Effects of Wheel Surface Defects on Ground Borne Vibration

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Abstract: Wheel ground borne vibrations, may have a significant impact on human activity and on nearby buildings. In metropolitan cities, metro lines and their development may cause such vibrations. Despite many works and solutions for path and receiver, the excitation source could also have a great effect. Wheel and rail damages are the two sources of vibration which can increase the damage impact by a factor of 5x. Wheel damage would increase dynamic vertical force noticeably and an increase in ground-borne vibration is expected. In this study with the help of finite element modelling, wheel damage including wheel flat, spalling and wheel oval is studied for a slab track and results are discussed. The studied parameters are velocity and wheel damage and their effect on ground-borne vibrations are examined.

Keywords: ground-borne vibration; FEM; metro; wheel defect; moving load

1 Introduction

Excessive ground vibrations may have a significant impact on human comfort and on the built environment. Ground vibration may also have a detrimental effect on the railway safety, with the deterioration of the embarkment and fatigue effect on rail. Vibrations in the frequency range relevant to the whole-body perception from tracks onto the ground surface, propagate parallel to the ground surface via Rayleigh wave modes with low rates of attenuation with distance [1]. Analysis of these effects requires realistic models of ground vibration generation and propagation. In particular, it has been shown that it is important to include the effects of both the railway track structure and the layered structure of the ground [2-7]. During the last decade various approaches which different accuracy have been carried out to investigate vibration levels from the lines, and also to design tracks and constructional measures to reduce vibration levels. The methods can be classified as either numerical, analytical or empirical methods. Some studies based on analytical approaches can be found in Kausel [8], Krylov and Ferguson [9], and Barber [10] as an effective tool for solving the wave propagation problems. Numerical models using the finite and boundary element method are under development for analysis of wave propagation problems in solids with emphasis on dynamic soil-structure interaction due to the passage of a train [11] [12]. Ground-borne vibrations induced by underground railways are a major environmental concern in urban areas. These vibrations propagate through the tunnel and surrounding soil into nearby buildings causing annoyance to people. Vibration is perceived directly or it is sensed indirectly as re-radiated noise. Tang et al. [13] studied the dynamic response and pore pressure model of the soft clay around the tunnel under vibration loading of Shanghai subway. Their results offered a valuable reference to the design loading, construction and the safe operation of the subway tunnel. Gupta et al. [14] compared two modular prediction tools for estimating vibrations due to underground railway traffic. It was demonstrated how the Craig-Bampton sub structuring technique allows to efficiently incorporate a track in the tunnel and to analyze the vibration isolation efficiency of a floating slab track in the tunnel, without the need to recomputed the impedance of the soil. Degrande et al. [15] presented a numerical model to predict vibrations in the free field from excitation due to subway trains in tunnel. The responses of two different types of tunnel due to a harmonic load on the tunnel invert were compared. The first tunnel was a shallow cut-and-cover masonry tunnel on the Paris subway network, embedded in layers of sand, while the second tunnel is a deep bored tunnel of London underground, with a cast iron lining and embedded in the London clay. Hussein and Hunt [16] developed a numerical model for calculating vibration from underground railways. Further, they investigated the wave-guided solution of the track, the tunnel, the surrounding soil and the coupled system. They also showed that the dynamics of the track have significant effect on the results calculated in the wavenumber-frequency domain and therefore an important role on controlling vibration from underground railways.

Auersch et al. [17] studied train-track-soil interaction using field test in Germany and Switzerland. Tests consist of mearing train, track and soil vibration, while the train passes with 9 different speeds. Studied tracks are two ballasted track (one on a concrete bridge and the other on ground) and a slab one. Up to 10 points in Switzerland are measured and in some points axle box measurements are done.

They were able to determine the transmission function of the wave propagation from hammer tests and use it to determine the wheel dynamic force spectrum which showed a good agreement with the axle box tests. As a result of their work, the comparison of axle box and ground measurements confirms the prediction of ground-borne vibrations caused by trains using continuum mechanics models. dos Santos et al. [18] conducted a comprehensive study of ground-borne vibrations caused by train in Portugal railway. Their work consisted of three basic parts including determining ground and track characteristics and measuring the vibrations caused train. Accelerometers were mounted both on the rails and on different distances from the track. They also used a system consisting of several lasers to measure the vertical displacement of the track and in total 20 train passages were recorded. In another study, he presented a three-dimensional numerical model for predicting vibrations caused by train [19]. He used the field test data in ref. [18] to validate the results of this model. Green functions were used to describe the response of the ground.

