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GROUND VIBRATION GENERATED BY THE PASSING OF A TRUCK ON A SPEED BUMP

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Abstract. *The growing levels of traffic in urban areas is becoming an increasingly important environmental issue in modern and developing countries. As a heavy vehicle travels over an uneven road surface a complex dynamic interaction occurs which induces dynamic loads into the ground. The generated ground vibrations propagate outwards and can lead to discomfort and / or damage to nearby bystanders and structures. The research presented in this paper is focused on the development of a two-step numerical model to estimate the ground vibrations generated from a heavy vehicle travelling over a speed bump (or geometric obstacle). The first step employs a multibody system to model the heavy vehicle and simulate the dynamic interaction between the vehicle and the geometric obstacle, while the second step makes use of the finite element method to simulate the propagation of ground vibrations. The multibody model is used to produce a time-history of the dynamic loads (i.e. contact forces) generated at the tyre-pavement interface, which is then input into the finite element ground model. Validation of the approach is undertaken through a comparison with well-established experimental results. The influence of various parameters, such as vehicle speed and geometric properties of the obstacle, were investigated through a sensitivity analysis. The resulting model is flexible and can be used to evaluate numerous vehicle-obstacle combinations on the ground vibrations generated.*

1 INTRODUCTION

It has been well established that ground vibrations in traffic-heavy areas can induce discomfort (and in some cases, injury or fatigue) to the local population. While traffic-induced vibrations rarely contain the intensity to cause considerable structural damage, they are certainly an important source of discomfort to those living or working in these zones [1]. Of the generated ground vibrations, the vertical component is most significant at ground level, while the influence of the horizontal component steadily increases for structures with a greater number or floors [2].

One of the most significant sources of ground vibration in urban areas is due to the passage of vehicles over transient features on road surfaces (e.g. speed bumps, potholes, rail crossings, etc.). In particular, the ground vibrations generated due to heavy vehicles can be of considerable concern [3].

The vehicle-ground interaction is a complex problem and the prediction of the vibrations would require a simultaneous solution of the equations of the vehicle and the ground. However, since the stiffness of vehicle's suspension system and tyres is much smaller than the stiffness of the ground, the problem can be decoupled into two quasi-independent models [4]. The research presented in this paper is focused on the development of a two-step numerical method to simulate the ground vibrations generated due to the passage of a heavy vehicle over a geometric obstacle. The first step involves the simulation of the vehicle-pavement dynamic interaction using the multibody approach. Previously, models of vehicle-pavement interaction were developed using a lumped-mass tyre model [5]. In this paper, a rolling tyre model was used.

The second step uses the dynamic loads generated from the multibody simulation in a ground model to simulate the propagation of ground vibrations due to the passage of the vehicle. The Finite Element Method (FEM) is used to model the ground due to its convenience and versatility [6].

This paper presents an outline of the development of the two-step model and its validation based on experimental results from the literature [7]. A sensitivity analysis is also presented to study the influence of some parameters of the interaction on the ground vibrations.

2 VEHICLE-ROAD INTERACTION MODEL

With the multibody approach, a mechanical system is represented as a combination of bodies and force elements, each with well defined properties. It is important to note that a system can be represented by various multibody models of different complexity depending on the dimension of the model and the number of bodies and Degrees of Freedom (DoF).

For a road vehicle, a simple model would contain the minimum necessary amount of bodies (a car body and two wheels in 2D) while a more complex model would take into account other parts of the vehicle.

In most models, the vehicle-road interaction is simulated with a lumped mass model ; the tyre-type link between the wheel and the road surface is represented as a spring and damper, such in the model developed by Lombaert et al. [7].

The dynamic interaction between the vehicle and the road is simulated using EasyDyn [8], a C++ library which allows for the solution of motion equations of multibody systems.

If the roll motion is neglected, the situation can be represented as a two dimensional system. The vehicle model used is the simplest combination of bodies possible (a car body and two wheels), each with their own intertial properties and connected by springs and dampers. The road is considered as a rigid surface whose, profile can be defined as a shape function, and the vehicle will interact with it via the tyres. The various parameters (inertia properties, stiffnesses and dampings) are based on Lombaert's case study [9].

In order for the simulation to occur properly, the transposition matrix of each body must be correctly defined since they represent the relative position of the bodies within the system. DoF must also be defined, with caution as some are master DoF, which are imposed (horizontal displacement of the vehicle, rotation of the wheels) while others are slave DoF (vertical displacement of the bodies, rotation of the car body) whose values depend on the master DoF and the dynamic interaction simulated.

