EVALUATION OF TRUCK CABIN VIBRATION BY THE USE OF A DRIVING SIMULATOR

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Abstract

A new method for generating very realistic road descriptions of real roads for simulations is presented. The method has been developed and used for modelling an existing road in Sweden, which is considered to be challenging for truck drivers due to large undulation and unevenness. Using an advanced driving simulator vibration forces have been recreated and analysed. Low frequency vibrations around 1 Hz are dominating and is of the order that would expected from driving on this road. Smaller vibrations of a higher frequency, 7–12 Hz, are also present. These could be front axle vibrations, but more investigations are needed to be more conclusive.

Keywords: Road model, Driving simulator, vibrations, front axle vibrations, HGV

1. Introduction

Virtual prototyping and assessment by simulation has become a useful tool for vehicle manufacturers to reduce costs and development times. Specifically, using an advanced driving simulator early in the design phase may reveal defects in the construction, which otherwise would not be noticed until full scale prototyping.

This paper describes how a high end moving base driving simulator together with a realistic road model may be used for evaluation of a heavy truck trailer combination with respect to vibrations within the truck cabin. To realise this, a new method has been developed in order to recreate an existent road, with all its imperfections, in the simulator virtual environment. To be able to validate the impressions from the simulator, the specific road that is usually driven by Volvo GTT test drivers in field tests was measured and modelled.

In most driving simulator studies, the road design does not have to conform to an existing road. For some purposes, however, it may be crucial that the virtual road describes the real road as close as technically possible. Another example besides vibration studies is fuel consumption evaluation with respect to driver behaviour, where road inclination and unevenness must be modelled with high accuracy.

For this study it was considered important to model a real road as realistically as possible in order to facilitate comparisons with real driving on the road. This applies not only to simulation of the road surface condition, but also road curvature, inclination and crossfall, as well as the surrounding terrain. This paper concerns primarily the difficulties of merging different data sources into a road representation. Vibration measurements were carried out in the driving simulator using the road model. Similar measurements when driving the exact same road segment in reality were planned but could unfortunately not be performed within time for the conference. Hence, the focus of the paper is on the task of road modelling and the vibration measurements are discussed in a more general way.

2. Road Simulation

To recreate a specific road several data sources were used. The main data was retrieved from measurements with the VTI Road Surface Tester (RST). The RST (see Figure) is a device that has been developed with the purpose of measuring the road condition for maintenance purposes. It is equipped with many sensors. The road surface texture and short wave undulation is measured with 17 infrared laser sensors placed at the front of the vehicle, each measuring the road surface height with a resolution of 0.03 mm.

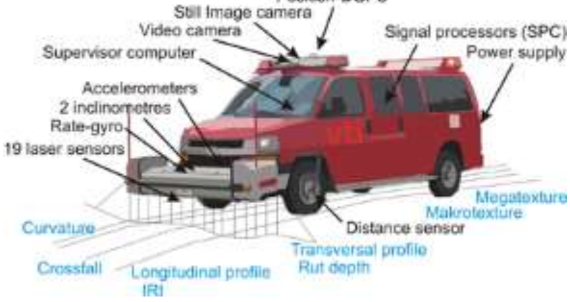

Figure 1 - VTI Road Surface Tester (RST)

It is also equipped with accelerometers, inclinometers and a rate gyro, which gives information of road curvature, crossfall and general elevation. A differential GPS (so called DGPS) relates the measurement data to specific road positions. Measurements can be carried out at a speed of 70 km/h with a sampling length of 0.1 meter for the measurement instruments. Shorter sampling length is possible at lower measurement speeds.

In a Swedish national project (Known Roads), the RST has been used for measuring several roads in the vicinity of Gothenburg, Sweden, with the purpose of road modelling. They were mostly two-lane rural roads, but in some cases also motorways and multilane city roads. For this study a specific rural road of length 35 km, denoted RV180, which is particularly hilly and uneven was chosen since it is a very common road for Volvo to conduct truck tests. This two-lane road was measured with the RST in both directions at a speed of 70 km/h and with a sampling length of 0.1 m. This will not give any information about the road surface texture, but the general unevenness of the road will be well captured. Wavelengths of 0.2 m can thus be measured, which when travelling at 20 m/s can induce vibrations up to 100 Hz in the vehicle.

