

Roller coaster train dynamics: the effect of the zero-car location

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ABSTRACT — In this work, the influence of the zero-car location of a roller coaster train on its lateral dynamics is investigated. Both an experimental set-up and rigid multibody dynamics simulations are used to study the dynamics of two fundamentally different train designs. Both the experiments and the simulations show that a train that has its zero-car located at the rear of the train experiences less lateral vibrations, yet the difference with trains that have a front-running zero-car is very small. In particular, larger differences are observed when comparing the different train designs with each other. Hence, it is concluded that the influence of the zero-car location on the train dynamics is small and that future efforts aimed at improving a roller coaster train's dynamic behavior can best be focussed at optimizing the roller coaster train's fundamental design.

1 Introduction

Modern steel roller coasters that contain geometrically complex track elements, such as high-speed turns and inversions, have been manufactured since the second half of the twentieth century. During this relatively short history of the modern steel roller coaster, an endless variety of attractions has been developed by manufacturers and theme park operators. Besides the many different track lay-outs that have been realized, the variety in train designs has grown drastically. Important design decisions for the train's configuration are directly dependent on the expected loads. Because the dynamic loads on small so-called junior coasters are low, these roller coasters are typically equipped with simple train designs. On the other hand, high speed thrill rides experience much larger loads, which requires more advanced chassis designs. In particular, these roller coasters are equipped with more sophisticated bearing systems on the main axles and wheel carrier suspensions.

The overall appreciation of roller coasters by the general public is primarily determined by the level of thrill and sensation of the ride geometry in combination with its storytelling and theme. However, in recent years, the experience of manufactures, theme park operators and roller coaster enthusiasts has indicated that also passenger comfort is an important determining factor in a roller coaster's success. For a roller coaster to be well appreciated, its desired experience could be described as "smooth" or "natural" in some sense. Unbalanced lateral forces, i.e. the dynamic forces passengers experience in their sideways direction, are a primary source of discomfort, as they contribute to the unpleasant feeling of "shakiness" or "rattling". Hence, for a comfortable ride experience, it is essential to minimize the lateral forces exerted on the passengers. To this end, the lateral inclination of the roller coaster track, also referred to as banking, is designed such that it minimizes the lateral forces in turns. With an accurate predication of the train's velocity, each track section can be banked such that the average lateral force is close to zero at all times.

However, in practice there will be a certain amount of play between the roller coaster train and track. Trains with a fixed wheel suspension in fact need this play for geometrical reasons, in order to make it through turns. Unfortunately, the presence of this play will allow the roller coaster trains to vibrate continuously, mainly in the lateral direction. Over the years, roller coaster manufactures have developed a large number of different train

configurations in order to cope with this lateral play. There are important differences in the way coaches are connected together to form a train. Also, the way the chassis, axles and wheel suspension assemblies are connected together within one coach varies from design to design. For example, nowadays almost all manufacturers equip their high-speed roller coaster trains with a wheel suspension system that uses pretension to ensure contact between the wheel and the track at all times. Yet, no scientific publications can be found that discuss the influence of roller coaster train configurations on the ride dynamics in general and the lateral vibrations in particular.

In this work, the influence of the zero-car location on the lateral train dynamics is investigated. Typically, each coach of a roller coaster train has a single main axle, either at the front or rear of the coach. This means that at one end of the train, an additional axle is required to support the final coach. This final axle is referred to as the zero-car. In practice, both front-running and rear-running zero-cars are commonly used. It is widely believed that there is a difference in the dynamic behavior between both train configurations, which is likely due to stability considerations.

The purpose of this work is to investigate the difference between front-running and rear-running zero-cars on the lateral vibrations of roller coaster trains. To this end, both experiments on scale models and rigid multibody dynamics simulations are performed with two different train configurations. For both train configurations, experiments and simulations are performed in which the train travels in both directions, thereby in fact changing the location of the zero-car from the front to the rear.

Figure 1 shows a schematic overview of the considered train configurations. In the top configuration, the left and right wheel carriers are fixed rigidly to the main axle, which is allowed to rotate relative to the chassis. In the bottom configuration, the left and right wheel carriers are allowed to rotate relative to the main axle, which is fixed rigidly to the chassis. In both configurations, different coaches are connected together by spherical joints.

The experimental setup and its results are presented in Chapter 2. The simulation model and results are presented in Chapter 3. The most important conclusions are summarized in Chapter 4.

