonlinear terms, with the assumption of small displacement, were arranged in the equation of motion (3); the linearized equation of motion became, in implicit form, as follows:

$$\ddot{\theta} + \frac{6k_\theta}{m_{c,h}\,L_h^2}\theta = 0 \quad (4)$$

The first bending frequency of the car body was used to determine the stiffness of the torsion spring in the flexible rail vehicle model in DYMOLA. Therefore, the influence of flexible body on vertical ride comfort was included in the simulation.

The damping coefficient was quite complex to determine, and, for rail vehicle car bodies, whose natural frequency is between 8–12 Hz, the structural damping is negligible, according to a previous study [18]. Therefore, it was neglected in this study.

3. Ride Comfort Evaluation

Comfort, which is a part of well-being, is disturbed by various disturbances in the physiological and physical environment (movements, temperature, noise, seat characteristics, etc.) [14]. A recent study [24] on metro vehicle comfort investigated the issue in a more comprehensive way, by considering ride dynamics, thermal comfort, humidity and illuminance. They suggested that these factors should also be considered together with ride dynamics to increase the attractiveness of the railway system. For example, the EN 13129:2016 standard [25] sets comfort parameters for air conditioning in passenger compartments of railway vehicles, and it outlines conditions, performance values and measurement methods. The ride comfort in dynamical terms represents the comfort level of the passenger who is affected by the vibrations from any direction during the travel [26]. These vibrations are mainly determined by the direction, frequency and amplitude of the vibration.

In this study, a widely used method for comfort evaluation was used: the method of the ISO 2631 standard. According to ISO 2631, a frequency range of 0.5–80 Hz must be considered [20]. Humans are most sensitive in the frequency range of 4–10 Hz, and this range is significant for comfort evaluation in the vertical direction [27]. ISO 2631 states that measurement data gathered from the floor in the middle of the car body can be used for ride comfort evaluation in rail vehicles.

This evaluation method uses the frequency-weighted r.m.s (root mean square) accelerations, according to the following equation:

$$a^{wrms} = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{0.5} \quad (5)$$

where a^{wrms} is the root mean square of weighted accelerations, $a_w(t)$ is the weighted acceleration as function of time and T is the duration of measurement in seconds. The weighting filter, according to ISO 2631, for vertical comfort evaluation is as follows:

$$W_k(s) = \frac{(s + 2\pi \cdot f_3)}{s^2 + \frac{2\pi \cdot f_4}{Q_4} \cdot s + (2\pi f_4)^2} \cdot \frac{\left(s^2 + \frac{2\pi \cdot f_5}{Q_5} \cdot s + (2\pi \cdot f_5)^2\right)}{s^2 + \frac{2\pi \cdot f_6}{Q_6} \cdot s + (2\pi \cdot f_6)^2} \cdot \frac{2\pi f_4^2}{f_3} \quad (6)$$

where $W_k(s)$ is the vertical comfort filter as a transfer function, and its variables, used in the function, are given in Table 2. The calculation scheme of this filter is embedded in the VAMPIRE software.

Table 2. Parameters of the vertical frequency weighting filters (f_i's are in Hz).

Weighting	f_3	f_4	f_5	f_6	Q_4	Q_5	Q_6
W_k (ISO)	12.50	12.50	2.37	3.35	0.63	0.91	0.91

The values used in the transfer function are the frequency values, represented by f_i, and the resonant quality factor values, represented by Q_i. Together, they determine the frequency weighting process. The levels of the ride comfort according to ISO 2631 are given in Table 3.

Table 3. Ride comfort levels according to ISO 2631.

a^{wrms} (m/s^2)	Ride Comfort
$a^{wrms} < 0.2$	Very comfortable
$0.2 \leq a^{wrms} < 0.3$	Comfortable
$0.3 \leq a^{wrms} < 0.4$	Medium
$0.4 \leq a^{wrms} < 0.6$	Little comfortable
$0.6 \leq a^{wrms}$	Fairly comfortable

4. Simulation Results and Discussion

The selected track had the maximum service speed of 200 km/h and the data of vertical irregularities taken from VAMPIRE are shown in Figure 7. Journeys of rigid and flexible vehicles were simulated over a 1000 m section of straight track at speeds of 145 km/h and 200 km/h. The vertical accelerations were recorded in the middle of the car body.