For and even better description of the roads curvature and elevation it was decided to use also external information. The horizontal information about the road is described accurately in the Swedish National Road Database (NVDB), where GPS coordinates has been measured along the road at high precision two produce a two-dimensional description of the Swedish road network. The absolute road elevation was retrieved from flight measurements of the landscape along and surrounding the road, supplied by Lantmäteriet which is the organization in Sweden responsible for the national maps. Height data was given in a raster with 2x2 meter grids.

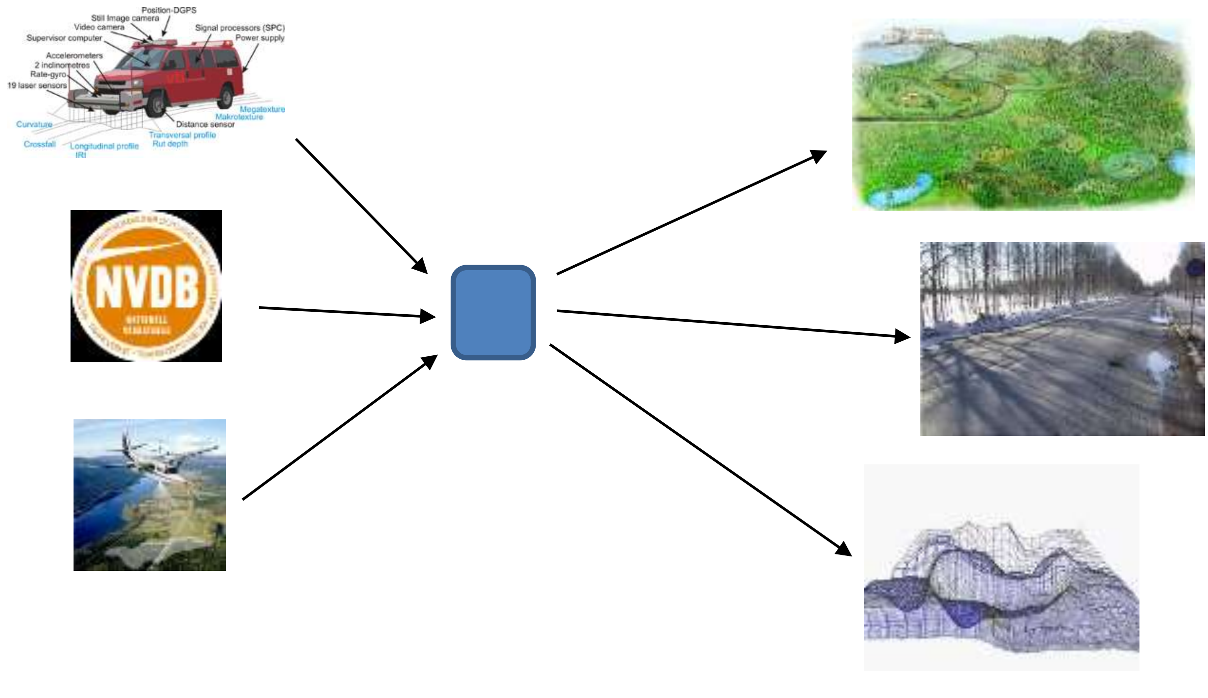

Figure 2 - Input sources and output road model

As illustrated in Figure 2, three different sources of road information had to be merged into one road model describing the roads horizontal properties (curvature), elevation and surrounding terrain, and finally the road surface itself. The process that was developed is described below.

2.1 Horizontal Properties

Although state of the art GPS equipment was used in the RST measurement vehicle, it was clear from inspection of the measured GPS positions in Google Earth that the accuracy of the data (one measurement series for each lane) was not good enough for modelling of the road curvature. Thus, data was acquired from the Swedish National Road Database, where GPS coordinates has been measured along the centerline of the roads at high precision.