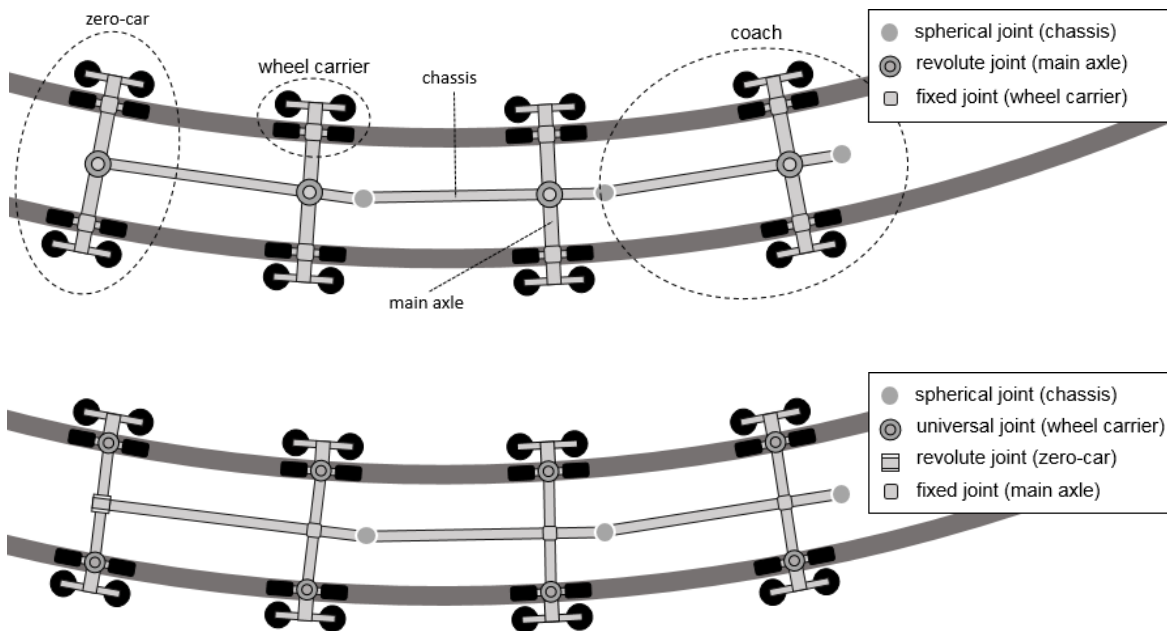


Fig. 1: Considered train configurations: train with rotating main axle (top) and train with rotating wheel carriers (bottom).

2 Experiments

An experimental set-up is constructed out of K'NEX, a commercially available plastic toy construction material. The experimental track consists of a 1.12 m high slope followed by a 2.50 m long straight horizontal test track and a 1.60 m long straight horizontal brake section. The experimental trains both consist of four coaches. All four chassis of a train are equipped with a calibrated (x, y, z) -accelerometer. The total added weight to each coach due to the measurement equipment is approximately 0.87 kg. The mass of a single car and the zero-car are approximately 1.8 kg and 1.3 kg respectively. This results in a total mass of the train of approximately 12 kg.

Although the set-up is constructed from plastic parts, the flexibility of the track and train does not play a significant role. Relatively high stiffness is obtained by implementing a maximum number of triangular structures. As a consequence, it was possible to observe the rigid body behavior of the train fairly well.

In order to get an idea of the experimental set-up, Figure 2 shows one of the trains including all measurement equipment, Figure 3 shows a top view of a chassis of both trains, Figure 4 shows the wheel carrier assembly in more detail and Figure 5 shows one of the trains on the slope.

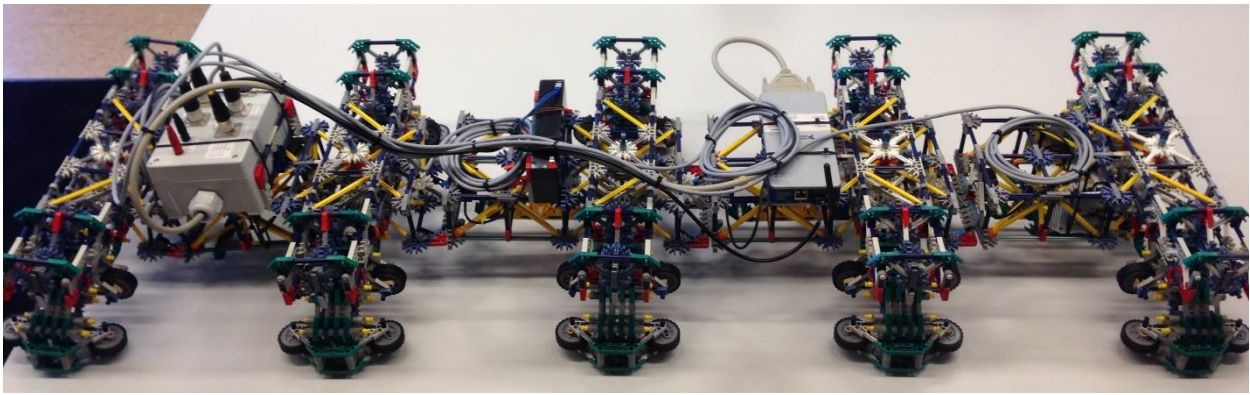


Fig. 2: Train including measurement equipment.