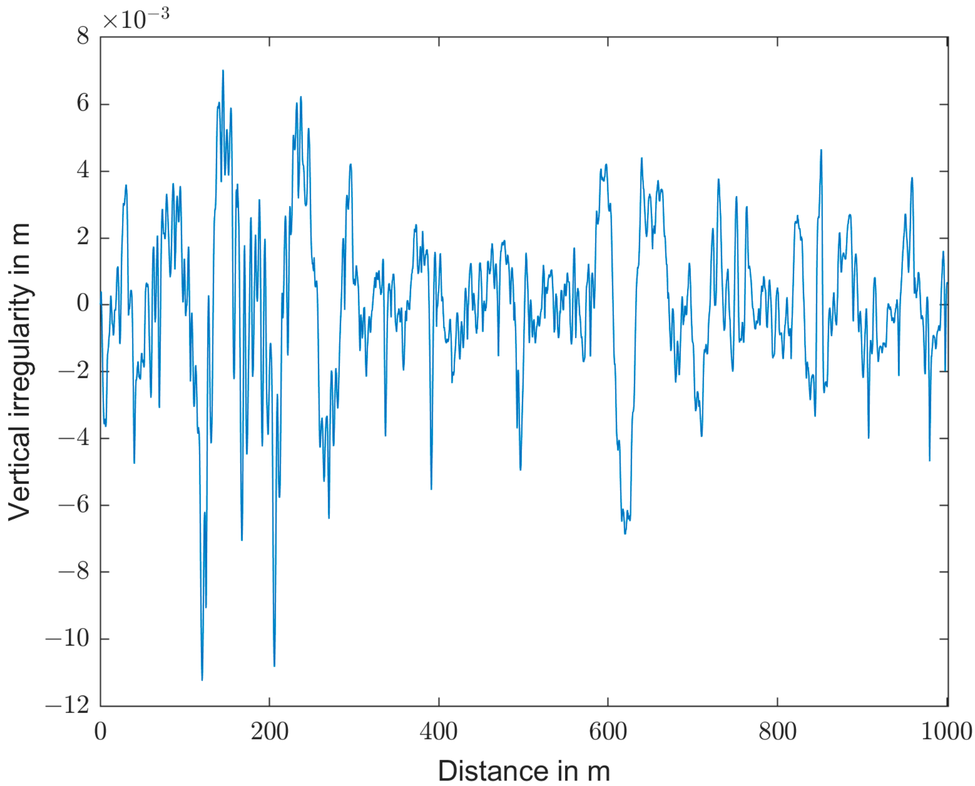

Figure 7. Measured track irregularity data for 1000 m section of a track.

DYMOLA uses the DASSL algorithm (differential/algebraic system solver) for the mechanical system analysis. The tolerance of the integration in DYMOLA is 0.0001, which was proven to be optimal.

The integration algorithm used in VAMPIRE is the Euler–Cromer method, with a time step of 0.001. The Euler-Cromer method was chosen because it is a method proposed by VAMPIRE for this type of analysis, which is a transient response analysis (time domain response of a vehicle to track irregularities). The effect of body flexibility is considered in the transient response analysis.

The output time step was chosen as 0.02, to enhance computational efficiency and facilitate a reasonable comparison between the results of the two software. The stiffness of the track (including the rail) does not play a significant role in simulations when investigating ride comfort and frequency range of interest [7]; therefore, the track was chosen to be rigid. Other assumptions for the analysis are as follows:

- Wheels maintain contact with the rails, transferring track irregularities directly to the bogies.
- The vehicle speed is constant during travel.