Google can also be used in order to find a road's alignment in world, by making a travel direction request between the ends of the road, either in Google Maps or Google Earth. The direction can be exported to a kml-file (in xml format) in order to be parsed in any software. The coordinates are GPS points in WGS84 system.
The data set of Google is like NVDB not uniformly sampled, i.e. relative few data points constitute the road path accurately enough. However, we have seen examples where Googles direction deviates from the true alignment (according to NVDB).

The horizontal properties of a road can be described by its curvature, which is the inverse of the curve radius. A road is normally projected and constructed using three kind of elements: straight sections (zero curvature), circle segment (constant curvature) and clothoids (curvature changes linearly with distance). The clothoide element is used for joining straight and circular segments. Plotting the road curvature as a function of distance, as in Figure 3, results in a diagram with either horizontal lines, representing straight lines (if zero curvature) and circles, or lines with an inclination representing the clothoids.

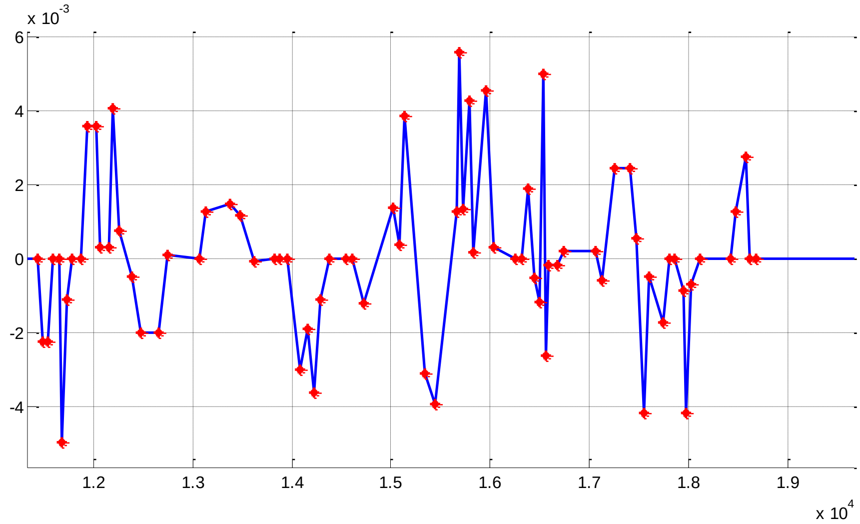

Figure 3 – Road curvature (1/m) as a function of distance (m) for part of the road

The problem of modelling the road curvature from a set of GPS coordinates can be formulated as a least square minimization problem: find the number and positions of the knots (indicated as red points in Figure 3) that minimizes the distance between the GPS points and the resulting two-dimensional road stretch. However, due to the complicated representation of clothoid curves in Cartesian coordinates it is a very difficult problem, and despite plenty of research carried out no one has been able to find an optimal solution.

Many different optimization schemes was tried and eventually a novel method (Baran et al., 2010) turned out to be successful in fitting a clothoide spline to the NVDB GPS-data

2.2 Elevation

Theoretically, the road elevation could be determined from integration of the inclination measured by the RST vehicle. However, from comparisons of measurements conducted in opposite directions of the same road it was evident that the drift of the inclinometer sensor was too large, leading to a substantial deviation of the elevation compared to reality. This is general problem for inclination measurements. It was not possible to cancel the drift by removing low frequency content, so another approach was necessary.

Since the surrounding terrain also was going to be modelled terrain elevation data had already been acquired from Lantmäteriet. Using the continuous description of the roads horizontal positions from the clothoide spline, together with the flight height data allowed for the road elevation at any point to be determined from bilinear interpolation. This elevation, however, only contains low frequency information so high frequency elevation information from the RST inclinometer measurements had to be superimposed in order to reach the desired level of detail, as described below.