The heavy vehicle model is represented in Figure 1. In order for the vehicle to maintain a constant speed, the time derivative of the configuration parameters q_0, q_4 and q_6 (master DoF) were locked according to the speed of the vehicle.

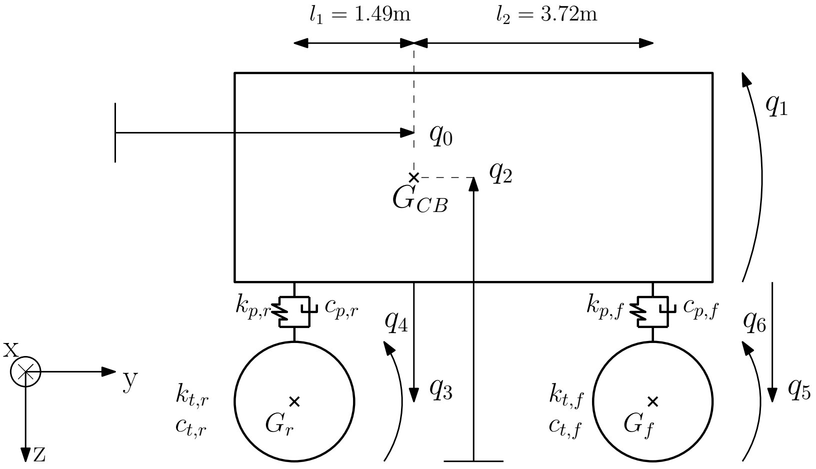


Figure 1: Vehicle-road interaction multibody model used for this work.

The simulation performed with this model results in a time history of the contact forces between the wheels and the road (both rear and front). This interaction is the sum of the static component, due to the weight of the vehicle and a dynamic component caused by the interaction with the geometric obstacle.

3 GROUND MODEL

Soil is a complex discontinuous material composed of solid particles, water and air. It exhibits anisotropic and non-linear behaviour. For a dry soil, it is reasonable to neglect the non-linear behaviour if the shear strain is less than 10^{-5}, which is the case for traffic-induced ground vibrations [9]. While several methods exist to model soil for a dynamic simulation, the FEM was chosen for this study. It is frequently used in vibration modelling due to its convenience and versatility and is not limited by geometric complexity. The only downside of the FEM is the increased computational time compared to other methods [6].

Of all of the ground material properties, the damping is one of the most influential on the propagation of vibrations [10, 11]. Soil damping is usually represented by the complex valued Young's modulus and shear modulus, leading to complex wave propagation values for the velocity. However, such an approach is not suited for use in time domain analysis, as it would result in a non-causal response [12].

The Rayleigh damping model is well suited to time domain FEM. It is based on the construction of the damping matrix **C** from the mass and stiffness matrices **M** and **K**, respectively.

$$\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K} \tag{1}$$

This implies that the loss factor η can be expressed as the sum of the proportional contributions of the stiffness and mass [13] as shown in the following equation:

$$\eta = \frac{\alpha}{\omega} + \beta\omega \tag{2}$$

From this, it is possible to obtain a stiffness-proportional viscous damping by setting α equal to zero [13]. For each layer, β was obtained from the hysteretic damping values (η) used by Lombaert et al. [7], as well as an estimated value of the dominant frequency of the ground vibrations obtained with his model, using the following formula [14]:

$$\beta = \frac{\eta}{2\pi f} \tag{3}$$

The ground was therefore modelled using the FEM, as a superposition of homogeneous layers with well defined properties (density ρ, Poisson's ratio ν, Young's modulus E and viscous damping β). A viscous damping model has the advantage of being usable in time domain analysis, unlike hysteretic damping and is also less complicated to implement than a Rayleigh damping model [15].

The infinite nature of the ground must also be taken into account to avoid wave reflection at the domain border [6]. Since it is obviously impossible to build an infinite model, correct boundary conditions must be defined in order to represent the infinite behaviour of the medium. As shown is Figure 2, infinite elements (Figure 3) are added at the border of a thin hemispherical shell. This is performed prior to the creation of the internal part of the ground model in order to reduce the computational time. The road, which also consists of several layers, is added on top of the hemispherical ground model. The bodies are bound together by a *tie*-type constraint to ensure that their common surface remains the same throughout simulation.

