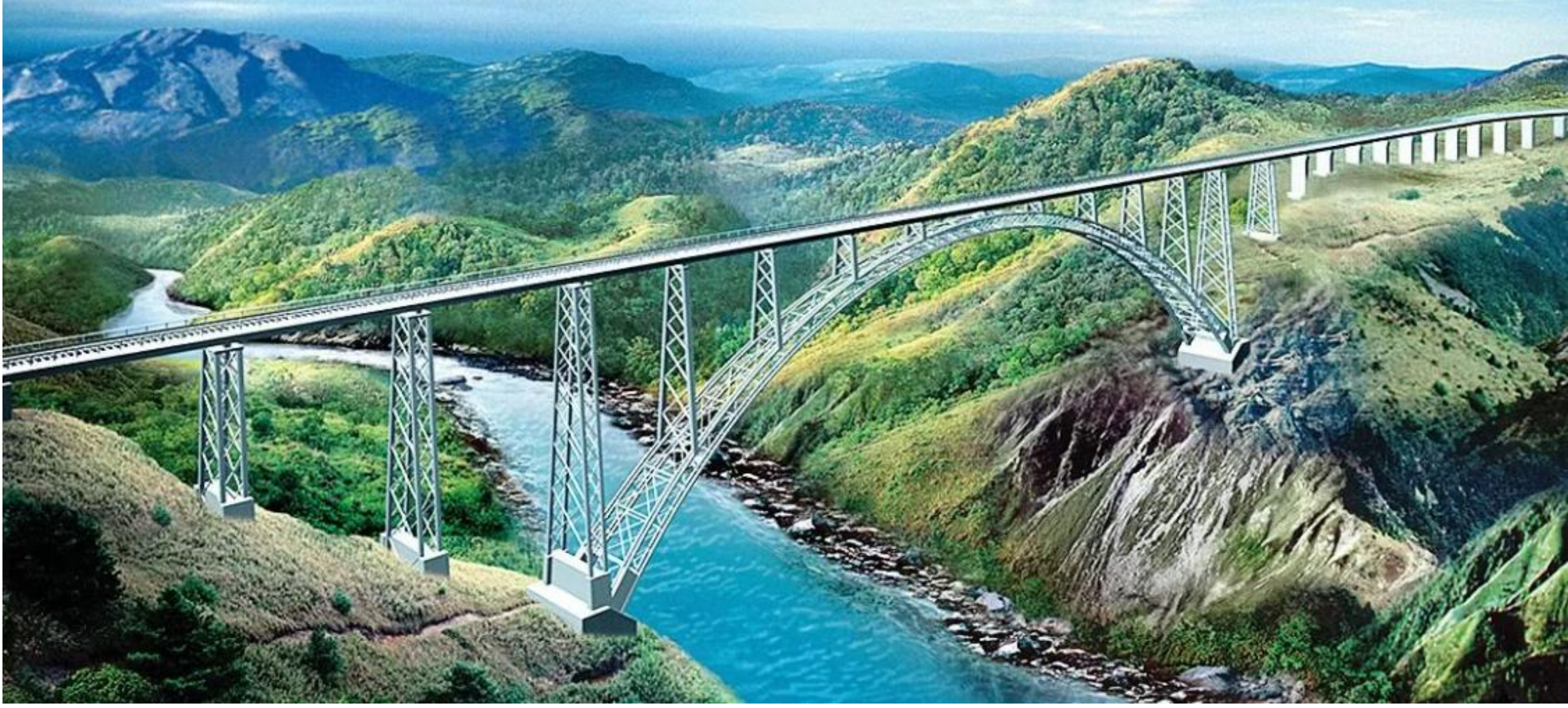

Chenab Railway Bridge, India (Mageba, 2018)

Vehicle-bridge dynamics

Numerical simulation of vehicle-bridge dynamics using VI-Rail

TU Delft

N.A. van Vliet
4952669

Vehicle-bridge dynamics

Theoretical modelling and numerical simulation of vehicle-bridge dynamics using VI-Rail

By

N.A. van Vliet

in partial fulfilment of the requirements for the degree of

Bachelor of Science
in Civil Engineering

at the Delft University of Technology
on Tuesday April 5, 2022

Supervisor 1:	Dr. Zili Li
Supervisor 2:	Dr. Meysam Naeimi
Superivisor 3:	Dr. Zhen Yang
Coordinator:	Dr.ir. Pierre Hoogenboom

Preface

In this bachelor thesis, the dynamic effects of a railway vehicle crossing a bridge is reviewed. A dynamic model is developed, simulations are carried out and the results of the forces and displacements are analysed.

As a Civil Engineering student, I mainly have an interest in the structural engineering courses at the Delft University of Technology. This is the reason why I choose a subject in the direction of the Structural Engineering Master. I also read a lot in the news about road bridges in the Netherlands being overly used, thereby passing the original design load of the bridges. I also was interested in trying some new software and doing analyses. This is how I choose vehicle-bridge dynamics as a subject.

This thesis is intended for anyone interested in the topic of vehicle-bridge dynamics, but it is written so that other students at technical universities can understand the matter at hand.

During this thesis with a total duration of 8 weeks, I learned a lot. At the beginning of the project, I struggled a lot with the software. I started in VI-Rail to learn how to perform simulations, then continued with Adams View to create a bridge and tried to import it into VI-Rail. Especially with all the different software versions, this was hard to do. Therefore, after a while I decided to try to do finite element analysis in Adams View, but continuously errors kept coming when trying to mesh the model. Then Zili Li set a meeting with some people from the railway faculty to see if they could help me. Xinxin Yu created a model for me, in which I finally could perform the sensitivity analysis. Especially during the first 5 weeks, I stressed a lot as I kept struggling to create a model. Luckily, in the end it all worked out.

I would mainly like to thank Meysam Naeimi for his continuous support and feedback during our weekly meetings. Furthermore, I would like to thank Xinxin Yu for helping me with creating a model. I also would like to thank Zili Li for his input during the thesis and Zhen Yang for reviewing my thesis. Lastly, I want to thank my thesis coordinator, Pierre Hoogenboom.

N.A. van Vliet
Delft, April 2022

Abstract

Rail transportation is on the rise. A lot of bridges in the Netherlands are currently outdated due to the increasing frequency of vehicles. Trains can cause a lot of dynamic loads, which can cause structural failure. The effect of a passing railway vehicle on the normal contact forces and the displacement of the vehicle is examined. Initially, various vehicle, track and bridge systems are reviewed in literature. A model of the bridge and vehicle is created in VI-Rail and Flextrack simulations are carried out. A sensitivity analysis is performed as the stiffness of the beam and the velocity of the vehicle are changed and the effects on the normal contact force and displacement are studied. A higher stiffness of the bridge deck material means lower peaks in normal contact forces of the left front wheelset and lower displacements of the primary suspension. A higher velocity of the vehicle means higher contact forces and higher displacements. The conclusion is, therefore, that it is important to design stiff bridges and to keep the velocity low, although this might not be desirable. Since in this research only short spans and beams are being studied, for future studies, it might be interesting to enlarge the spans or to create more than the current two pillars. Furthermore, the forces and displacements can be evaluated in other parts than the left front wheel, respectively, at the primary suspension.

Contents

1 Introduction

The world population is growing. Furthermore, global development tends to people using more resources and more goods imported from all over the world. This leads to massive increases in transportation. Rail transportation is on the rise, trains are running more frequently, trains become longer, and trains become heavier. A lot of the created infrastructure is therefore outdated, although strict safety margins have been used in the building process and an increase in usage was modeled in their development.

Especially for bridges, structural failure is daunting. Trains, especially with their axles on a set distance can induce a lot of dynamic loads, which can cause failure. A famous example of an induced vibration is that of the Millennium Bridge in London. Applied forces will always cause slight deformations, but it is of utmost importance that these remain small enough for railway tracks, especially for high-speed trains. Those vehicles are very sensitive for track deformations. A lot of research has been done into the dynamic effects of a train on a railway track. Bridges are also often studied by civil engineers. The coupling between the vehicle on the railway and the bridge can be of great influence for the structural performance of the bridge.

More research should be done to investigate the structural performance of railway bridges under the dynamic load of a passing train.

This report will answer the following question: what is the influence of a dynamic load of a passing train on railway bridge? This will be answered via Flextrack analysis in the VI-rail software. Therefore, a model of a vehicle-bridge system is used. This system is a heavily simplified system and mainly the vertical directions are of importance. Some key parameters on the vehicle and the bridge will be varied, and their dynamic influences investigated, thus a sensitivity analysis is performed. These variables are the E-modulus of the beam and the velocity of the vehicle.

The structure of this report is the following. Chapter 2 will cover the information obtained from the literature. It will discuss models found in other research, information regarding trains, track, and railway bridges, and used theories. Chapter 3 will discuss the methodology. It will explain the developed model and key parameters to be varied, which will include the design for the bridge used. Chapter 4 will cover the results. Chapter 5 consist of the discussion. Chapter 6 provides a conclusion of the results obtained.

2 Review of the literature
A lot of people have already created bridge-railway models. First literature on various models of vehicle-bridge systems will be discussed, including models of the various elements.

2.1 Model
To understand the various vehicle-bridge models, it is a good start to look first at the various parts in such a system. Therefore, the various parts of a systems will be schematized separately.

2.1.1 Vehicle
A train often exists out of multiple vehicles being pulled forward by a locomotive. A vehicle exists out of a car body placed upon two bogies. A bogie contains the wheels and a bolster. In Figure 1 - Railway carriage model , a model of a vehicle can be seen. Each car body is attached to two bolsters, who each have 4 wheels. The connections exist out of springs with dampers. In this model the wheel-rail contact is also modelled with springs.