2.3 Road Surface

In addition to the elevation, which is a measure that only applies to the centre of the road, there are three other important properties which are measured for each lane individually:

- High frequency elevation for each lane
- Crossfall for each lane
- Road irregularities within each lane

The high frequency elevation is constructed from high pass filtering of the integrated measured inclination. The sampling length is 0.1 m, and a filter cutoff length of 10 m was used for the filtering. For the measured road the maximum amplitude of the high frequency elevation is about 0.1 m.

The crossfall is an angle specifying the lateral inclination of a road lane. It is determined at each sample point from the 17 laser data points using linear curve fitting.

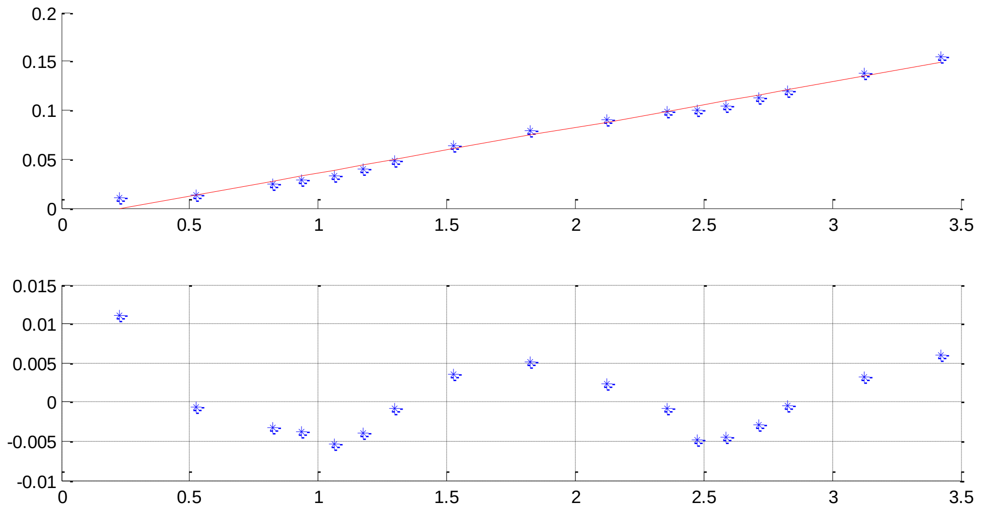

Figure 4 –Top: height of the individual laser tracks (blue) and the derived crossfall (red) for one sample. Bottom: the height of the laser tracks after the crossfall has been subtracted.

After subtracting the crossfall from the laser tracks only the road irregularities are left. This is illustrated in Figure 4, where laser data for a sample taken in a left turn is shown. After removing the crossfall two typical rut tracks with a depth of about 1 cm appear.

2.4 Lane Merging

To match the two separate measurements of the lanes is similar to the problem of matching the RST data with the roads clothoide description. The measurements of two lanes along a road segment usually have different lengths due to the fact that inner curves are shorter than outer curves. Thus, even if the lanes are well matched at one point, alignment will shift along the road depending on the road curvature. The two measurements were made with slight lateral overlap, allowing a comparison of the measurements, which revealed alignment discrepancies. An attempt was made to rescale the measurement distances by projecting the path of the vehicle on the to the centre line of the road for both measurements. While this resulted in a better match between the measurements, it was far from good. Instead, a synchronization algorithm was developed where identical peaks are identified within low pass filtered versions of the measurements, allowing for a variable scaling of the sample point positions for one of the measurement files in order to match the other. The method works well, and while being less sophisticated than e.g. Dynamic Time Warping, it is not as computationally demanding.

After merging the two RST measurements into one data set, it had to be matched with the derived clothoide description. GPS matching from the two sources is not accurate enough and again the synchronization algorithm was used. A very good agreement was found between the curvature measurements from the RST and the clothoide description, making a match of the data sets feasible. A good agreement between RST data and road curvature is necessary since the road crossfall is strongly connected to road curvature.

2.5 Road Representation

To be able to use this road description in the driving simulator, the data had to be represented in the form of OpenDrive and OpenCRG models. These are two international open file format standards for road representation in driving simulators, where the former describes the main properties of the road, and the latter the high frequency road surface information.