The output data from the simulation is the displacement, velocity and acceleration time histories of the ground in the 3 axes at different distances from the road. In order to do that, a dynamic-implicit step was defined with a time increment of 10^{-5} s over a period of 5 s and those points were defined every meter on a straight line perpendicular to the road, with a distance ranging from 0 - 24 m.

The mesh is chosen differently for the areas in the model. The external shell is meshed with 0.8 m long hexahedral finite elements (C3D8R) which allows for the generation of infinite elements (CIN3D8) at its border. The internal part is meshed with 1 m long tetrahedral elements (C3D4) for the most part, but some regions of interest (i.e. the location of the road and the vibration measurement points) are meshed using 0.3 m long

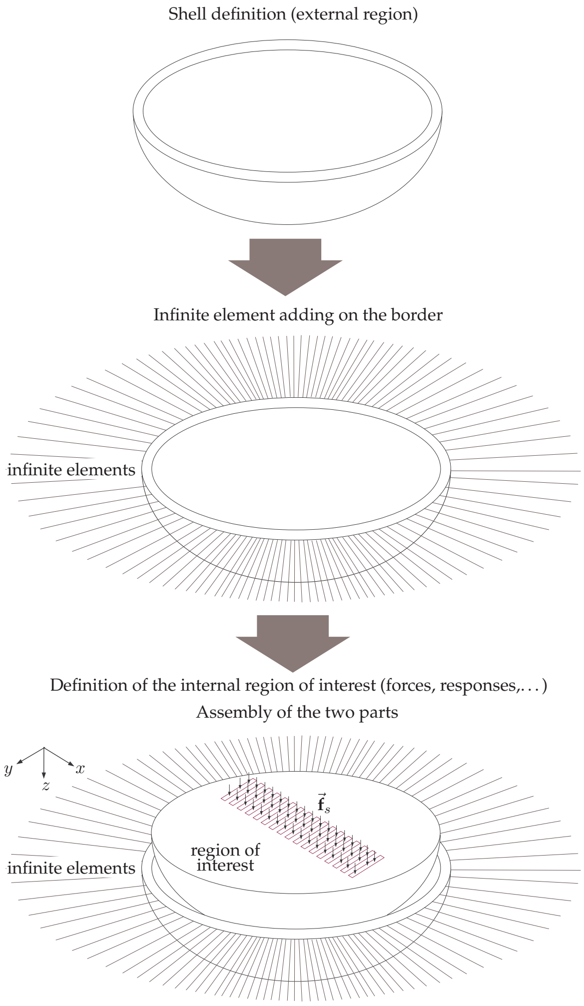
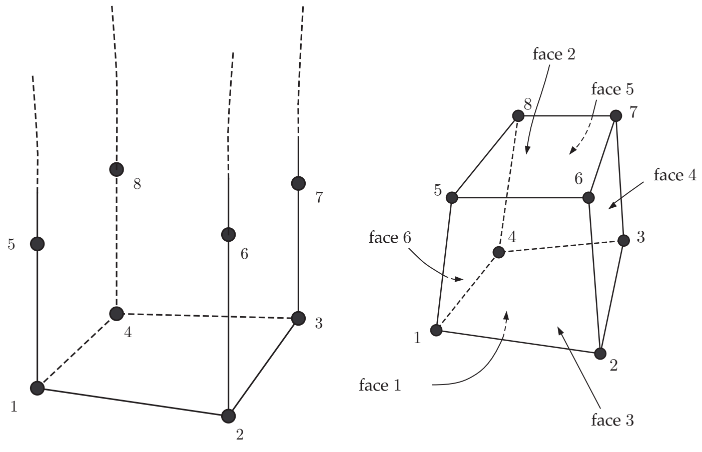


Figure 2: Illustration of the procedure to develop the ground model [6].



(a) (b)

Figure 3: Comparison of infinite elements (left) and finite elements (right) [6].