There are few researches on effects of wheel damages on ground vibration compare to solutions on path and receiver. One of the dynamic impact forces which have significant effect on ground vibration is generated by wheel flat. When a steel wheel, such as these fitted to all railway rolling stock, is braked too heavily causing wheel-locking, the effect of sliding along the rail is to machine or grind a small flat on the wheel rim. This occur still on older rolling stock; however, modern anti-lock braking systems seek to avoid this occurrence. The result is a wheel which can impart periodic damage to the rail during subsequent motion, until the ‘flat’ is removed by re-grinding or re-profiling for larger flats. Existence of wheel flat induces additional damage beyond the rolling contact fatigue. Furthermore, the discontinuity of slop between the smooth circular part of the rim and the flat induces harsh vibration of track. So, in this paper by FE modelling of a slab track for Tehran metro, effects of velocity and damage dimension is studied. Three damage possibilities are considered: wheel flat, wheel RCF, which causes spalling and wheel ovaling.

2 FE Modelling

The developed model involves the vehicle loads, the track and the ground. Since the load is assumed to be symmetrically distributed on the two rails, half of the track is sufficient to derive the train model. Only vertical vibrations are taken into account. To overcome plane stress/strain limitations, third dimension is modeled explicitly. Galvin et al, [20] uses a coupled FEM/BEM approach where the track is modeled using FEM and the unbounded domain is accounted for by BEM. However, a pure FEM solution is utilized by Banimahd et al, [21] and Kouroussis et al. [22]. A challenge presented by this approach is that absorbing boundary conditions must be implemented at model boundaries to prevent spurious waves contaminating the solution. The authors employed absorbing layers, to mitigate such a wave, by using Dashpot elements, in the ABAQUS software.

2.1 Track Modeling

Track geometry and material properties were modelled in accordance with international union of railways [23] specifications. 20 m of slab track was modeled in accordance with Tehran metro line. The model was symmetrical in the track direction, so only half of all track components and half of the supporting soil was modeled. The rail was modeled as a continuously welded beam with I section profile in accordance with UIC54 profile, Figure 1. The rail was connected to the slab section by using rail pad and base plate sections.

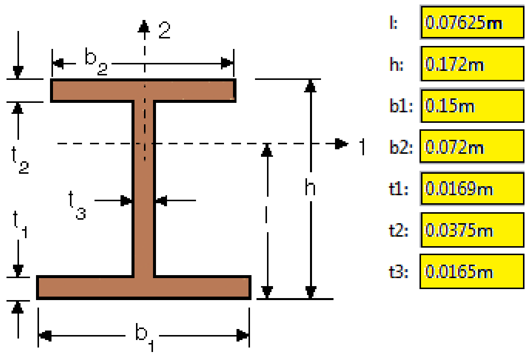


Figure 1
Rail profile dimensions

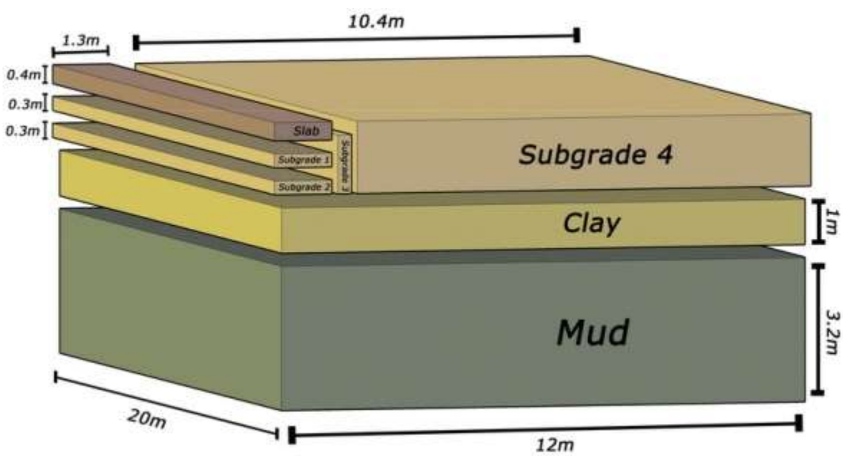


Figure 2
Soil components modeling

2.2 Soil Modeling

Soil properties of the test site was modeled as a stratified linear elastic material consisting of three layers with varying material properties as defined in Kouroussis et al [24].