In OpenDrive road curvature, elevation and crossfall are described analytically as splines functions. While the road curvature already was described analytically, the elevation and crossfall data was not. Spline fitting can be cumbersome, especially with boundary conditions and demands of continuous derivative (denoted C1 continuity). Initially, this was too difficult and instead spline fitting using cubic polynomials with C0 continuity was used. However, trials in the driving simulator using Volvo's vehicle model of an A-double truck trailer combination showed that C1 continuity was indeed necessary, as heavy bumps otherwise would be present.

A method for spline fitting of cubic C1 polynomials with boundary conditions was therefore developed in-house and used for representing elevation and crossfall within the OpenDrive format. In addition, the road surface finer structure from the laser measurements was also fitted using the same method. By specifying a desired tolerance of how well the fitting represents the actual data points, it is possible to model the measured data at the desired accuracy. For this road a tolerance was set that resulted in a discrepancy consisting of noise with a maximum amplitude of 5 mm. This discrepancy was stored as a large data grid within the OpenCRG format.

3. The Driving simulator

Tests were conducted in VTI's latest moving base driving simulator, the Sim IV, which is located in Gothenburg, Sweden. It is a moving base driving simulator with interchangeable cabins and has been in operation since May 2011. The motion system combines the possibilities of a hexapod motion base with the extended motion envelope in x- and y-direction through a 5x5 m sled-system.

Figure 5 - The VTI Sim IV moving base driving simulator

Vibrations from the road will be generated by the hexapod movements, and the performance is shown in Table 1 and 2. As evident from the specifications, the acceleration and excursion capabilities of the hexapod should be more than enough to generate road induced vibrations with correct amplitudes. Due to motion queuing algorithms and coupling to the eigenfrequencies of the construction, actual movements may deviate from the vehicle movements in the simulation for certain frequencies. The exact behavior is still under investigation.

Table 1 - Hexapod performance

	Excursions	Velocity	Accelerations
Surge	-408 / +307 mm	+/- 0.80 m/s	+/- 6.5 m/s^2
Sway	-318 / +318 mm	+/- 0.80 m/s	+/- 6.0 m/s^2
Heave	-261 / +240 mm	+/- 0.60 m/s	+/- 6.0 m/s^2
Roll	-16.5 / +16.5 deg	+/- 40 deg/s	+/- 300 deg/s^2
Pitch	-15.5 / +16.0 deg	+/- 40 deg/s	+/- 300 deg/s^2
Yaw	-20.5 / +20.5 deg	+/- 50 deg/s	+/- 300 deg/s^2

Table 2 - Sled system performance

	Excursions	Velocity	Accelerations
Surge	+/- 2.5 m	+/- 2 m/s	+/- 5 m/s^2
Sway	+/- 2.3 m	+/- 3 m/s	+/- 5 m/s^2

4. Experiments

Vibration measurements were conducted in the driving simulator using an iphone with an app called "Sensor Data". This allowed for accelerations to be measured at 100 Hz in all three directions using the in-built accelerometer of the smart phone. The phone was attached on the panel next to the driver chair as shown in Figure 6. Using a smart phone for the measurement was chosen due to its simplicity, facilitating an identical measurement setup for subsequent experiments on real trucks.

Figure 6 – Position of the smartphone in the simulator cabin for measuring vibrations

Three separate 6 minute long drives along the same road section was carried out at a driving speed of about 60 km/h. Unfortunately, after finishing the measurements it was found that the phone had stopped logging data after 60 seconds for each drive, resulting in a large loss of data. Still, the remaining data could be analyzed and allowed for some interesting observations.

The measured vertical acceleration of one drive is shown in Figure 7. The plot is representative for all the drives, and it shows that the maximum acceleration is around 1.5 m/s^2. In addition to the measured acceleration, the logged simulated vertical acceleration of the truck (taken at a point 1.15 meters above the centre of the front axle) from the driving simulator kernel is shown.