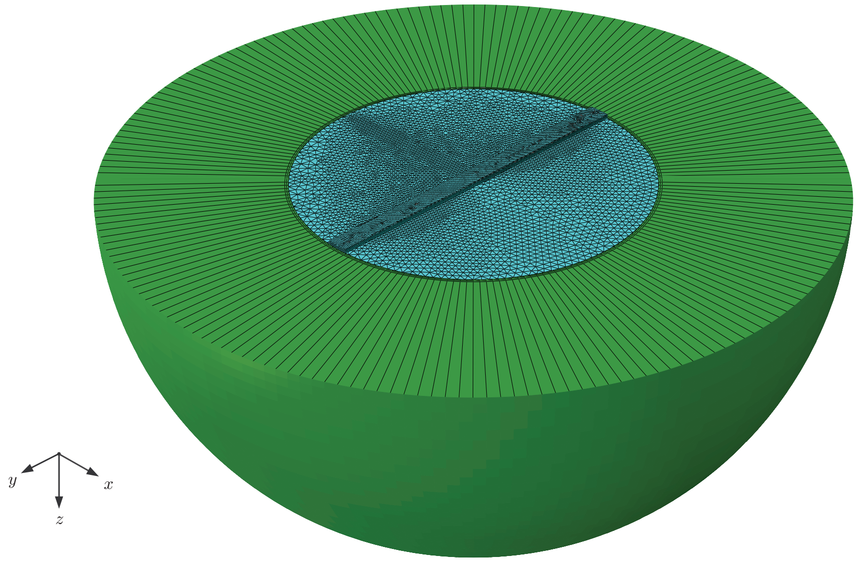


Figure 4: The meshed ground model used to simulate wave propagation in the soil

elements. The road is meshed with 0.3 m long hexahedral elements. The completed ground model is presented in Figure 4.

Finally, the moving loads are implemented through a Fortran subroutine that explicitly defines the location and magnitude of the contact pressures between the tyres and the surface of the road for every time increment of the simulation as illustrated in Figure 5. Since the vehicle has a constant speed, it is straightforward to define the position as a function of the time. The pressure is defined with condition statements based on the results of the multibody simulation.

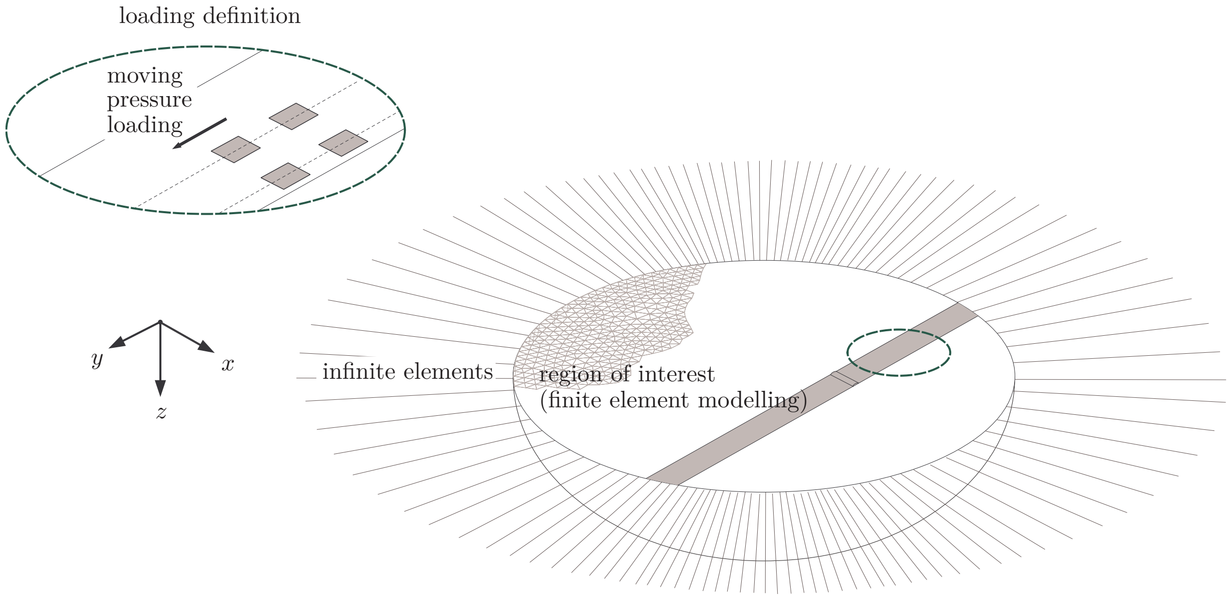


Figure 5: Implementation of the moving loads on the ground model.

4 RESULTS

From the simulation, the time history of the free field displacement, velocity and acceleration in the lateral, longitudinal and vertical directions at various distances from the road are obtained.

Due to the presence of infinite elements, the defintion of appropriate boundary conditions was not possible and a permanent displacement of the whole model is taken into account. This continuous component of the displacement can be removed using a high-pass filter to isolate the ground vibration component due to the dynamic loads.