The uppermost layer consisted of 0.4 m of slab section and the second layer consisted of 0.6 m of subgrade. The third layer consisted of 1 m of clay section and the fourth layer consisted of 3.2 m of mud section, the bottom of which was bounded by an absorbing boundary condition to simulate an unbounded domain. A summary of soil material properties is found in Table 1.

Table 1
Track and soil material properties

FEM part description	Young's modulus (GPa)	Poisson's ration	Density (Kg/m^3)	Thickness (m)
Rail	207	0.3	7850	-
Slab	30.8	0.2	2400	0.4
Subgrade 1	22.9	0.2	2400	0.3
Subgrade 2	3.54	0.24	1900	0.3
Subgrade 3	3.4	0.24	1900	0.3
Subgrade 4	3.37	0.24	1870	1.2
Clay	0.035	0.24	1850	1
Mud	0.003 MPa	0.25	1800	3.2

A uniform stiffness proportional Rayleigh damping value of β=0.0004s was assumed for all layers in accordance with Kouroussis et al [22]. This implementation was essential to accurately model energy dissipation in the soil layers.

2.3 Commercial FEM Software Implementation

Modeling the vehicle interaction with track is time consuming specially in 3D domain and may cause problems in convergence especially in high frequency excitations. Therefore, ABAQUS moving load was defined using Subroutine. This subroutine defines distribution of non-uniform load magnitudes as a function of time and position, at a set of predefined integration points. The moving load codes consisted of axle load of vehicle and the wheel flat impact load which applied to the rail in each 3 m in track length. Parameters of model which are used in this study are listed in Table 2.

Table 2
Parameters in FE dynamic analyses

Axle load (KN)	Wheel profile	Wheel diameter (m)	Train speed (m/s)	Flat size (m)
80	S1002	0.86	5, 13, 22	0, 0.02, 0.04

The model consists of total 42710 elements, 35826 C3D8R solid elements for soil, 6884 B31 beam elements for rail, Figure 3.

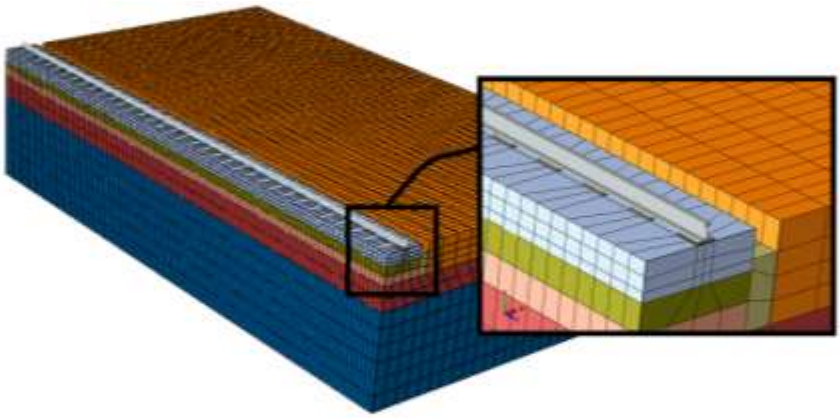


Figure 3
Track and soil mesh generation

The phenomenon of wheel flat in the railway occurs usually because of various reasons, such as locking the wheels when braking or reducing the adhesion force between the wheels and the rail. This failure creates not only impact forces that cause damage to trains and tracks but also cause noise and vibration. Figure 4 shows an example of wheel flat. Other common train wheel failures such as out of roundness (OOR) are really usual. In this type of failure, unlike the wheel flats, no impact occurs. In fact, OOR causes the amount of contact force amplitude to increase. Figure 5 shows a wheel that the length and the depth of the flat are *a* and *b*, respectively. The flatness of the wheel is indicated by a circular chord.