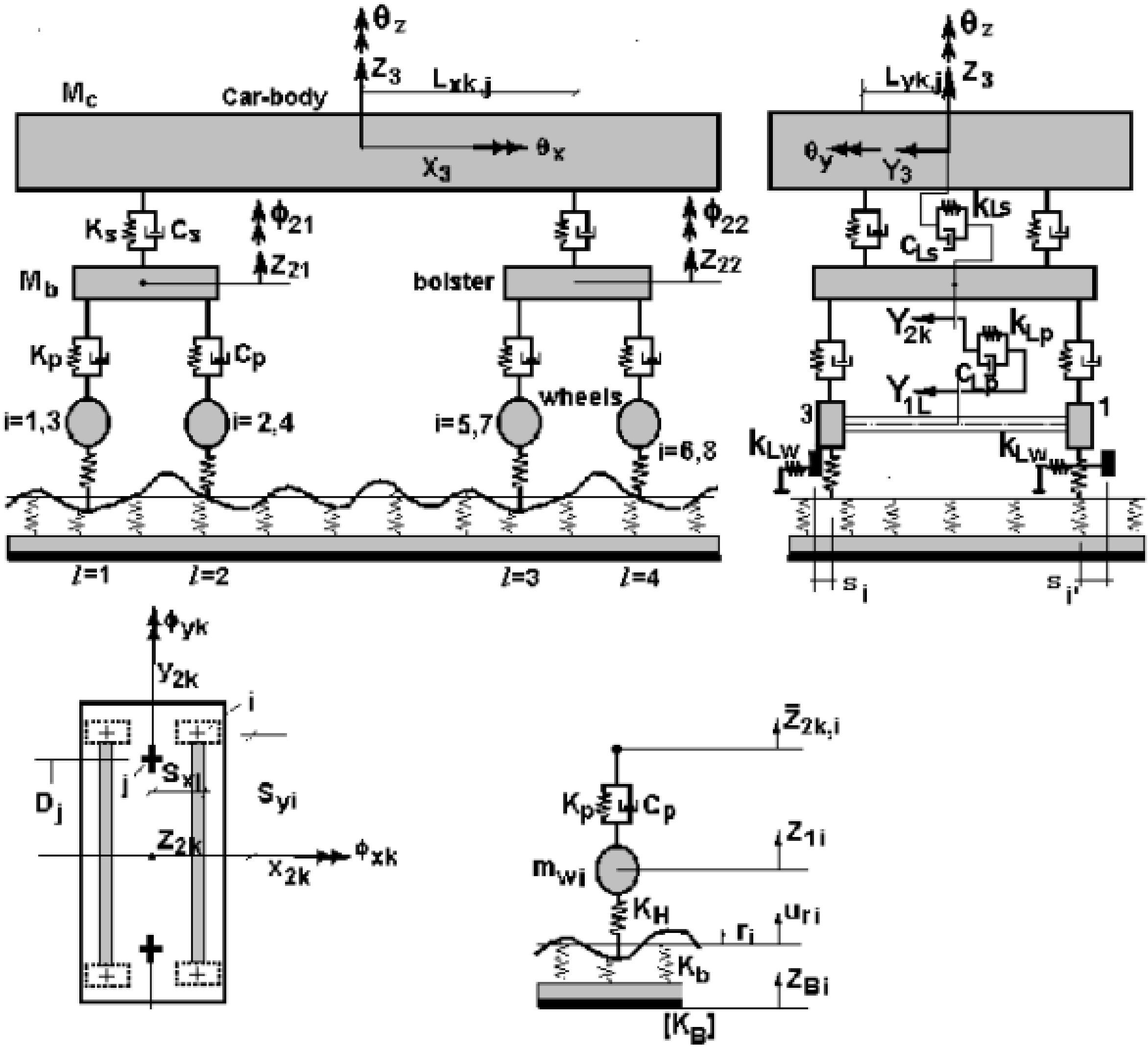

Figure 1 - Railway carriage model (Zhang, 2000)

Other vehicle models used in papers can be seen in Figure 2 - Railway vehicle model and in Figure 3 - Vehicle model . The similarities between the different vehicle models can be easily seen.

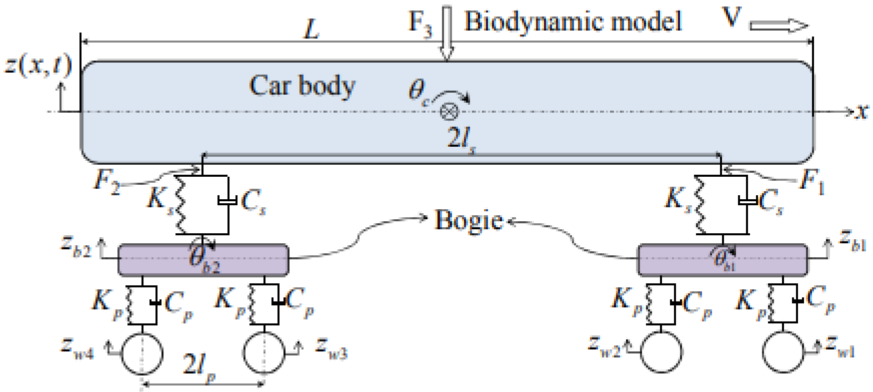

Figure 2 - Railway vehicle model (Pradhan, 2017)

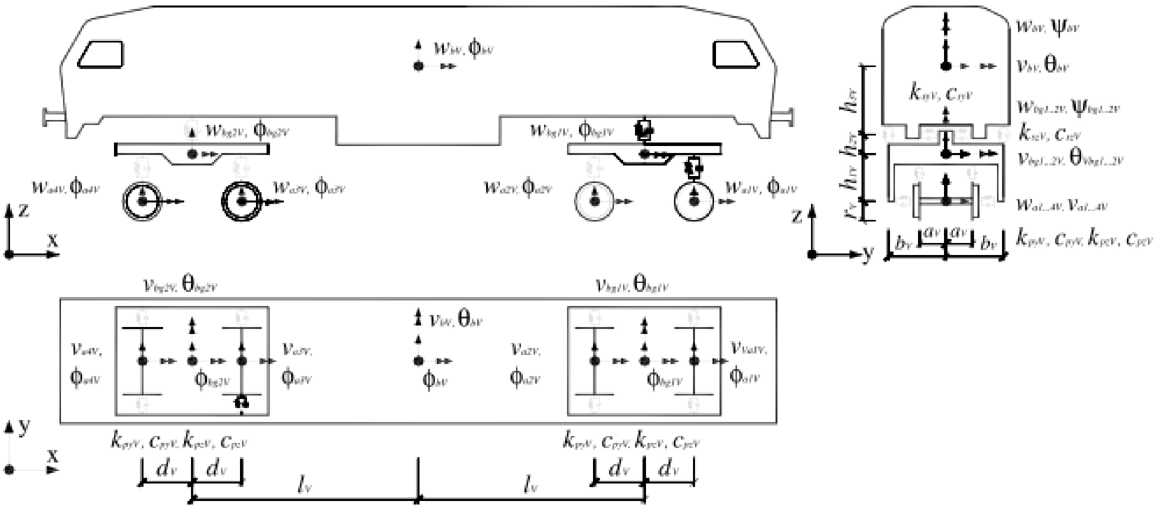

Figure 3 - Vehicle model (Majka & Hartnett, 2007)

The speed of different vehicles can also have a great influence on the dynamic performance and structural forces of railway bridges. Therefore, it is interesting to look at the various speeds that railway vehicles are allowed to travel at. In the Netherlands this is regulated by a track section limit. In Figure 4 - Track section speed limit the track limits in various parts in the Netherlands can be seen. Most tracks (colored red) have a limit of 140 km/h. Some parts of the High Speed Line have parts were 160 km/h can be reached and the Thalys can reach 300 km/h just before entering Belgium.

Figure 4 - Track section speed limit (ProRail, 2008)

2.1.2 Track

The railway track provides a smooth surface for a train to run over, allowing for a very efficient means of transportation due to the low friction. For the rails to be perfectly aligned, a very specific foundation must be laid upon the ground. This means that there are various layers beneath the track. Those layers can be seen in Figure 5 - Railway track schematic: base, formation layer, sub ballast, ballast, sleepers, and the rail.

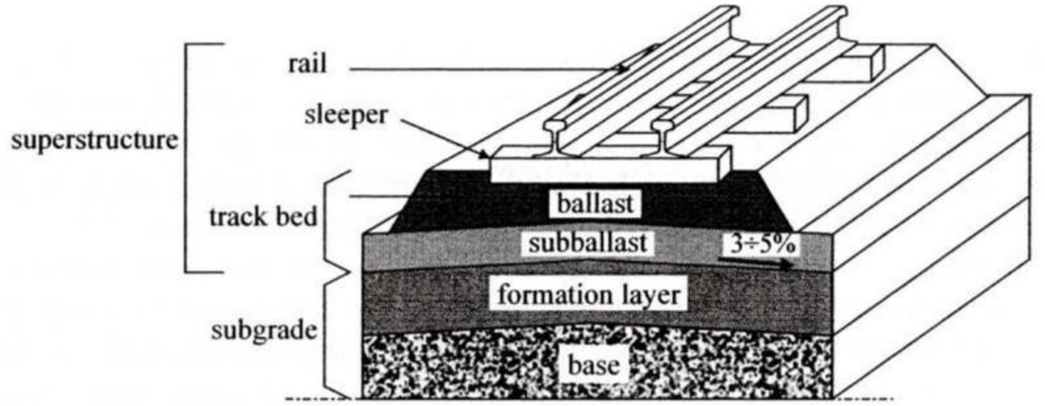

Figure 5 - Railway track schematic (Andrade, 2006)

Currently, however ballast less tracks are being used more often. They are great for soils with settlement or for railway tracks on pile foundation. They require a lot less maintenance and are often used on bridges. Two examples can be seen in the figures below.

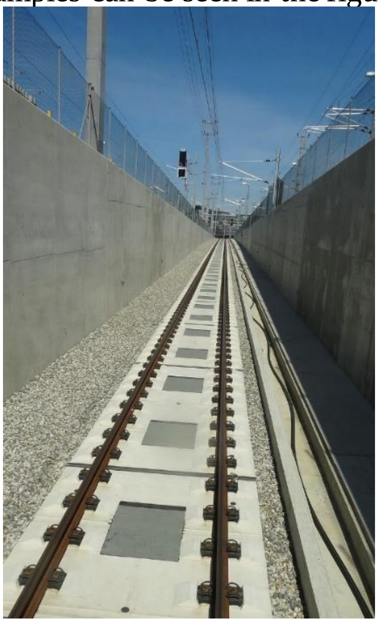

Figure 6 - Ballastless track in Vienna Central Station (Piereder, n.d.)

Figure 7 - HSL Zuid (Google, 2019)

The rail-wheel contact is important in railway engineering. Hertzian theory is a classical contact theory. It is especially useful in multibody dynamics, although no theory is perfect, and it also has some drawbacks. Most contact theories are based on Hertzian contact theory. Hertzian contact theory assumes the following:

- Frictionless surfaces.
- The strains are small and within the elastic limit.
- The surfaces are continuous, and the contact area is much larger than the contacting bodies.

2.1.3 Bridge

Various railway bridge models exist. The easiest is a simple linear beam element with a moving load. A lot harder is the 10 DOF's model. All types can be seen in Figure 8 - Railway bridge model types (Salama, Eraky, Yahya, & Samir, 2020).