4.1 Validation

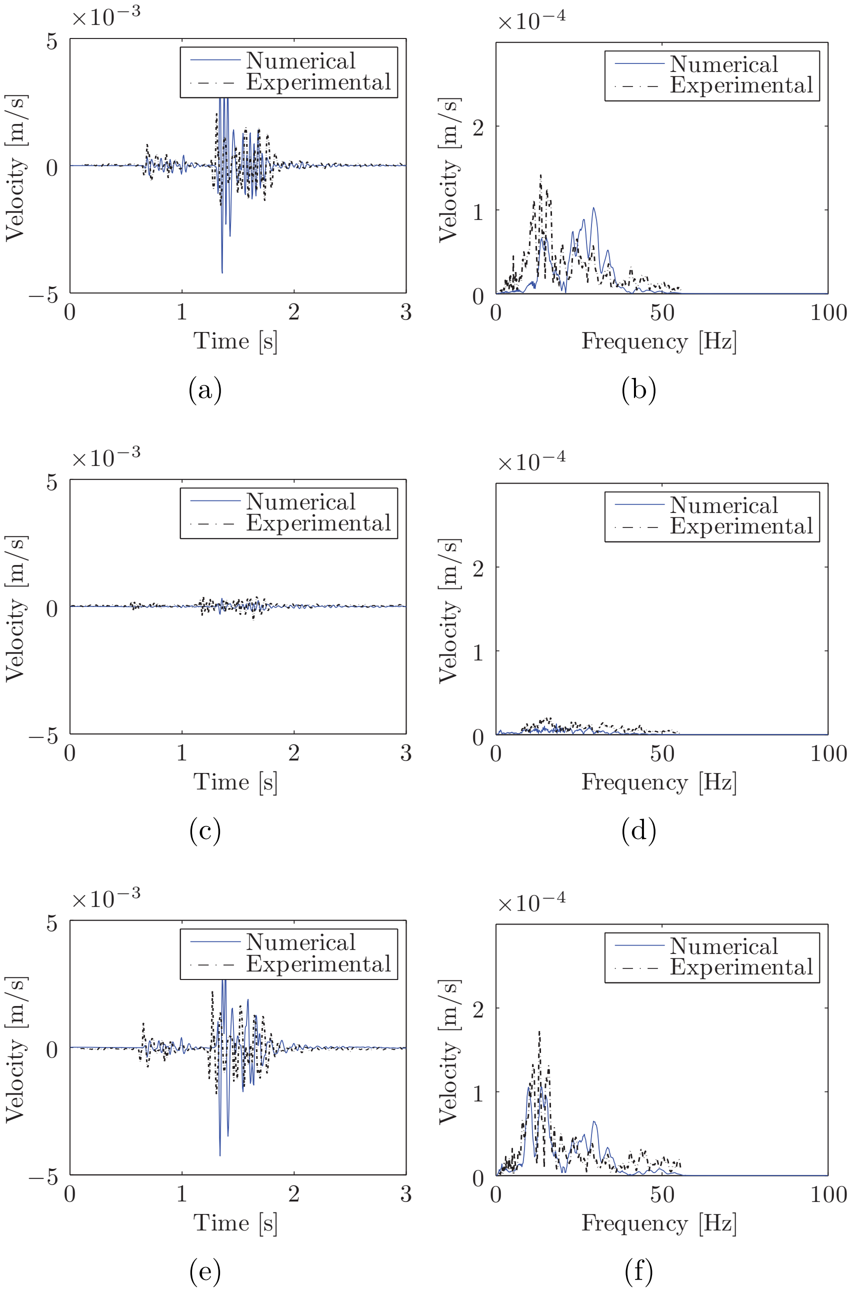
In order to validate the model, experimental results obtained by Lombaert [7] were compared to those from the simulation of the same situation. The inertial and geometrical properties of the vehicle are based on the Volvo FL6 truck (also provided in [7]). The vehicle traversed a 1.7 m long and 54 mm high trapezoidal traffic plateau at a constant speed of 30 km/h. Figure 6 shows the comparison between the predicted and measured time histories of the ground vibrations. The results are similar with the exception of a slight overestimation of the maximum magnitude, which corresponds to the moment the rear axle encounters the obstacle. A comparison between the simulated and experimental frequency spectra was also performed, and those are found to agree well. There is a slight underestimation within 0 - 20 Hz, and a slight overestimation at frequencies greater than 20 Hz.