The results of the simulations of the DYMOLA and VAMPIRE models were compared at speeds of 145 km/h and 200 km/h; in total, the following eight simulation cases were executed:

- DYMOLA rigid vehicle—VAMPIRE rigid vehicle (145 km/h)
- DYMOLA flexible vehicle—VAMPIRE flexible vehicle (145 km/h)
- DYMOLA rigid vehicle—VAMPIRE rigid vehicle (200 km/h)
- DYMOLA flexible vehicle—VAMPIRE flexible vehicle (200 km/h)

In addition, zoom plots for 1 s intervals were provided for each comparison case. The results are shown in the following Figures.

Firstly, the results of rigid vehicles with a velocity of 145 km/h are shown and it can be seen from Figure 8 that the acceleration curves of the two models agreed well. However, the DYMOLA model had slightly higher acceleration values. There was a highest peak at about 4 s of simulation, creating the largest difference between the models in this region in Figure 8 (left). This was an indication of the behavior of a low stiffness structure to a sudden dynamic excitation.

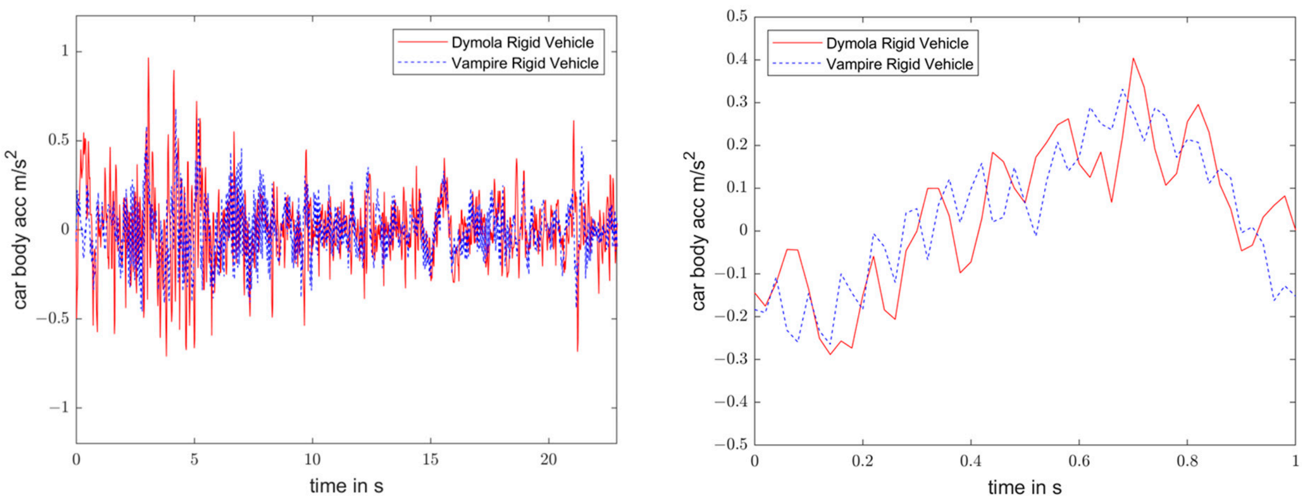

Figure 8. Left: Car body middle acceleration of rigid vehicles at 145 km/h, right: zoom view of 1 s interval.

Subsequently, Figure 9 shows the results of flexible vehicles at a speed of 145 km/h. Again, there was good agreement in terms of vibration tendencies, but the DYMOLA model had higher acceleration values.