In the moving load model axle loads are place onto a beam. Irregularities are not considered. The finite element method can be used to perform the dynamic analysis, an analytical approach is also possible. The second model is a rolling mass. Again, irregularities are not considered. Interesting is the fact that the included inertia makes the resonance frequency lower. The first interaction model is that of the sprung mass. This model with a lumped mass can be solved and compared to the moving load problem by setting the stiffness to infinite values. The model of two degrees of freedom (DOF) is more realistic. The wheels and the lumped train mass can move, allowing for analysis of a basic vehicle and suspension. The four DOF model includes the rotational effect of a car body along with translation of the wheels and car. The complete 2D model consists of 7 translational DOF's, 4 wheels, 2 boogies and the car body and 3 rotational DOF's (car body and boogies) (Salama, Eraky, Yahya, & Samir, 2020).

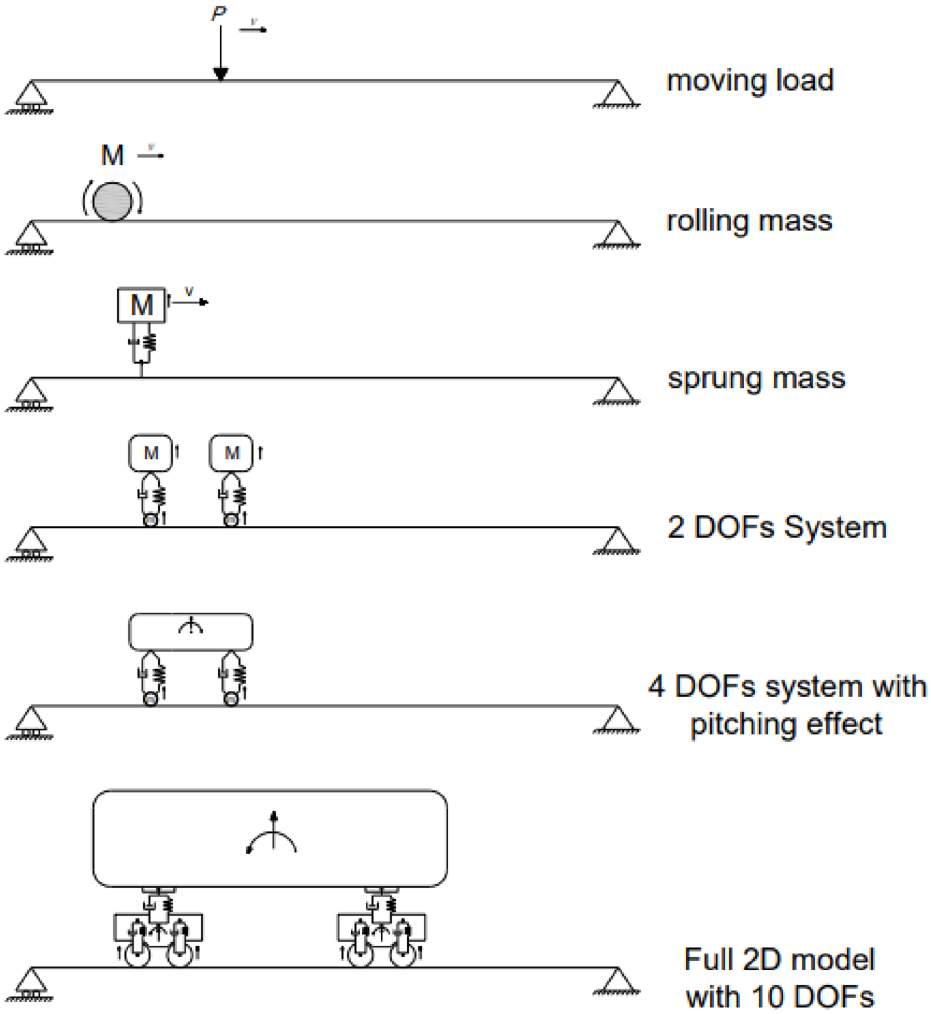

Figure 8 - Railway bridge model types (Salama, Eraky, Yahya, & Samir, 2020)

Apart from the model of the bridge, the materials used for the beam are also of great importance. Bridges in the past were always build from stone, but with advancement in technology newer building materials are now being used which are stronger, lighter, and more durable. These materials include steel, concrete, and other composite materials.

3 Methodology

Initially the model used to build the track and bridge is explained (VI-Rail, 2018). The next step is showing the imported vehicle from the VI-Rail software. Then the sensitivity analysis of the stiffness and speed is explained, as well as the timestep determined.

The model of the bridge according to Figure 9 in VI-Rail is used. The model consists of a 60m track rigidly connected to the ground followed by three beam elements of each 2m long. This means that the bridge is relatively short, this will significantly decrease the programming time and the time required to run the simulations. The beams are based on lumped mass theory. The masses of the beams are located at the supports. The bridge piers are rigid bodies and connected via a spring and damper system to the ground. The properties of the bridge piers can be seen in Table 1 - Bridge pier properties. The computer model for the bridge in VI-Rail can be seen in Figure 10 and the support properties in Figure 11.

Table 1- Bridge support properties

Mass [kg]	500.0
I_{xx} [m^4]	100.0
I_{yy} [m^4]	100.0
I_{zz} [m^4]	100.0

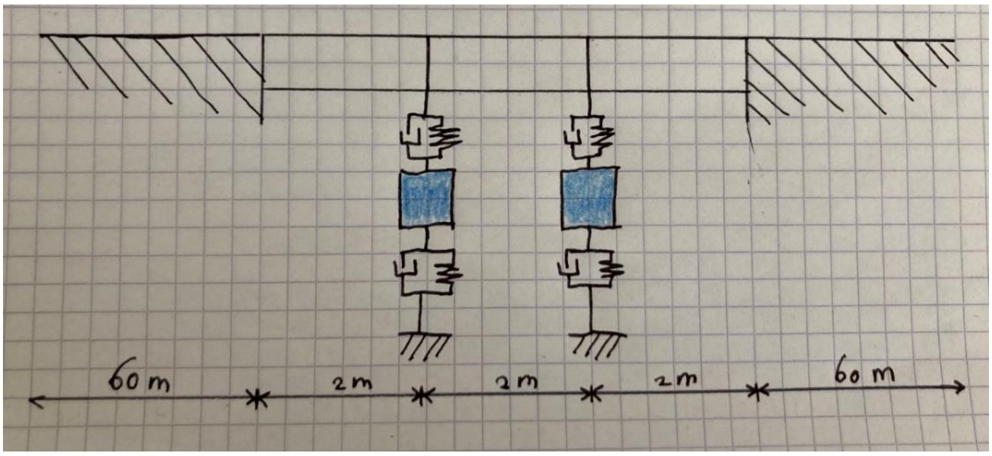

Figure 9 - VI-Rail model

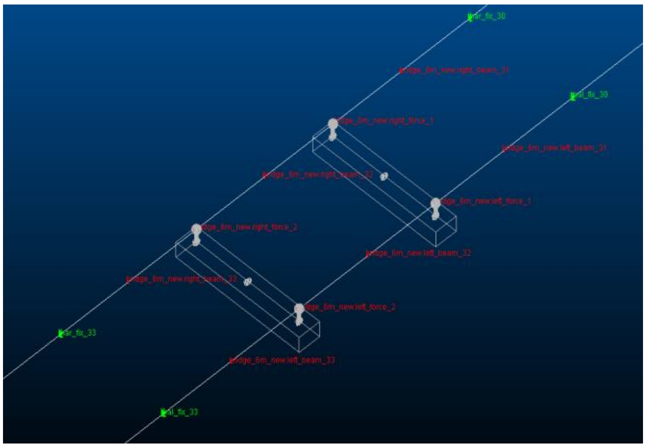

Figure 10 -Computer model for the bridge in VI-Rail

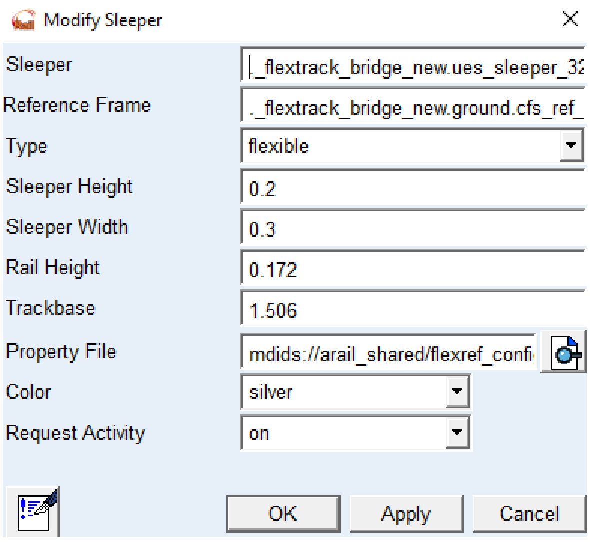

Figure 11 – the beam support properties (sleepers) in VI-Rail bridge

For the vehicle the Erri Wagon of the VI-Rail shared library is used. The Erri Wagon (Figure 12) is based upon the templates of the Erri Front Bogie (Figure 13), the Erri Rear Bogie (Figure 14), and the Car Body (Figure 15).