4.2 Sensitivity analysis

With the two-step model validated, a sensitivity analysis is undertaken to investigate the influence of the shape of the geometric obstacle and vehicle speed on the generated ground vibrations. The Peak Particle Velocity (PPV), defined in equation 4, is a simple and efficient method to compare the magnitude of different vibration records, and is directly related to discomfort [16].

$$PPV = \max(|v_z(t)|) \tag{4}$$

For the sensitivity analysis, the first case examined the PPV of the ground vibrations due to a trapezoidal (H = 54 mm, L = 1.7 m) and half-sine (120 mm) shaped obstacles. The comparison presented in Figure 7(a) shows that the vibrations generated in the case of a trapezoidal obstacle have a greater magnitude than in the case of a sine-shaped bump of similar dimensions. This is explained by the presence of sharp angles on the trapezoidal profile whereas the sine-shaped profile is smoother. Figure 7(b) demonstrates that the magnitude of the ground vibrations is twice as high when the speed of the vehicle is doubled. Since the goal of a speed bump is to cause discomfort to the occupants of a vehicle when the speed limit is exceeded, it is expected that the generated ground vibrations will also have a greater level.

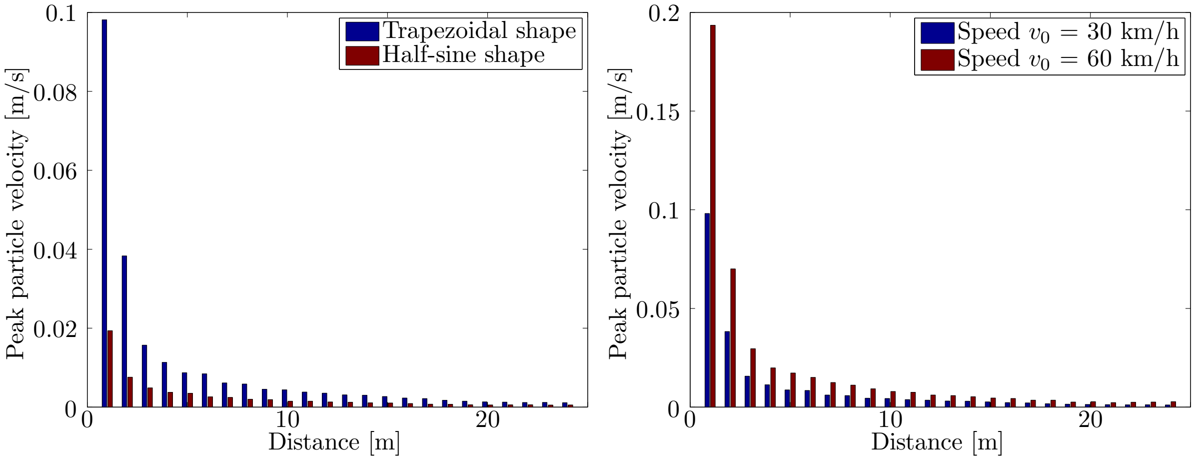


(a) (b) (c) (d) (e) (f)

Figure 6: Numerical and experimental time histories (left) and frequency content (right) of the free field velocity at 8 m from the road, for a Volvo FL6 truck travelling at 30 km/h on a 1.7 m long and 54 mm high trapezoidal traffic plateau in the x (top), y (middle) and z (bottom) directions.

5 CONCLUSIONS

Ground vibrations induced by heavy vehicles are an important source of discomfort in urban areas. These vibrations are caused by the dynamic interaction between the axles of the vehicle and different types of surface unevenness such as a speed bump. This work was focused on the development of a two-step model which can be used to predict the ground vibrations produced by road vehicles travelling over a speed bump in dense traffic areas. The model allows to customize the parameters of the vehicle, the geometric obstacle and



(a)

(b)

Figure 7: Sensitivity analysis of the effect of (a) the obstacle geometric shape and (b) the vehicle speed on the *PPV*.

the ground. The model was validated using an experimental case study of a Volvo FL6 truck travelling over a traffic plateau. Finally, a sensitivity analysis was undertaken to investigate the influence of the shape of the geometric obstacle and the vehicle speed on the magnitude of the vibrations. The results show that the level of vibration is higher when the obstacle profile presents sharp angles. It has also been shown that the level of vibration increases directly with the speed of the vehicle.

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