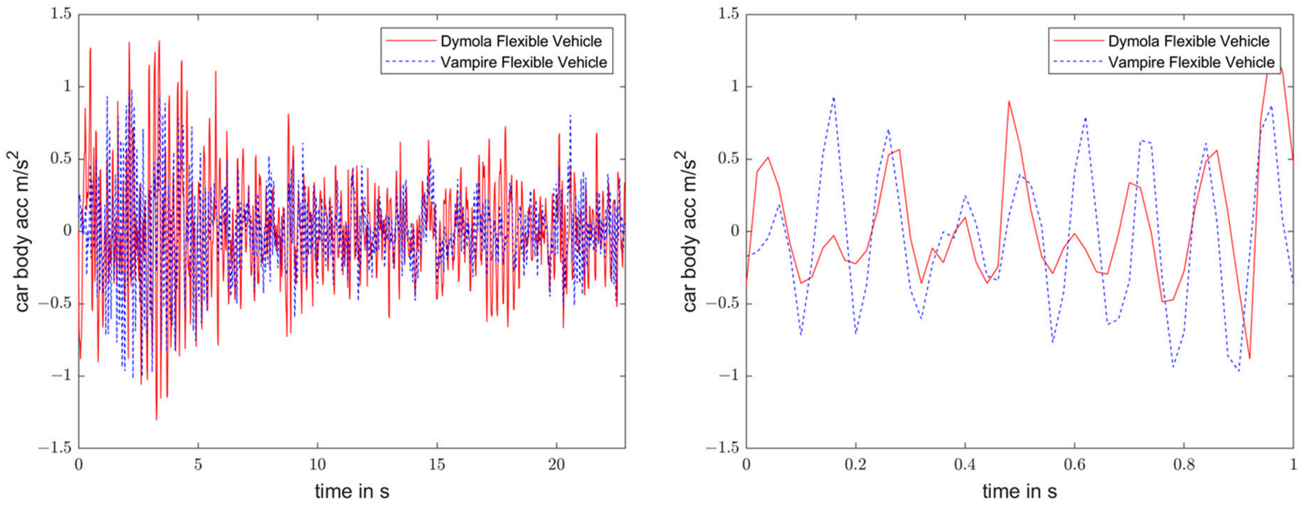

Figure 9. Left: Car body middle acceleration of flexible vehicles at 145 km/h, right: zoom view of 1 s interval.

The travel at a velocity of 200 km/h was simulated for rigid vehicles and the accelerations are shown in Figure 10. The results were in satisfactorily good agreement. However, the DYMOLA model could not capture some of the peaks (especially between 2–4 s), but the vibration trends of both models seemed to be similar in general. Another observation is that there were higher oscillations in the 200 km/h rigid case than in the 145 km/h rigid vehicle case, which was caused by the higher speed, as expected.

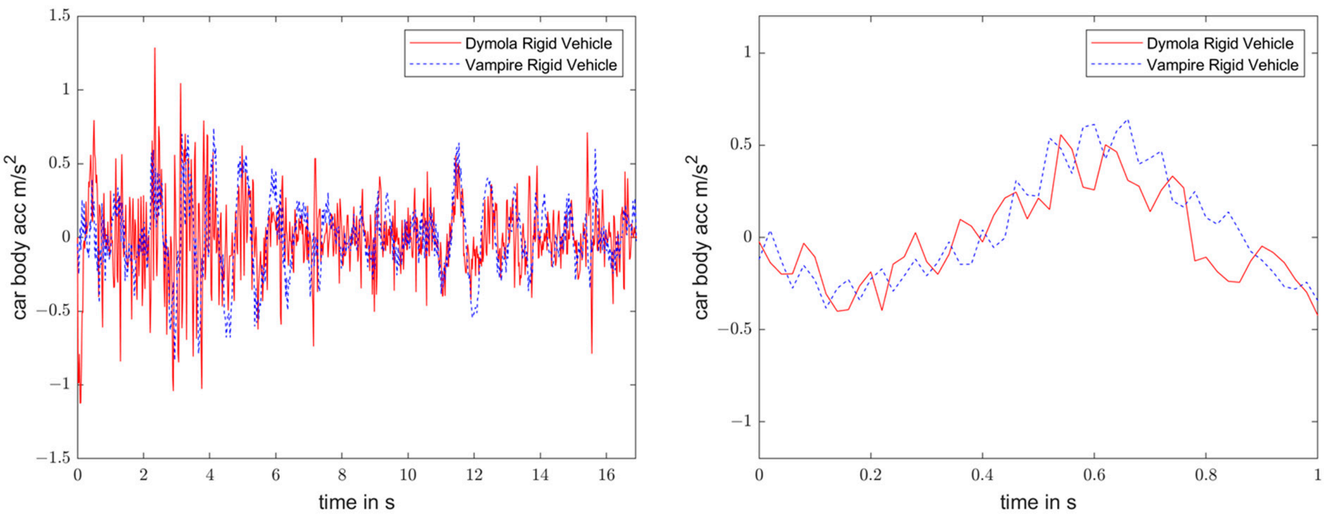

Figure 10. Left: Car body middle acceleration of rigid vehicles at 200 km/h, right: zoom view of 1 s interval.