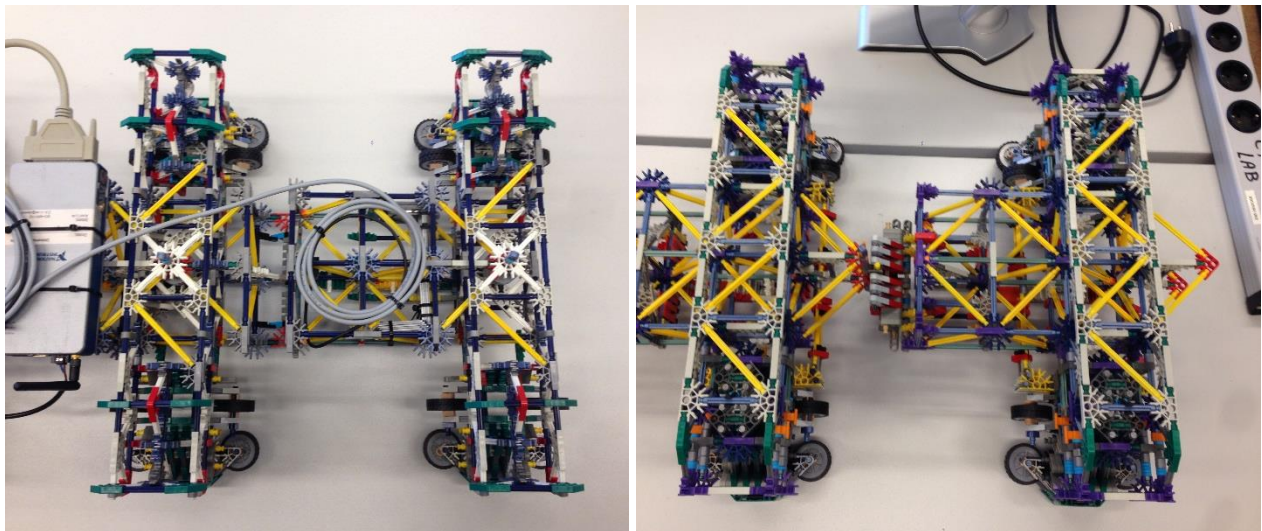


Fig. 3: Top view of the train with a rotating main axle (left) and the train with the rotating wheel carriers (right).

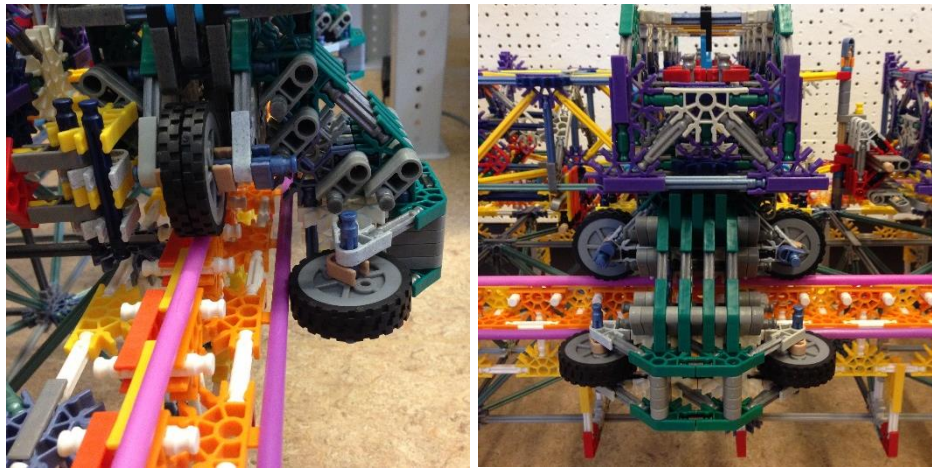


Fig. 4: Wheel carrier assembly in front view (left) and side view (right).

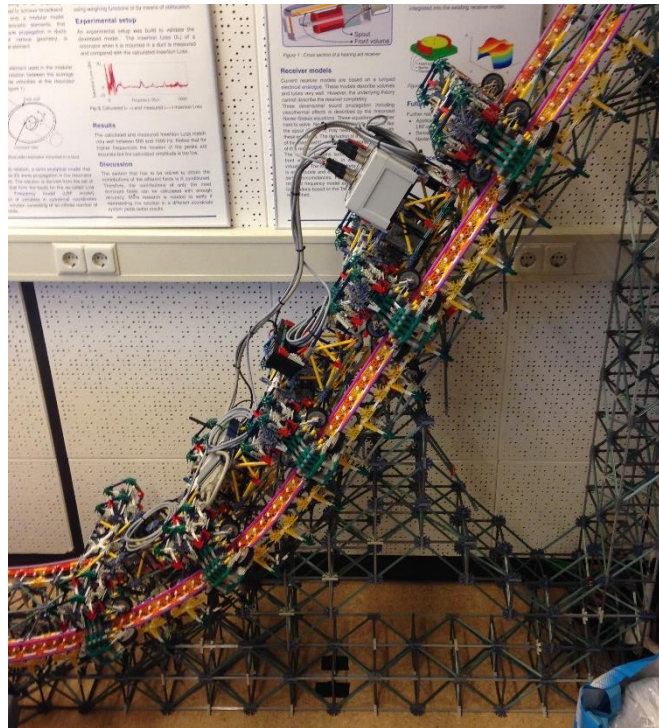


Fig. 5: Train on the slope.