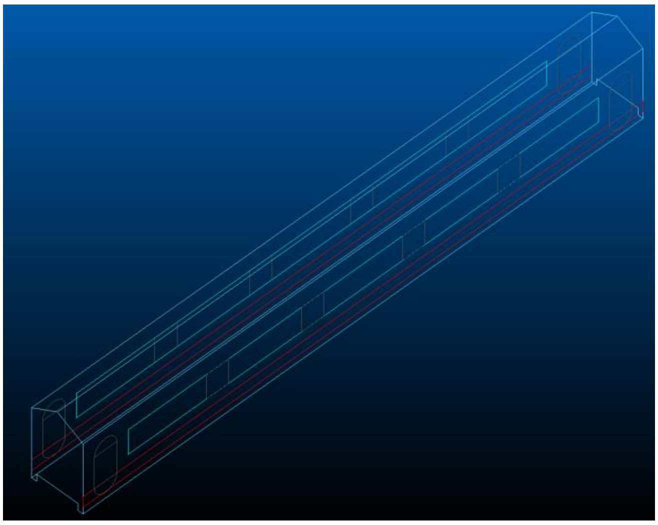

Figure 12 - Erri Car Body

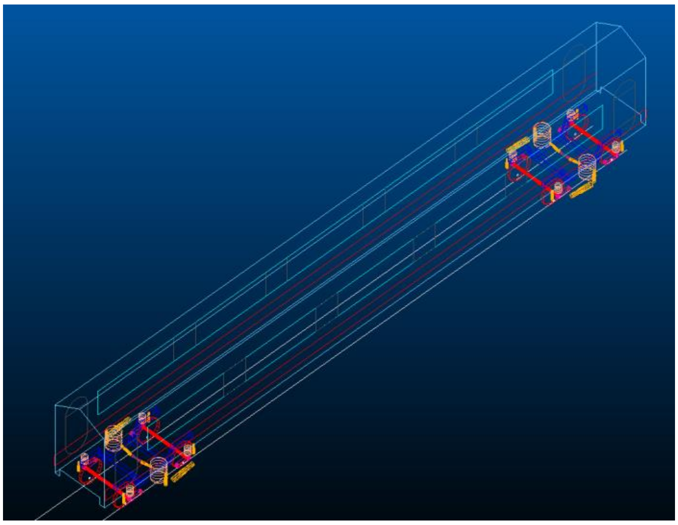

Figure 13 - Erri Wagon

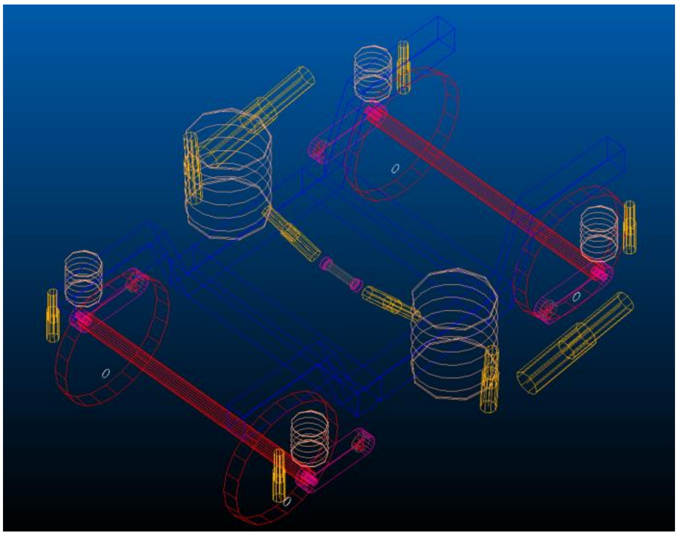

Figure 14 - Erri Front Bogie

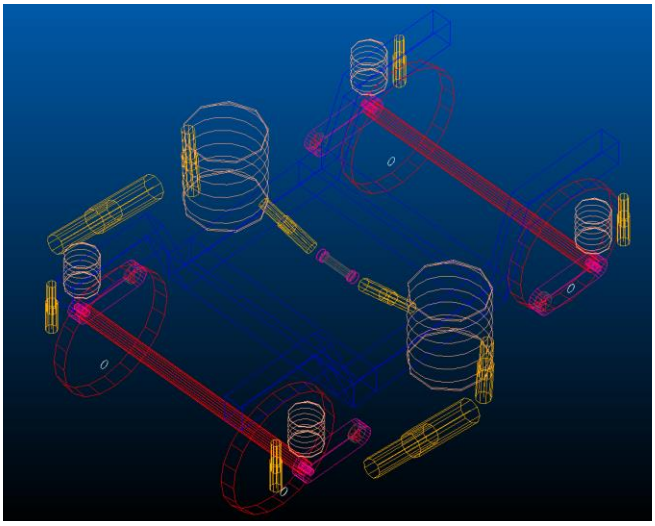

Figure 15 - Erri Rear Bogie

Sensitivity Analysis

The model created can be modified in the template file in the template builder of VI-rail. Various elements can be modified. In this report a sensitivity analysis will be performed. A Flextrack simulation (Figure 16 - Flextrack Analysis Settings) will be performed in the VI-Rail environment. Therefore, the stiffness of the beam elements (Figure 17 - Beam Settings) will be varied, as well as the speed of the vehicle. The wheel normal contact force of the left front wheel is compared.

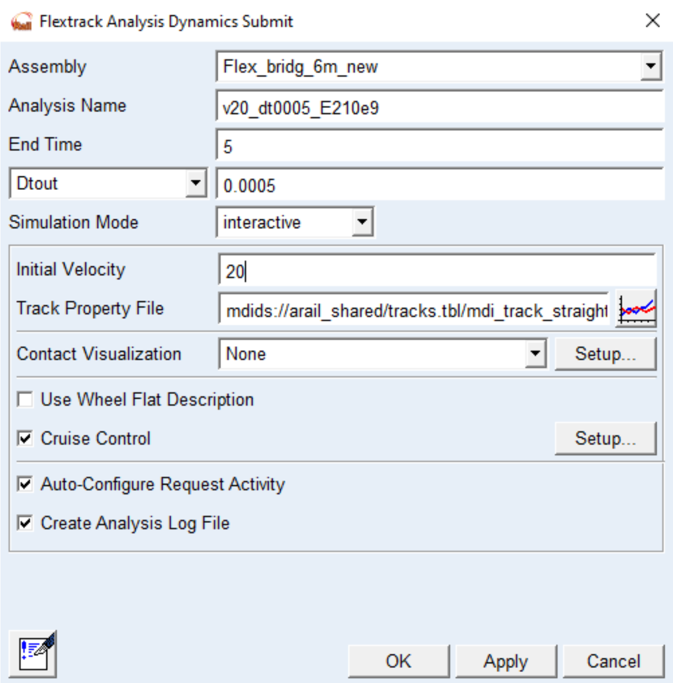

Figure 16 - Flextrack Analysis Settings

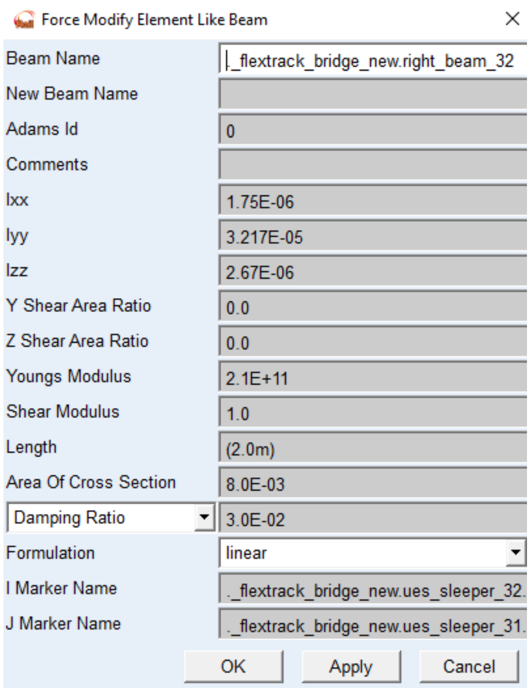

Figure 17 - Beam Settings

Stiffness

Various materials have various stiffness properties. Often steel is used for railway bridges, but of course other elements can also be used. The Young's Modulus of various materials have been used for the beam elements. Materials such as wood, aluminium, titanium, steel and even diamond are compared. Although diamond is obviously a very unrealistic building material, it is still used since it is a very stiff material and therefore interesting. All materials and their respective Young's Modulus can be found in Table 2 - Young's Modulus of materials evaluated. The other settings of the stiffness flextrack analysis are fixed and set to the values in Table 3 - Simulation settings.

Table 2 - Young's Modulus of materials evaluated

Material	**Young's Modulus (*10^9) [N/m^2]**
Wood	10
Aluminium	69
Titanium	110
Steel	210
Diamond	1200

Table 3 - Simulation settings

Variable	**Setting**
End time analysis	5 s
Time step	0.0005 s
Velocity	20 m/s

Velocity

Trains do not always run at the same speed. Therefore, it is interesting to do the Flextrack simulations at various velocities. The simulations are performed at velocities ranging from 20 m/s up to 60 m/s, in 10 m/s increments. Converted to km/h this means speeds of 72 km/h up to 216 km/h.

Timestep

An important step in numerical analysis is determining the timestep. Accurate results are necessary, but the running time of the simulation needs to be reasonable as well. When running the stiffness simulations, a speed of 20 m/s is set as a fixed variable. Therefore, the speeds of the various simulations are fixed at 20 m/s. The end time of the analysis of the time can now be based upon the track length and the velocity of train. Since the train covers first 60m of rigidly attached track, already 3 seconds are required. Then the train needs to run over the short bridge of 3 beam elements of 2 m, so a total of 6m and then continue for some time to look at the dynamics of the vehicle. Finally, 5 s is chosen as the total simulation time.
The different timesteps can be seen in Figures 18 until 21. Initially 0.05 s is chosen as the timestep. It thus requires 100 timesteps to reach the total 5 seconds. This timestep is too large, since the plot of the normal contact force is very unstable and has sharp bends. The time step is increased up until the plot does not change that much anymore. A timestep of 0.005 seconds still gives not accurate enough results. A timestep of 0.0005 s has accurate results. As a final check the simulation is also ran with a timestep of 0.00005 s. The fact that these last two plots look almost the same is reassurance that the timestep of 0.0005 s is accurate enough. Note that the running time increases as the simulation with the timestep of 0.0005 s takes only approximately 6min to run, whereas the 0.00005 s timestep simulation takes almost an hour.