Finally, flexible vehicles were simulated at 200 km/h (see Figure 11). Both models had higher oscillations and amplitudes than in the 145 km/h flexible case. The vibration trends in this case had better agreement than in previous cases.

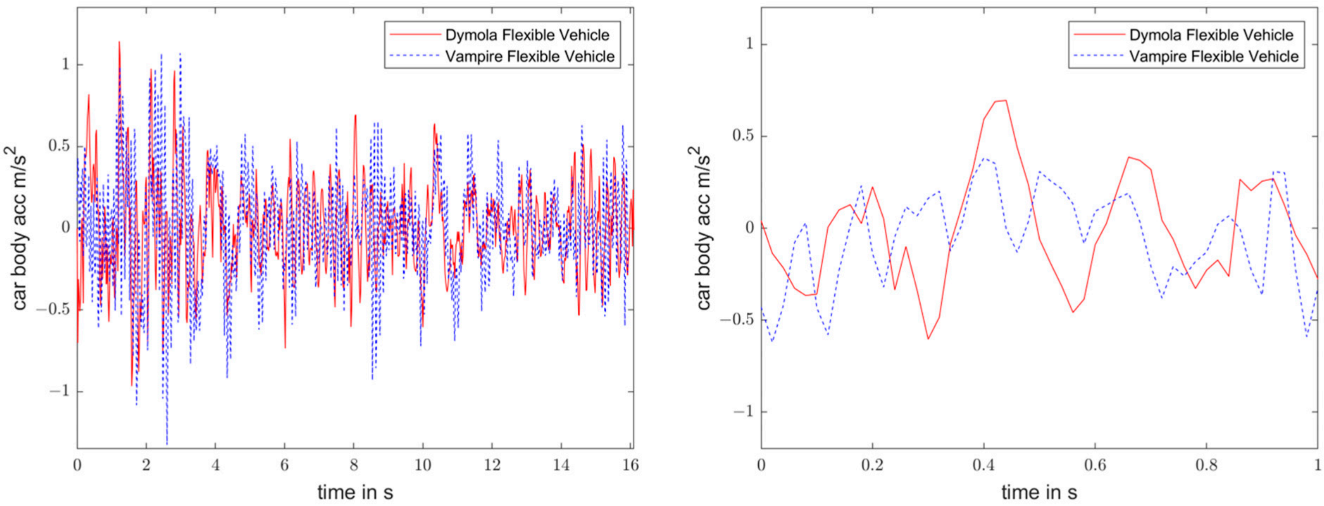

Figure 11. Left: Car body middle acceleration of flexible vehicles at 200 km/h, right: zoom view of 1 s interval.

The comfort weighted r.m.s values of the flexible vehicle models in both software and their differences are shown in Table 4. The weighted r.m.s of accelerations were calculated in VAMPIRE, based on the time history of accelerations using the ISO W_k vertical weighting filter. The difference was smaller at a velocity of 200 km/h than a velocity of 145 km/h. It suggests that the DYMOLA models had greater accuracy at high speeds. The reason for this could be the interaction between the input characteristic (track irregularity data of 200 km/h) and the dynamic system (flexible DYMOLA model), which resulted in a more realistic vibration history at 200 km/h.

Table 4. Comparison of a^{wrms} values of flexible rail vehicles in DYMOLA and VAMPIRE.