The accelerometers are used to measure the lateral accelerations when the train is traveling across the horizontal test track. For all measurements, the sample rate is 10 kHz. Measurements are performed with both trains, travelling in both directions. For each case, the train is released from two different heights: 0.94 m and 1.12 m. For repeatability purposes, five runs are performed for each set-up. From the measured lateral accelerations on the test track section, the root-mean-square (RMS) value is computed. Figures 6 to 9 show the experimental results. For all configurations, the zero-car is connected to the coach with accelerometer number 4.

From the results, it can be seen that in general the difference between the five test runs is small for each train configuration, such that it can be concluded that the experiments are well repeatable. It can be seen that when the train is released from a larger initial height, the severity of the lateral vibrations does not increase significantly. Looking at the average RMS value of all measurements, it seems that a train with a rear-running zero-car experiences slightly less lateral vibrations. Moreover, it seems that the coach that is connected directly to the zero-car itself vibrates slightly less compared to the other coaches of the same train.

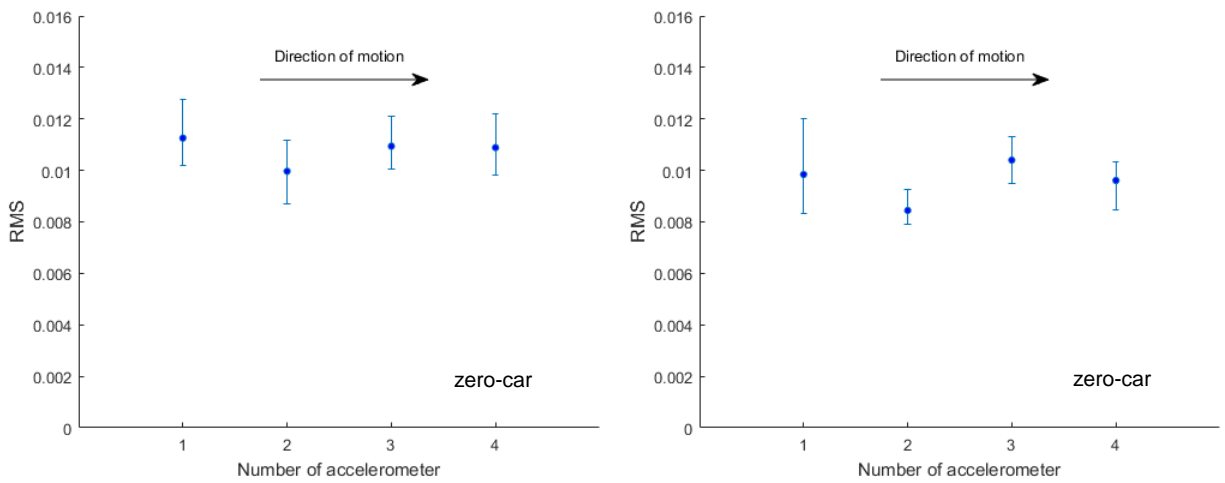


Fig. 6: Train with rotating main axle and fixed wheel carriers. Front-running zero-car. Initial height of 0.94 m (left) and 1.12 m (right).