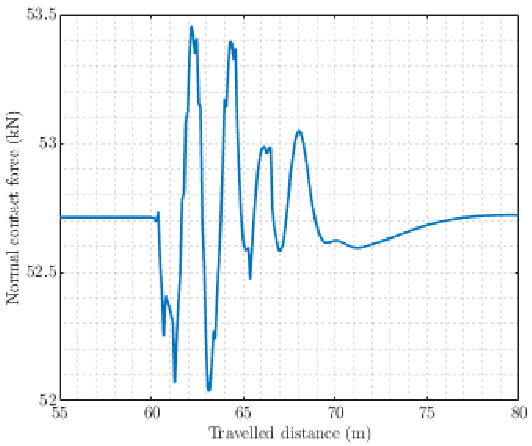

Figure 18 - timestep dt=0.05 s

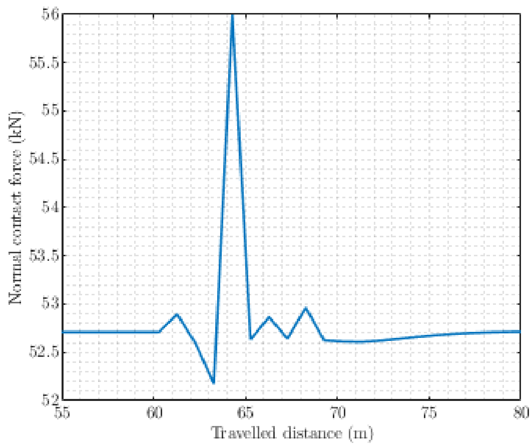

Figure 19 - timestep dt=0.005 s

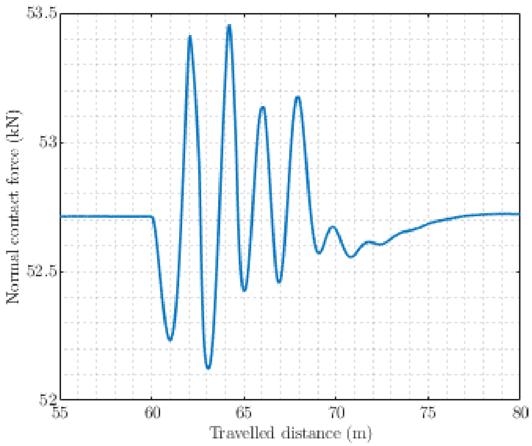

Figure 20 - timestep dt=0.0005 s

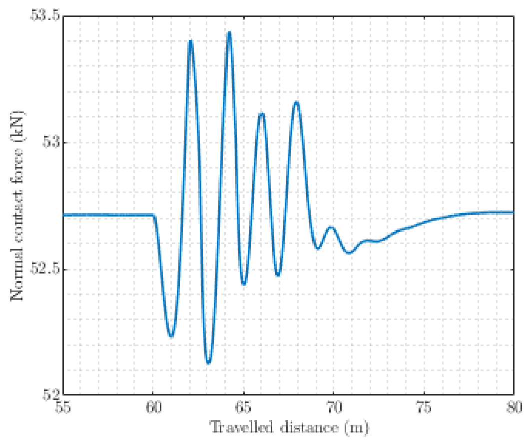

Figure 21 - timestep dt=0.00005 s

4 Results

The results of the sensitivity analysis of the stiffness and velocity are covered in this chapter.

Stiffness

The results of the various simulations are shown in Table 4. On the left side, the E-modulus of the various materials is given. These materials are wood, aluminium, titanium, steel, and diamond. The simulated results are given in the third column, the normal contact force in the left front wheel of the boogie. These normal contact forces are the maximum forces when the vehicle crosses the bridge. The normal contact forces plotted over the distances can be seen in various figures in Appendix 1. For example, for the first case (Normal force, E = 10E+9) the normal force reaches its peak at 62 m, which is approximately 54.0 kN. This force is selected as the basis for Table 4 – E-modulus results. Also, in the first case (Normal force, E = 10E+9), the first 60 m of the normal contact force is a horizontal line. As the train approaches over a rigid track, the normal contact force is equal to the gravity, which is also given in Table 4 – E-modulus results. The additional force is the maximum normal contact force minus the gravity, so the excitation in the normal contact force graph caused by the bridge. In the last column the maximum displacement in z-direction is given. These displacements can be seen in various figures in Appendix 1.

Table 4 – E-modulus results

E-modulus [N/mm^2]	Gravity [kN]	Normal contact force [kN]	Additional force [kN]	Dz Max [m]
1.00E+10	52709	54020	1311	5.60E-04
6.90E+10	52709	53734	1025	4.67E-04
1.10E+11	52709	53625	916	4.34E-04
2.10E+11	52709	53436	727	3.74E-04
1.20E+12	52709	52947	238	1.73E-04

To effectively see the effect of the stiffness on the additional normal contact force a plot is created in Figure 22 - Plot E-modulus against additional normal contact force. Various trendlines have been considered and a logarithmic turned out to be the best fit. Clearly, as the stiffness decreases there is a severe increase in the forces.

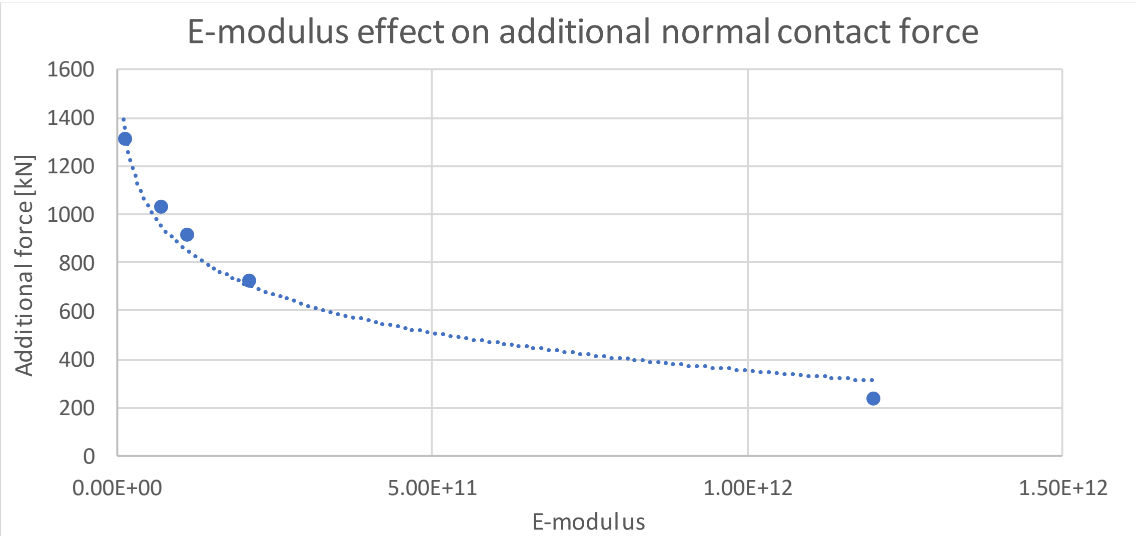

Figure 22 - Plot E-modulus against additional normal contact force

The displacement of the train is measured in the primary suspension on the front left side. The plots of the displacement as the vehicle moves over the bridge can be seen in various figures in Appendix 1 for varying stiffness. The displacement is also plotted against the E-modulus in Figure 23 – Plot E-modulus against displacement. The results are like the results of the normal contact force. Again a logarithmic relation is the best fit.

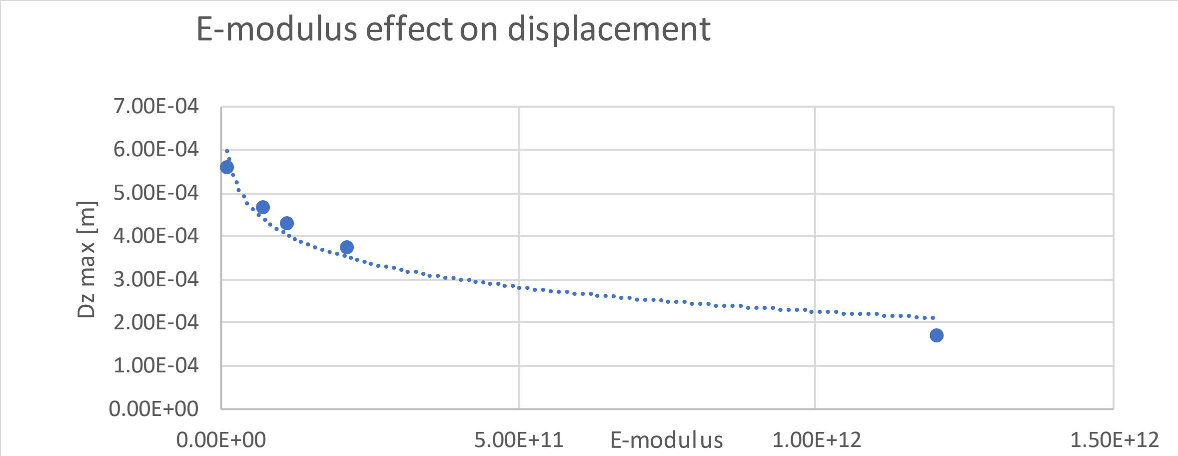

Figure 23 – Plot E-modulus against displacement

Furthermore, the excitations caused by the normal contact forces are plotted in the wavelet synchrosqueezed transforms (WSST) in f various figures in Appendix 1. Clearly the WSST's light up at a frequency of 10 Hz for all simulations. This is the result of vehicle crossing the bridge at 20 m/s with beam bearings 2 m apart.

Velocity

The results of the various simulations are shown in Table 5 - Velocity results. On the left side the velocity of the simulations is given. The results are given in the third column, the normal contact force in the left front wheel of the boogie. The normal contact forces are the maximum forces when the vehicle crosses the bridge. The normal contact forces and displacements plotted over the distances can be seen in various figures in Appendix 1.

Table 5 - Velocity results

Velocity [m/s]	Gravity [kN]	Normal contact force [kN]	Additional force [kN]	Dz Max [m]
20	52709	53436	727	3.74E-04
30	52709	54809	2100	4.81E-04
40	52709	56185	3476	5.29E-04
50	52709	57908	5199	6.34E-04
60	52709	60517	7808	6.35E-04

The effect of the velocity is plotted in Figure 24 – Plot velocity against additional normal contact force. The best fitting trendline is a 2nd degree polynomial. Furthermore, the trendline has been set to intercept the origin.

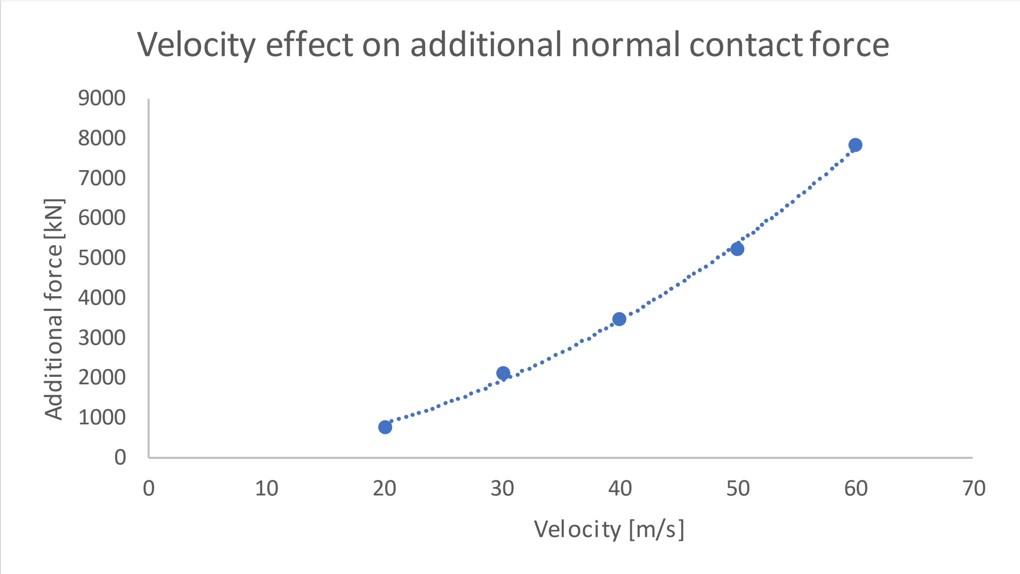

Figure 24 – Plot velocity against additional normal contact force

The results are different for the displacement and can be seen in Figure 25 - Plot velocity against displacement. The displacements increase with increasing velocity, but the increments become less and less.