Figure 4
An example of a wheel flat

In this study three types of wheel-flat are modeled. These wheel flats include RCF, oval and wheel flat. Each wheel-flats is modeled with several different sizes, RCF includes 0, 6 and 12 millimeters, oval includes 0, 1, 2 and 6 millimeters and flats including 0, 20 and 40 millimeters. In this paper, we mean the RCF defect, which is a series of spalling on the tread of the wheel. In this model [25], It is assumed that the angular velocity of the wheel (ω) is constant. When the wheel is placed on the flat, the distance between the center of the wheel and the rail, y(t), is minimum, which is obtained because of the difference between the radius of the wheel and the depth of the flat. Figure 6 shows the distance between the center of gravity of the wheel and the rail as a function of time.

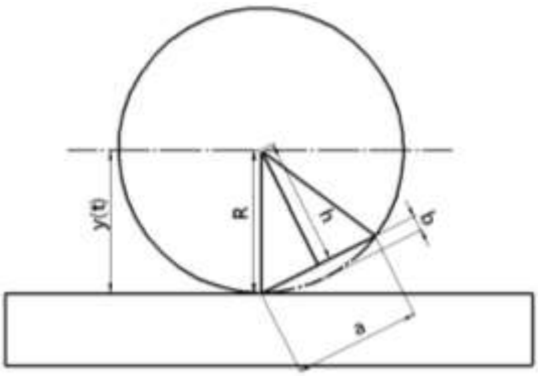


Figure 5

A train wheel with a flat of length a and width b

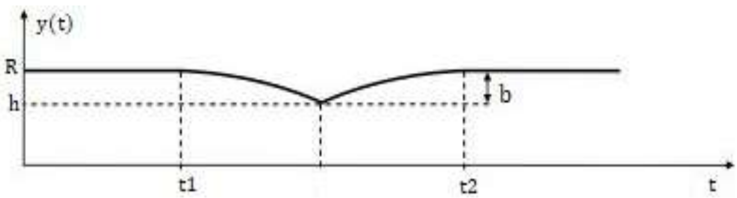


Figure 6

Displacement of the center of the wheel during the passing of the flat

When the circle segments in y(t) are approximated by a second-order polynomial, its time derivative, when it represents the vertical velocity of the wheel, appears as linear functions, and in fact, the vertical linear momentum of the wheel p(t) corresponds to it. The dynamic component of the vertical contact force between the wheel and the rail is easily obtained from the time derivative of the vertical momentum according to F(t)= $\dot{p}(t)$= m$\ddot{y}$. This value appears to be a negative constant value between t1 and t2 and the Dirac delta function t = (t1 + t2) / 2, which means that its value increases infinitely over extremely small period of time at that moment. In this paper, the above theory is used to model the force due to the wheel flat, in which the impact force cause by the wheel flat is applied alternately at time intervals equal to a full wheel round on the contact patch. For the other two faults, the same method has been used to model the fault force. The data point is located 10 meters from the center of the track, as shown in Figure 7.