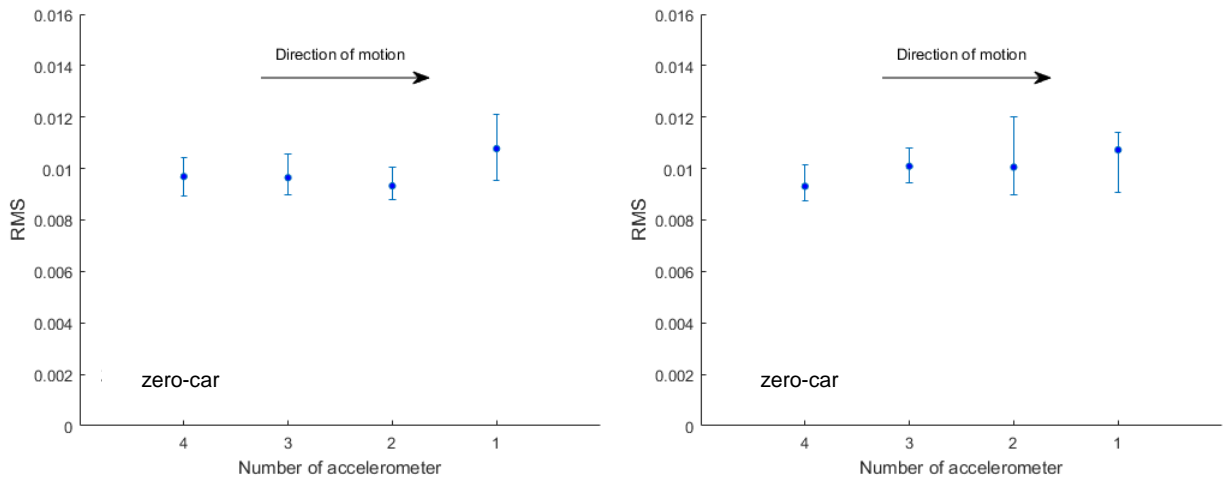


Fig. 7: Train with rotating main axle and fixed wheel carriers. Rear-running zero-car. Initial height of 0.94 m (left) and 1.12 m (right).

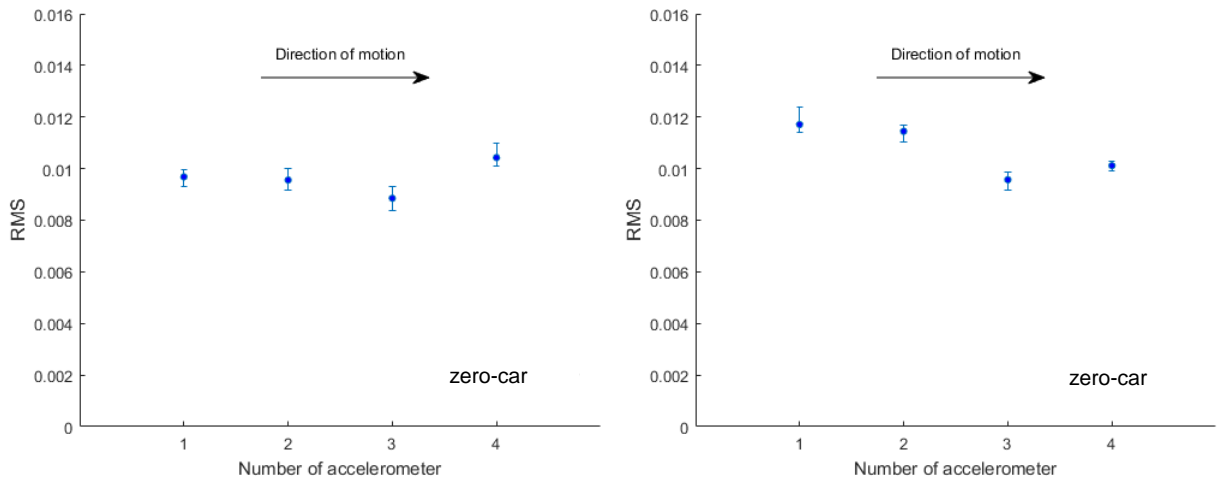


Fig. 8: Train with fixed main axle and rotating wheel carriers. Front-running zero-car. Initial height of 0.94 m (left) and 1.12 m (right).

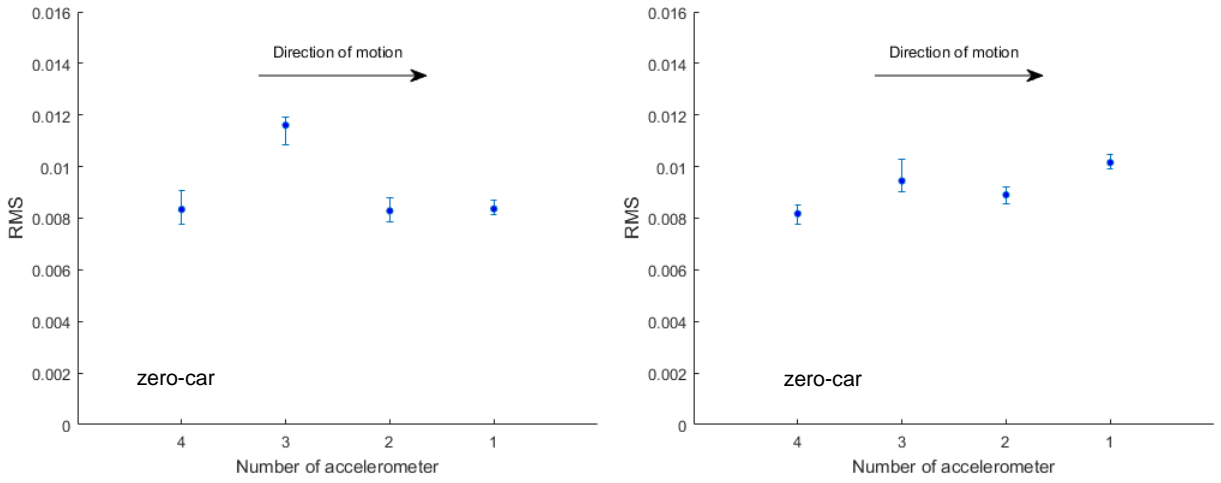


Fig. 9: Train with fixed main axle and rotating wheel carriers. Rear-running zero-car. Initial height of 0.94 m (left) and 1.12 m (right).