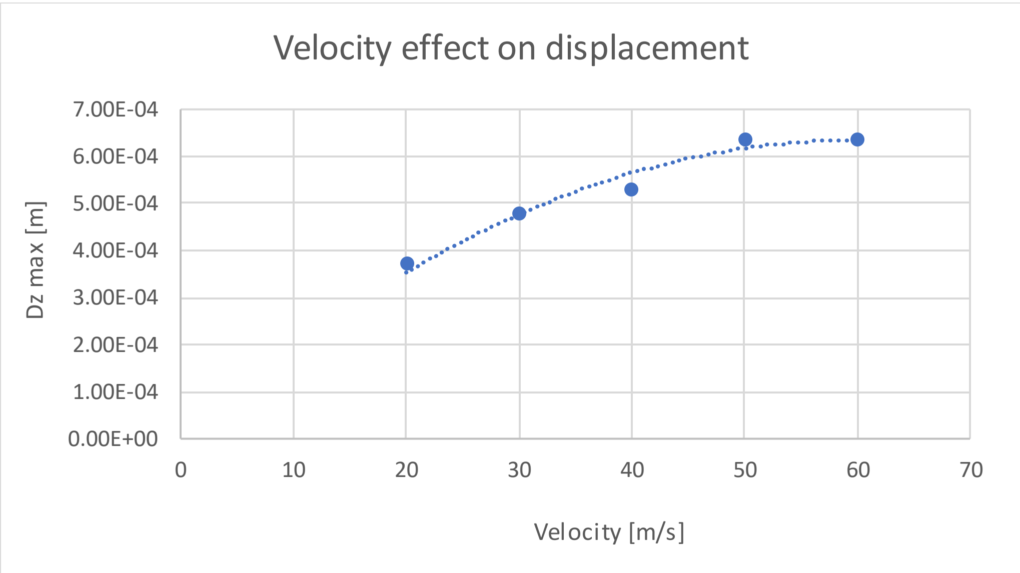

Figure 25 - Plot velocity against displacement

In the Wavelet SynchroSqueezed Transform (WSST) results for different cases are also provided in Appendix 1. Since the velocity changes, the time between the beam bearings is shorter, this means that the frequency should increase. The frequencies which light up for various velocities can be seen in Table 6 - Frequencies for velocities.

Table 6 - Frequencies for velocities

Velocity [m/s]	**Frequency [Hz]**
20	10
30	15
40	20
50	25
60	30

5 Discussion

In the results the relations between the stiffness, the velocity and normal force and displacement were found. These will be interpreted in this chapter along with the limitations of the study.

Interpretation

The results indicate that the stiffness is negatively correlated with the additional normal contact force. This is the result of the beam deflecting more due to the weight of the vehicle. As it reaches the bearing at 62 m, the train is pulled upwards again to its original level. If the vehicle must elevate slightly more, it consequently that the force is higher. Since wood bends more than steel, it is therefore understandable that the contact force for the steel beam is lower.

An increasing velocity does also increase the additional normal contact force on the beam. This might have to do with the increasing forward speed, causing the vehicle requiring more force to jump upwards faster. Interesting is the fact that the displacements do seem to increase less and less with increasing velocity, even though the additional normal contact force increases with a 2^{nd} degree polynomial.

Also, when looking at the graph for the normal contact forces on the left front wheel, the oscillations are interesting. The first 2 oscillations are relatively large, as the vehicle hits the bearings at 62 m, respectively 64 m. The two oscillations after this are small, as the primary and secondary suspension damp out the forces. The displacement has two initial peaks in downward z-direction as the beam bends due to the weight of the vehicle. After these two peaks the vehicle bounces slightly, mainly in the upward direction as the rail is rigidly attached to the ground again after 66 m.

6 Conclusion

The purpose of this research was to answer the following question: what is the influence of a dynamic load of a passing train on a railway bridge? This research was performed via Flextrack analysis in the VI-rail Train-Track simulation software. Therefore, a simplified model of a vehicle-bridge system was established in this research. The E-modulus of the beam and the velocity of the vehicle were varied and the resulting normal contact force in the left front wheel and the displacement of the primary suspension of the vehicle were reviewed.

It can be concluded that the additional normal contact force in the front wheel decreases with increasing the beam stiffness, similarly, the vertical displacement of the primary suspension. Furthermore, it can be concluded that the additional normal contact force in the front wheel increases exponentially with increasing the train velocity and the displacement increases as well, but it seems to be approaching an asymptote.

Therefore, a stiffer bridge and a lower speed are ideal for less stresses on structures such as railway bridges, as this greatly reduces the contact forces and vertical displacements.

7 Implementation

The data contributes a clearer understanding of the forces acting on vehicles on bridges. The results show that an increasing stiffness, decreases the normal contact forces. Furthermore, it decreases the displacements. Therefore, a stiff building material is of great importance in building vehicle bridges.

The speed of the vehicle does have an even greater influence on the forces as well as the displacements. It is therefore interesting where to compromise on a safe design and fast railway transport.

8 Recommendations for future work

There are some limitations to this research. Firstly, only a limited number of simulations were performed due to time constraints in total research and computer processing time, even though the timestep was wisely chosen.

Secondly, the bridge model is very straightforward with only two pillars and a span of only 6 m in total and 2 m for each beam. This is short for a bridge as spans of more than 100m between pillars are sometimes used.

Thirdly, the velocity used of 72 to 216 km/h is relatively large. Although realistic for passenger transport, railway cargo transport does often travel at lower speeds.

For future research, it is recommended to alter the bridge model to create more pillars and/or a longer total span. Furthermore, a different vehicle setup can be used instead of the Erri Wagon out of the VI-Rail library. Especially the high loads of freight cargo are interesting. Also, lower velocities can be used.

For this research all data has been pulled from the left front wheel for the contact normal force and primary suspension for the displacement. Forces and displacements on other elements can also be compared.

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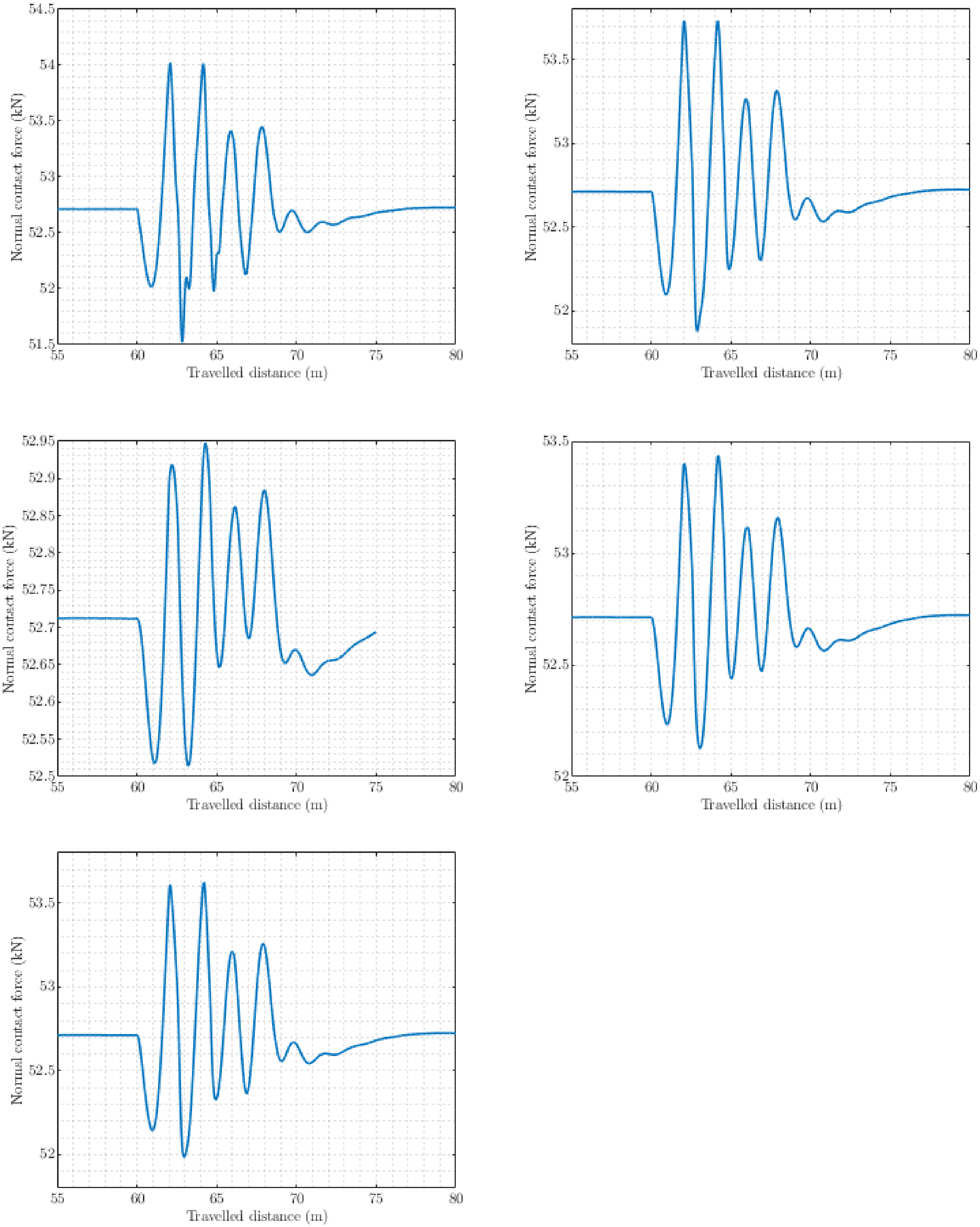
Dutch translation abstract