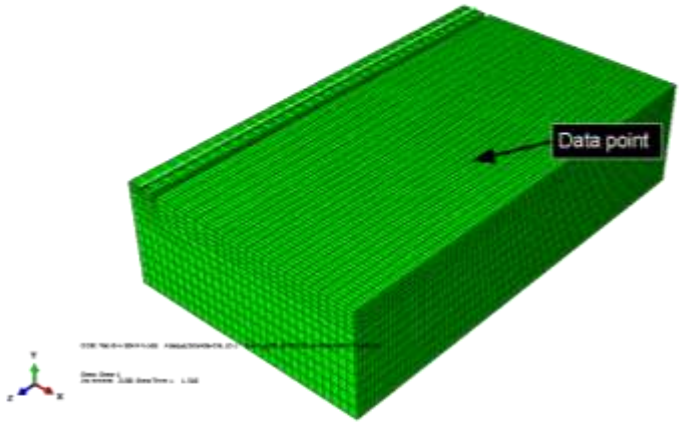


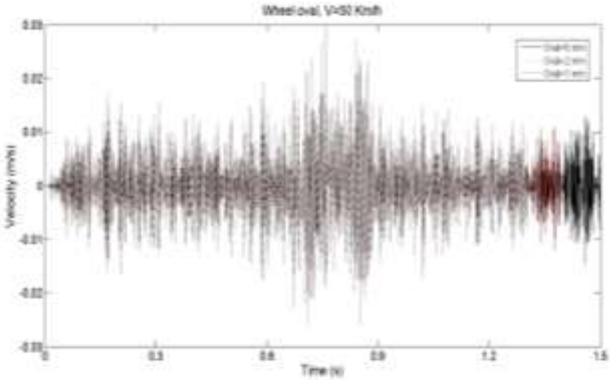
Figure 7
Position of the data point

3 Numerical Results

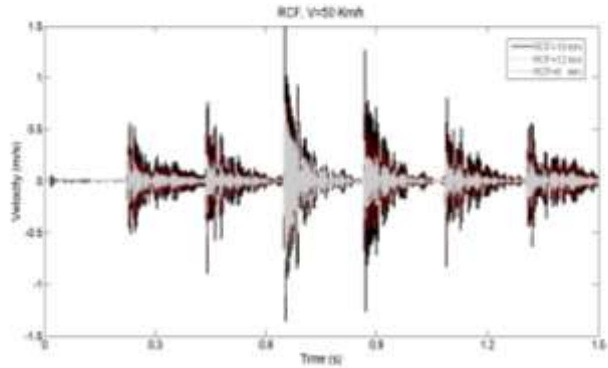
In this Study, three different wheel defects and defect size are considered for modelling. Using the finite element model, 3 different velocities for the moving load were analyzed. The examined velocities were 10, 20 and 50 km/h, respectively. To investigate the ground-borne vibrations caused by these passages, vertical velocity at 10 meters from the center of the track was considered as the output. The time domain results of vertical velocity at the surface of the ground for each of defects is shown in Figure 8. The maximum values of each signal for each velocity and each defect is shown in Table 5.

Table 5
Flat results

Velocity (km/h)	New wheel	Wheel flat		Wheel oval			RCF		
		20 mm	40 mm	1 mm	2 mm	6 mm	6 mm	12 mm	18 mm
20	0.0222	0.2101	0.1748	0.0485	0.0485	0.0485	0.3719	0.7444	1.1145
50	0.0217	0.4951	0.4151	0.0318	0.0318	0.0318	0.7512	0.9475	1.4903
80	0.0185	0.4911	0.5414	0.023	0.023	0.023	0.4646	0.8604	1.3012



(a)



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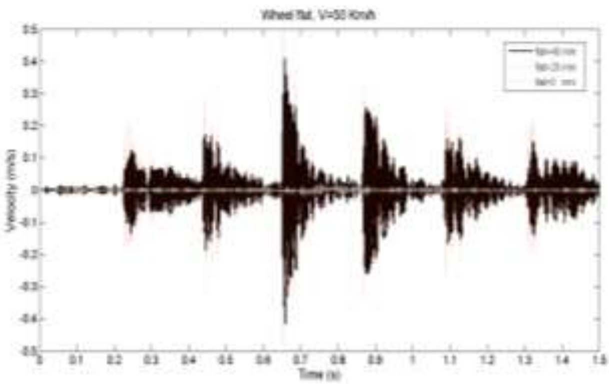
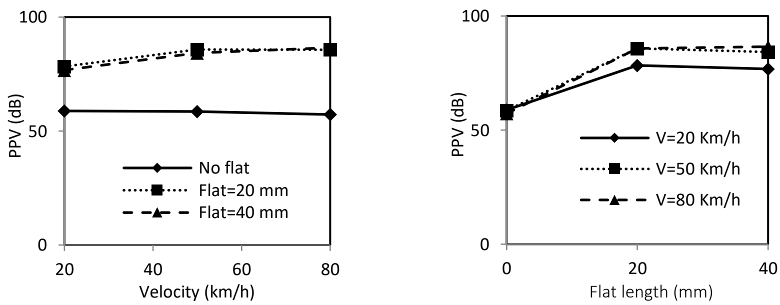