3 Simulations

In order to perform simulations of the rigid multibody dynamics of the different train configurations, Simscape Multibody is used, which is an add-on to Matlab/Simulink. CAD models of the two trains were created in SolidWorks and imported in the multibody environment. Figure 10 shows the CAD models of the two trains, where the zero-car is located at the left side of the train.

For running the simulations, a recreation of the track geometry of an existing roller coaster was made in the software package No Limits Coaster Simulator. This track consist of a variety of different track elements, such as vertical loops, corkscrews and a helix. In early simulations, it was observed that different train designs may behave differently as they travel through different track elements. By using a track with a variety of elements more realistic results are obtained, since most actual roller coasters contain a large variety of track elements indeed.

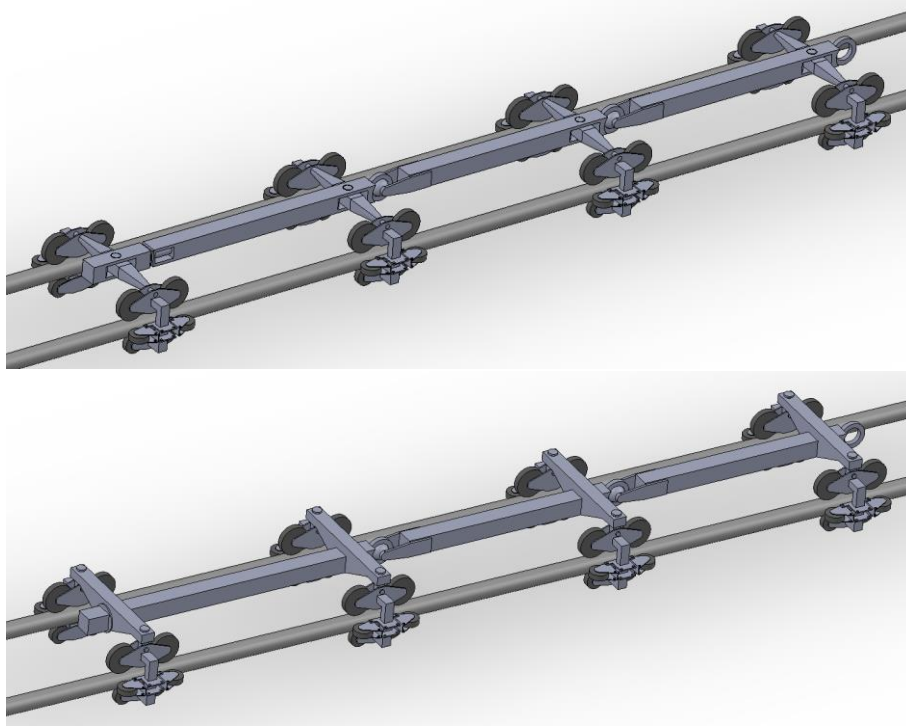


Fig. 10: CAD models of the train configurations: train with rotating main axle (top) and train with rotating wheel carriers (bottom).

The data provided by No Limits is a set of data points along the centerline of the track. These data points contain the position (x, y, z) , the vector pointing in the track's tangent direction \mathbf{F} , the vector pointing from the right track to the left track \mathbf{L} and the vector \mathbf{U} , which is perpendicular to \mathbf{F} and \mathbf{L} . Hence, the set $(\mathbf{F}, \mathbf{L}, \mathbf{U})$ in fact represents the mutual perpendicular unit vectors of a cartesian coordinate frame attached to the center point of the track. With this data and the width of the track, the (x, y, z) -coordinates of the left and right rail are determined.

In the multibody environment, the imported CAD parts of the train were connected with the appropriate kinematic joints, resulting in a complete rigid multibody model of the roller coaster train. The mass of specific parts is increased to ensure that the additional mass originating from the car and its passengers is taken into account. For both trains, it was assumed that the total mass of one coach is approximately 1000 kg, which is realistic for a typical high-speed roller coaster.

For the purpose of multibody simulations, it is common in the industry to use a point-to-curve constraint to connect the wheels to the track. However, due to the possible play between the wheels and the track, this constraint does not represent the real physical behaviour accurately enough. Therefore in this model, a contact model was developed for the wheel-rail contact. At each numerical time increment, this model calculates the contact force

applied to the wheel based on the position and velocity of the wheel and the geometry of the track. If there is no contact between the wheel and rail, the contact force is zero. To ensure realistic velocities along the track, friction is added to the wheels and to the center of mass of each coach. The force applied to the center of mass represents that air drag. Since a contact force model is applied, it is important for the accuracy of the simulation to use a very small time step size. Throughout all simulations, a step size of 0.0001 s was used.