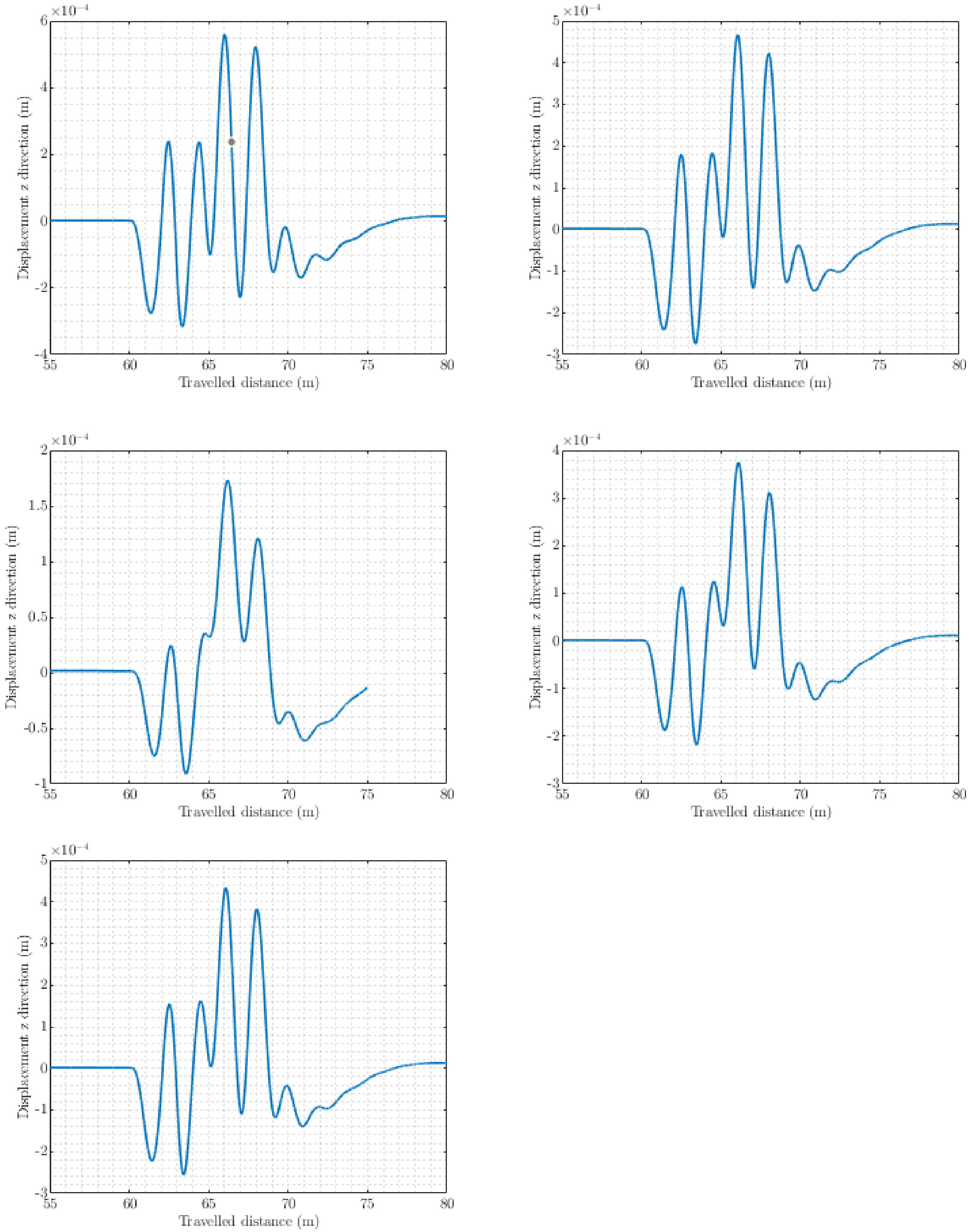
Treinverkeer is aan het toenemen. Veel bruggen in Nederland voldoen momenteel niet meer aan de veiligheidseisen door de toegenomen frequentie van voertuigen. Treinen kunnen veel dynamische belasting veroorzaken, wat tot structureel falen kan lijden. Het effect van een passerend voertuig op de normaalkrachten en verplaatsing van het voertuig wordt onderzocht. Eerst worden hiervoor verschillende modellen van voertuigen, sporen en bruggen bekeken in de bestaande literatuur. Vervolgens wordt een model gemaakt in VI-Rail en worden Flextrack simulaties uitgevoerd. Een gevoeligheidsanalyse wordt gedaan waarbij de stijfheid van de balk en de snelheid van het voertuig veranderd worden en de effecten op de normaalkracht en de verticale verplaatsing gesimuleerd. Een hogere stijfheid betekent lagere pieken in de normaalkracht en kleinere verplaatsingen. Een hogere snelheid betekent hogere normaalkrachten en hogere verplaatsingen. The conclusie is daarom dat het belangrijk is bruggen te maken van stijf materiaal en de snelheid laag te houden, ondanks dat dat misschien niet altijd wenselijk is. Aangezien in dit onderzoek alleen korte overspanningen en balken zijn bestudeerd, is het voor toekomstig onderzoek aan te raden de overspanning te vergroten en meer dan twee pijlers te plaatsen. Verder kunnen de krachten en verplaatsingen in andere punten onderzocht worden dan het linker voorwiel, respectievelijk de primaire vering.

Appendix 1.

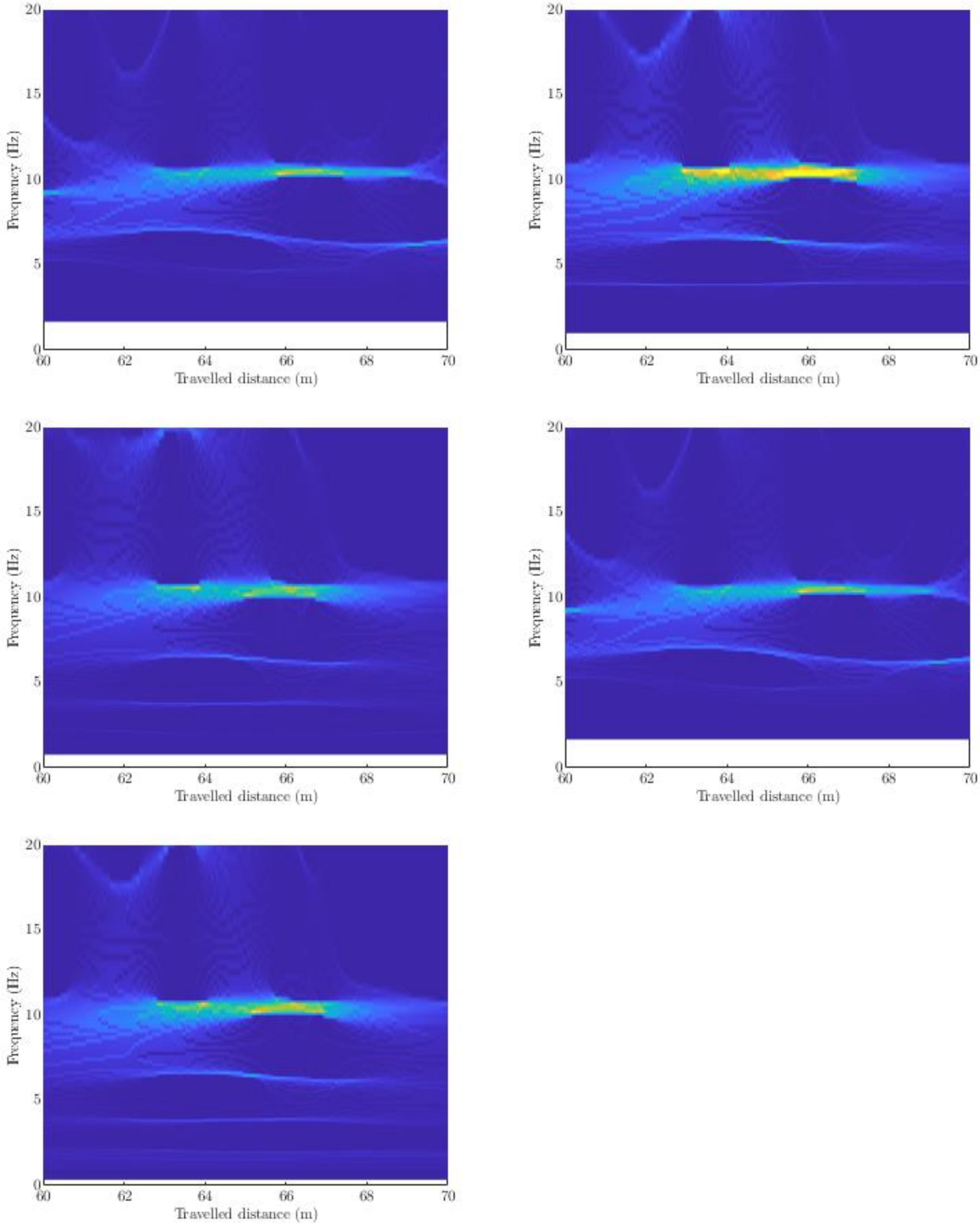
Results of the dynamic simulations for various cases studied in this research