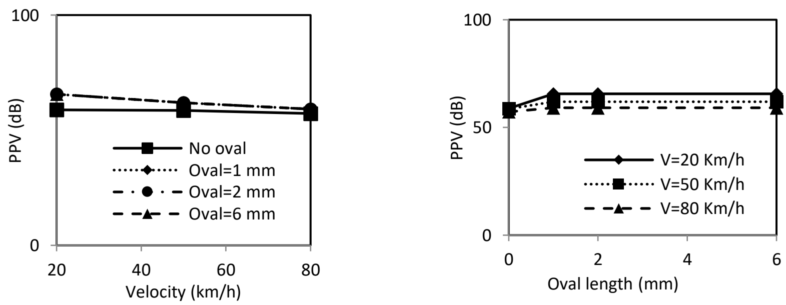
(c)

Figure 8
An example for the time domain results for v=50 km/h
a) wheel oval b) RCF and c) wheel flat

For better comparison, these values are converted to dB (reference 10^{-6} inch/s) and can be compared in Figure 9. According to Figure 9a, it can be concluded that effects of flat length is dominant compared to speed. So, for a wheel flat larger than 20 mm, decrease in speed in order to vibration reduction has no effect. Figure 9b for Oval type failure shows that the velocity is inversely related to the increase in vibrations caused by this defect. In other words, this failure mostly shows its effect on vibrations at low speed. Also, increasing the size of this defect does not show any effect on increasing the vibrations, or in other words, this defect is only a function of speed while studying ground-borne vibration. In fact, increasing or decreasing the defect length of the oval has no effect on the amount of vibrations, and it is only the presence or absence of this defect that can affect the vibrations. Also, from Figure 9c, which is plotted for RCF defect, it can be seen that, unlike the early stage, the size of the defect has a great effect on vibrations. As can be seen from Figure 9c on the left, increasing the size of the defect has a direct effect on the level of vibration and also the presence or absence of this defect has a greater effect on vibration level compared to other mentioned defects. The diagram also shows that increasing the speed has almost no effect on the vibration level and even in small failures, increasing the speed will reduce vibrations caused by this defect type.



(a)



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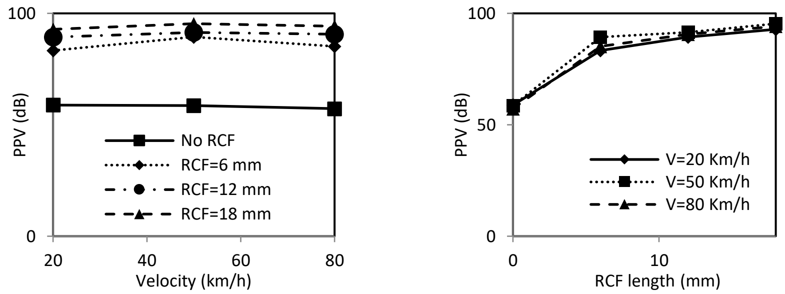

(c)

Figure 9
Wheel damage effect on PPV value (dB) for a) wheel flat b) wheel oval and c) RCF

Conclusions

This paper studied the effect of wheel surface defects and train speed, on ground-borne vibrations. For this purpose, the Finite Element Method (FEM) has been used to model railway track and its super structure. 20 meters of slab track was modeled according to Tehran metro line specifications. Three different wheel defects were considered including wheel flat, oval and RCF. For each type of defect, three velocities of 20, 50 and 80 km/h were considered, and time domain results were converted to dB for better comparison. The results showed that for the wheel flat defects, increasing the speed has less effect compared to speed, on ground-borne vibration. Also, increasing the size of the wheel flat, generally, does not have a significant effect on vibrations. For Oval defects, it was observed that the velocity is inversely related to the increase in vibrations caused by this defect and it mostly showed its effect, on vibrations at low speeds. Also, increasing the size of this defect does not show any effect on increasing the vibration level. In RCF, unlike oval, the defect size has a large effect on the vibration level and the presence or absence of this defect, has a greater effect on vibration levels than the others.

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