To compare the behaviour of the different trains, four simulations were performed: using both train configurations with both front-running and rear-running zero-cars. In each simulation, the train consists of 7 coaches, which is the same number of coaches the real train has. To give an idea of the overall ride behavior, Figures 11 and 12 show the normal accelerations and lateral accelerations (expressed in g's) of the zero-car for both train configurations in case of a front-running zero-car. It can be seen that the lateral accelerations are in general low compared to the normal accelerations, as it should be for a comfortable roller coaster experience. Both figures show that for both trains the overall ride dynamics is very comparable. However, the train with rotating wheel carriers shows slightly more vibrations compared to the train with a rotating main axle.

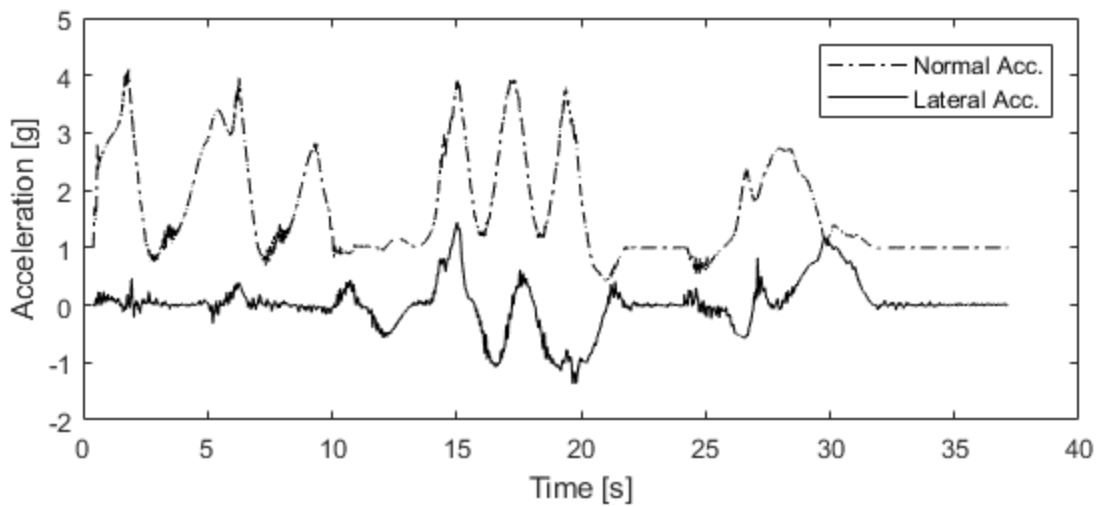


Fig. 11: Train with rotating main axle and fixed wheel carriers. Front-running zero-car.

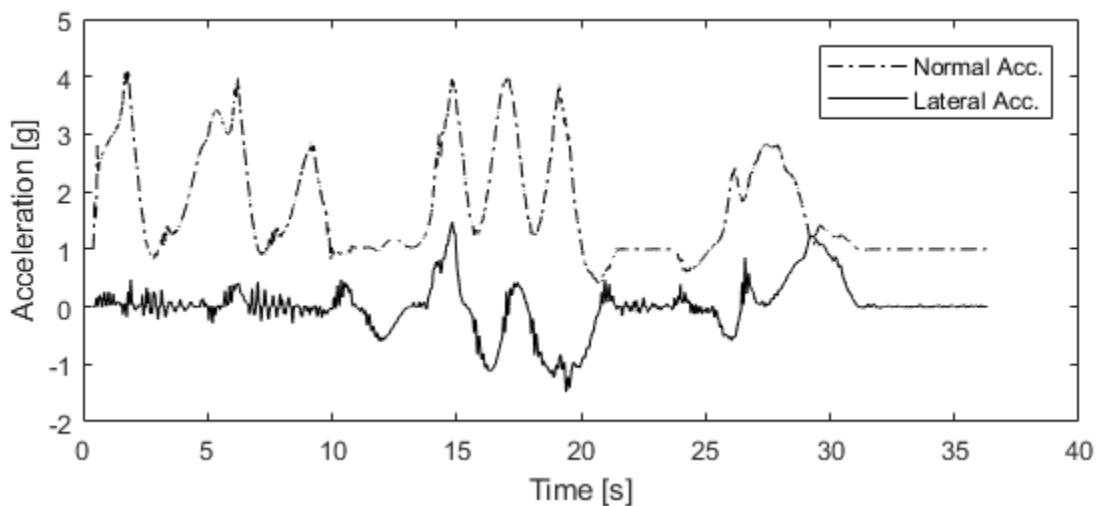


Fig. 12: Train with fixed main axle and rotating wheel carriers. Front-running zero-car.