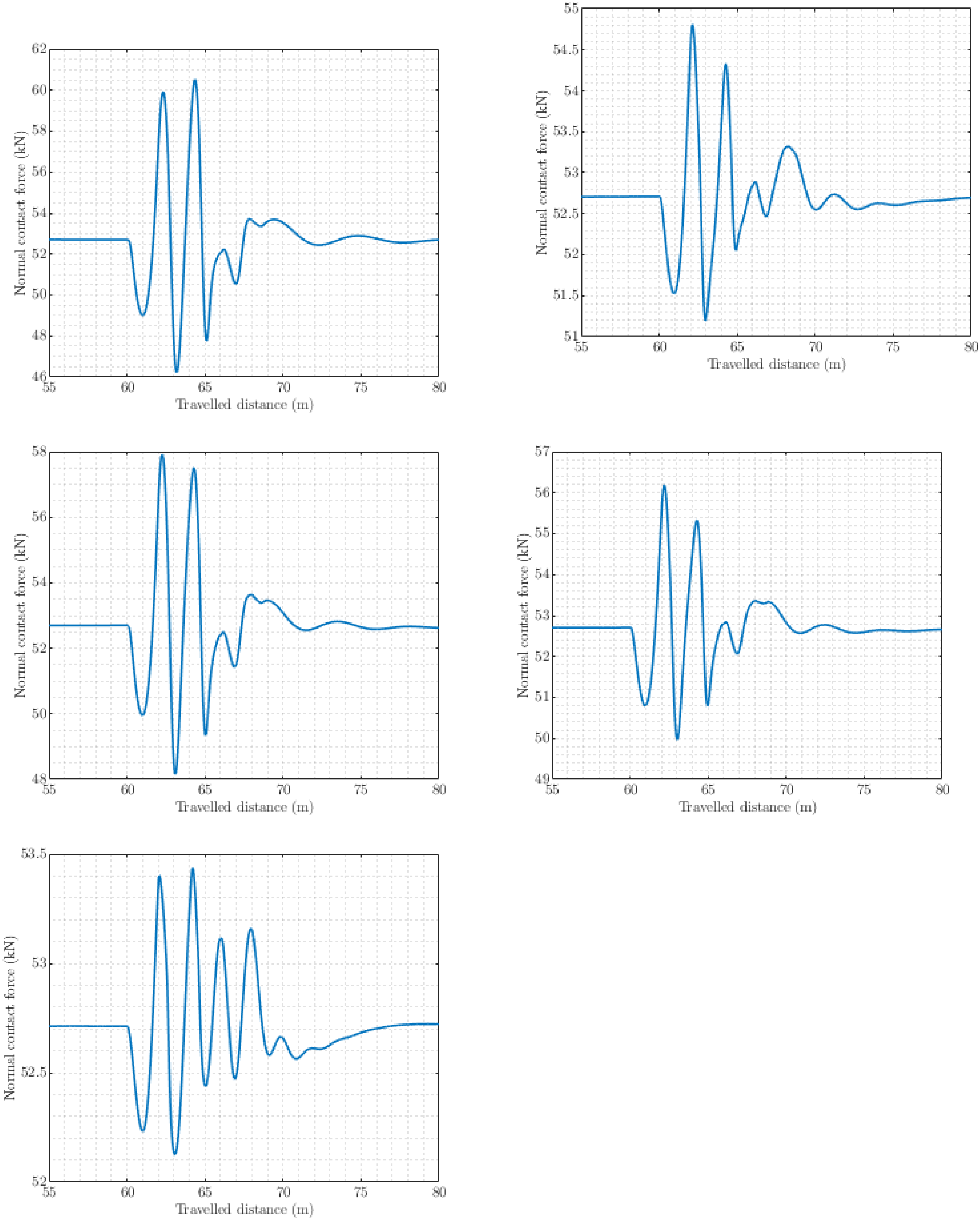
Results of Normal force distributions for various cases E = 10E+9, 69E+9, 110E+9, 120E+9, 210E+9, accordingly



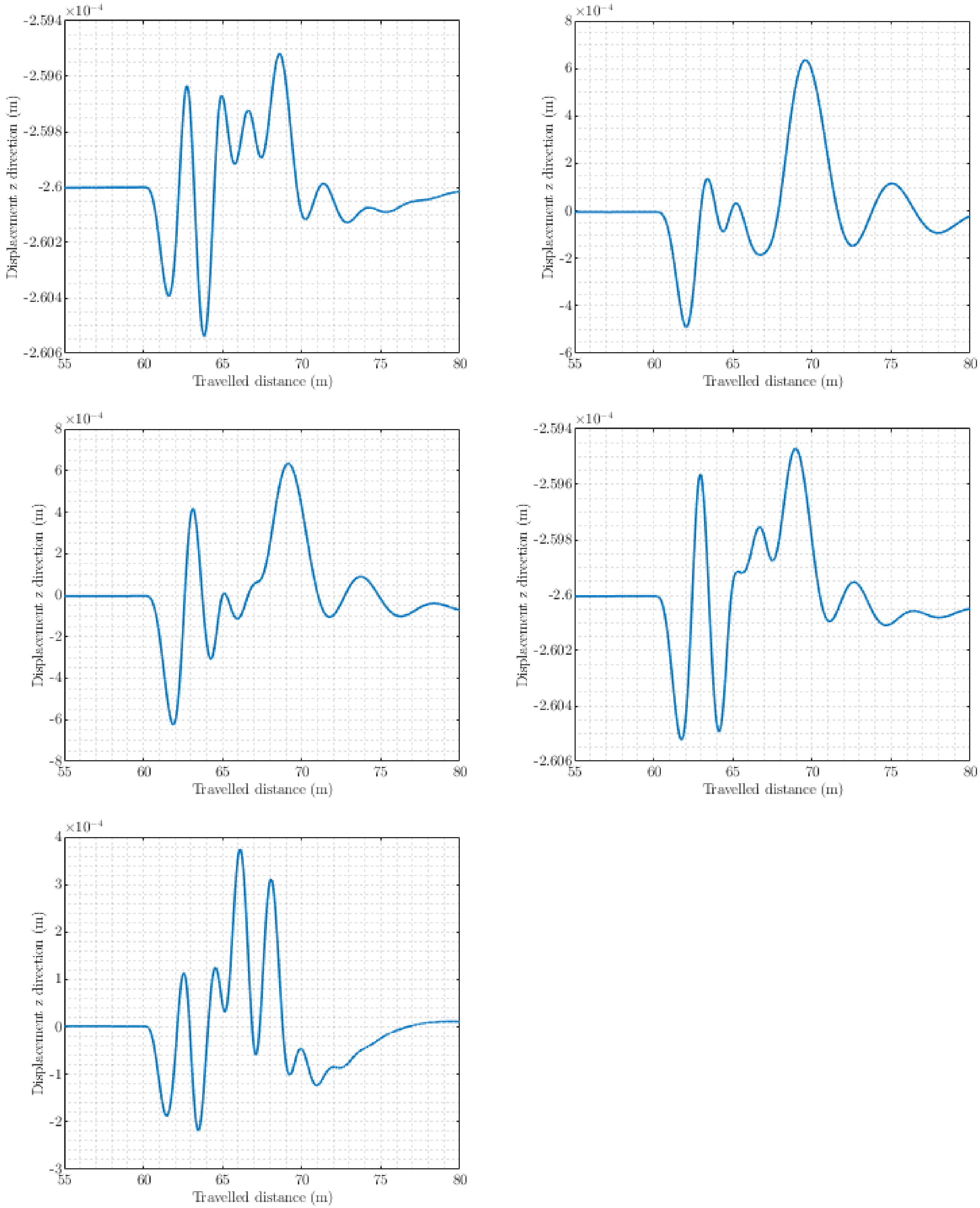
Results of vertical displacement distributions for various cases E = 10E+9, 69E+9, 110E+9, 120E+9, 210E+9, accordingly



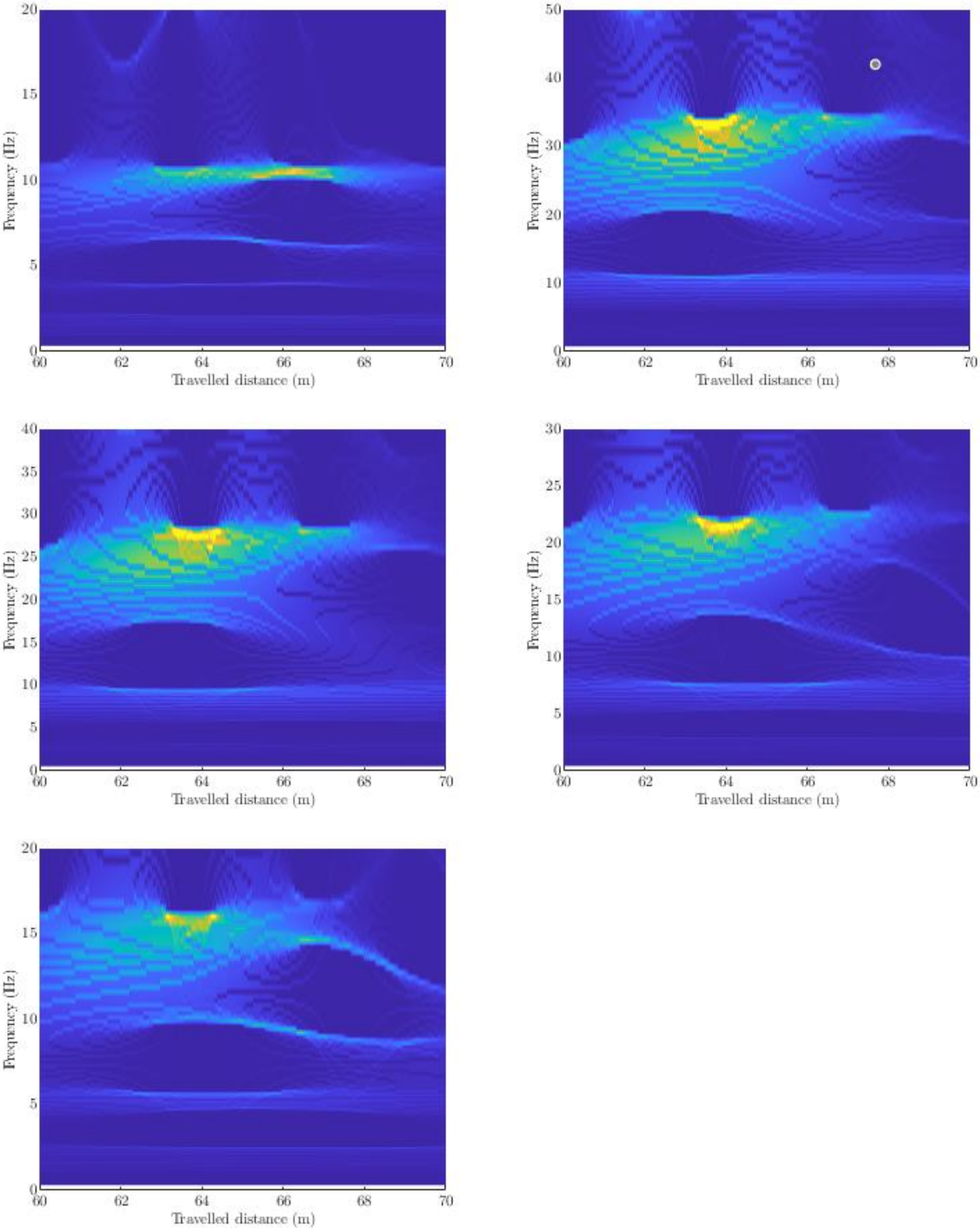
Results of WSST for various cases E = 10E+9, 69E+9, 110E+9, 120E+9, 210E+9, accordingly



Results of Normal force distributions for various cases V=20 m/s, 30 m/s, 40 m/s, 50 m/s and 60 m/s, accordingly



Results of vertical displacement distributions for various cases V=20 m/s, 30 m/s, 40 m/s, 50 m/s and 60 m/s, accordingly



Results of WSST for various cases V=20 m/s, 30 m/s, 40 m/s, 50 m/s and 60 m/s, accordingly