Speed	a^{wrms} of DYMOLA (m/s^2)	a^{wrms} of VAMPIRE (m/s^2)	Difference in %
145 km/h	0.225	0.191	17.801
200 km/h	0.293	0.269	8.191

Moreover, it is obvious that, for each case, as the speed increased, the amplitudes and frequency of the accelerations also increased, which in turn led to less ride comfort. All the simulated cases fell into the ride comfort levels of "very comfortable" and "comfortable" based on their weighted r.m.s of accelerations, as can be seen from Table 4. Furthermore, the DYMOLA model had an approximately 20% lower computation time than the VAMPIRE model.

5. Conclusions and Recommendations

In this study, a passenger rail vehicle is modelled with rigid and flexible bodies using the OOM software DYMOLA. The main purpose is to build a dynamic model that allows for a good insight into the vertical ride comfort of a given passenger vehicle configuration in the design phase. For these reasons, simulation results from the developed models are compared with the outcomes of VAMPIRE software (which is capable of conducting complex analysis on rail vehicle dynamics) in terms of computational efficiency and accuracy. Accuracy is ensured by the fact that the a^{wrms} values and general vibration trends in the DYMOLA model are in good agreement with the VAMPIRE model. The multi-body mechanics library of DYMOLA is used for the vehicle models. Linear suspension components are used in the vehicle models. Also, the calculations in VAMPIRE are performed with a three-dimensional configuration. The car body flexibility is modeled by dividing the car body into two equal parts in DYMOLA. The car body halves are connected with a torsional spring to obtain an approximate vertical bending mode behavior similar to the VAMPIRE model.

The results of the study have shown that modeling a rigid car body for the ride comfort analysis yields underestimated results, which is consistent with previous studies. In general, there is a strong correlation between the track irregularity and vibration trends in both models, indicating the accuracy of the models. Peak amplitudes and zoom views indicate that the rigid and flexible models in DYMOLA generally show good agreement with the VAMPIRE results. However, there are differences between the weighted-root mean square of accelerations that may result from variances in modeling approach. Specifically, the VAMPIRE model is three-dimensional, while Dymola is two-dimensional. Also, the car body in DYMOLA is divided into two parts, which may lead to a somewhat oversimplification for the car body behavior. However, the flexible DYMOLA model is simple, fast and represents the main aspects of a more complex rail vehicle model for the vertical ride comfort analysis. Furthermore, using the methodology in this study (object-oriented approach and flexible body modeling), parametric analysis and optimization studies focusing on ride comfort are possible. Using DYMOLA or MODELICA, which is open-source (white box) software, along with their various libraries (especially optimization) we can enhance the design processes for improving system-level performance.

Some recommendations can be given to improve the accuracy of the model according to the results of the study, as follows:

- The frequency response analysis of the model can provide valuable information about the body flexibility in DYMOLA. This paves the way for simulating car bodies with different bending frequencies, which could be a critical advancement for this study. Apart from that, the damping ratio can be adjusted with the help of frequency response analysis, which could be carried out in DYMOLA.
- The car body can be divided into more parts to obtain a more realistic view of the behavior of the car body.
- A three-dimensional model for the analysis of vertical–lateral movements can be developed in DYMOLA.
- Although the robustness of the model for several cases were demonstrated with the experimentally validated VAMPIRE model, further enhancement can be achieved through an iterative process, such that multiple simulation cases or varying parameters are executed in VAMPIRE, allowing for the identification of areas where improvements in the model are necessary.

Author Contributions: Conceptualization, Y.Ç.; Software, Y.Ç.; Visualization, Y.Ç. and F.E.K.; Supervision, M.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: This study was mainly realized by Frédéric Etienne Kracht at the University of Duisburg-Essen (Germany), with the scholarship support of Turkish State Railways (TCDD). First author thanks the Chair of Mechatronics and General Directorate of TCDD for their support. We also acknowledge support by the Open Access Publication Fund of the University of Duisburg-Essen.

Conflicts of Interest: The authors declare no conflict of interest.

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DOI: 10.3390/app14093848
URN: urn:nbn:de:hbz:465-20240611-101553-7