Figures 13 and 14 show the RMS values of the lateral accelerations of all configurations. Note that in these figures, car 7 is always the front running car. The zero-car is indicated with a circle. It can be seen that for all train configurations, the rear of the train vibrates less than the front of the train. It is observed that the train with the fixed main axle and rotating wheel carriers experiences slightly larger vibrations than the other train indeed. Also from these simulations, it can be seen that for both train designs, the rear-running zero-car trains experience less vibrations than the same trains with a front-running zero-car, although this difference is relatively small. This is a similar observation as was done in the experiment.

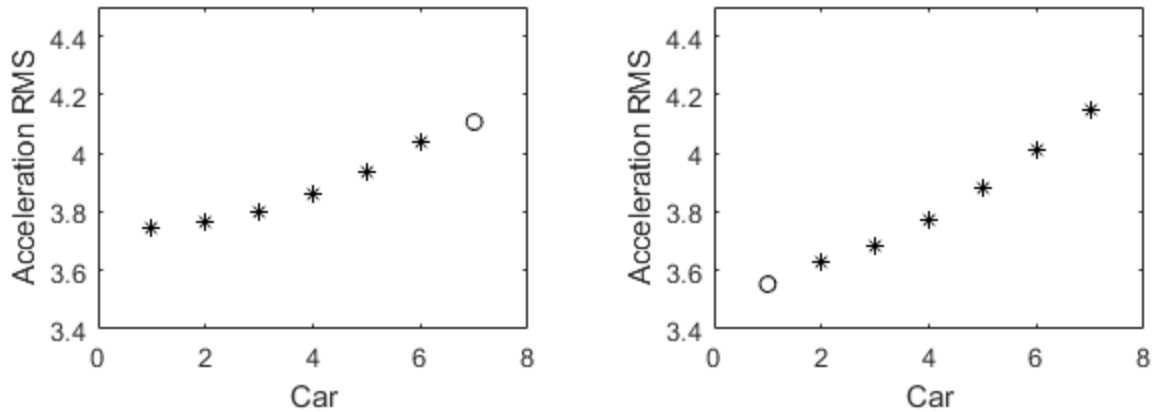


Fig. 13: Train with rotating main axle and fixed wheel carriers. Front-running zero-car (left) and rear-running zero-car (right).

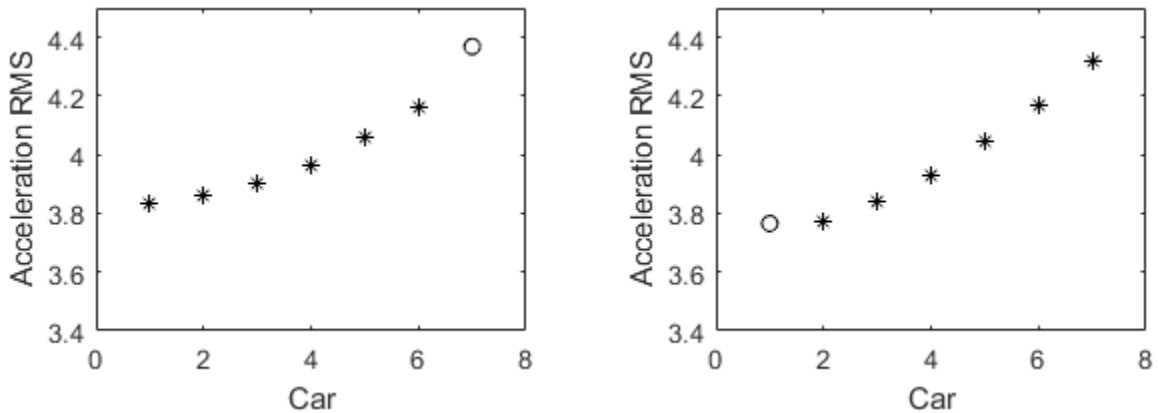


Fig. 14: Train with fixed main axle and rotating wheel carriers. Front-running zero-car (left) and rear-running zero-car (right).

4 Conclusions

Both in the experiments and simulations, small differences are observed between trains that use front-running and rear-running zero cars. Both the experiments and simulations show that rear-running zero-cars produce slightly lower lateral vibration levels. However, this difference is so small that in the opinion of the authors, it is not convincing to conclude that a certain zero-car location outperforms the other. In fact, the severity of lateral train dynamics seems to be much more influenced by the train design itself, than by a train's direction of motion. Based on this work, it is recommended to focus future research on comparing the lateral vibrations of multiple train designs in order to determine which train configuration yields the most ideal ride dynamics and thus the most comfortable ride experience. Subsequently, efforts in the field of design optimization can then be applied on this configuration.

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