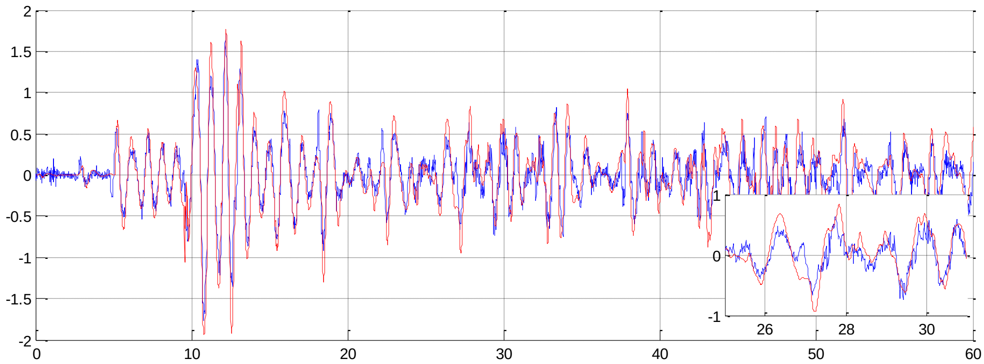

Figure 7 – Vertical acceleration (m/s^2) plotted as a function of time. Measured (blue) and simulated (red). Closeup in the right corner.

There is a very good agreement between the calculated vertical acceleration and what was actually measured inside the truck cabin.

The energy content at different frequencies is analysed with power spectral density (PSD) calculations. Figure 8 shows the PSD energy content for vibrations in all three directions, with different colours for the three separate measurements.

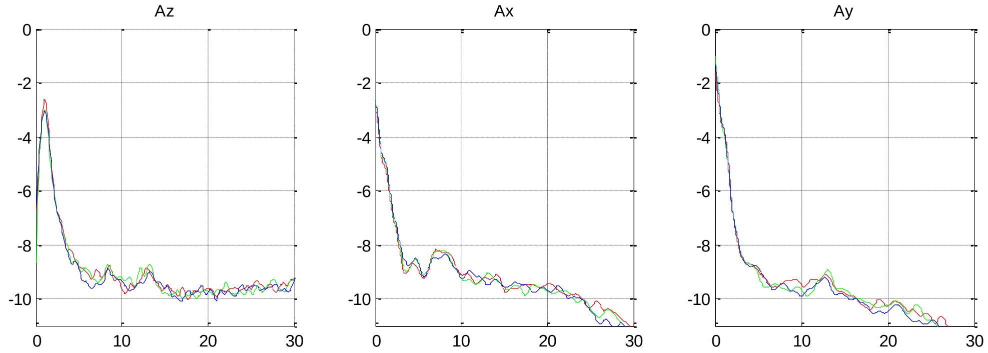

Figure 8 – PSD energy content plotted in log scale as a function of frequency for vertical (Az), longitudinal (Ax) and lateral (Ay) accelerations for three separate measurements.

Vertical vibrations has a large peak at around 1 Hz, which is to be expected and corresponds to a rigid body vibrational mode. The energy content in this vibration mode is in line with previous experiences on a roads with similar roughness as RV180. There is also energy content, although on a much smaller scale, around 7-8 Hz and 12 Hz. Peaks at those frequencies also show up in the longitudinal and lateral vibrations. It is unclear how to interpret these vibrations. Normally frame structure vibrations show up from 7 Hz and upwards, while front axle vibrations are around 10 Hz. The vehicle model has not been constructed for frame structure vibrations. Front axle vibrations, on the other hand, will likely show up in the simulation. As mentioned above, coupling to the eigenfrequencies of the simulator construction may effectively act as a filter on the produced vibrations, which adds to the complexity of generating the correct forces.

From a vibrational point of view, the vehicle model was primarily constructed for low frequency vibrations in the 1-3 Hz range. In that respect, the road model seems to generate satisfactory results in the driving simulator. Still, for a deeper understanding and improvement of the models, future work involves real truck measurements on the same road for comparison with the simulator data.

Acknowledgements

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5. References

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