Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 6(6):689-695

Fundamental Study on Pavement-Wheel Interaction Forces through Discrete Element Simulation

Yu Liu[1, 2+] and Zhanping You[2]

Abstract: The primary loads on the pavement surface come from the pavement-wheel interaction. This paper presents a discrete element modeling approach for interpreting the underlying mechanism of the pavement-wheel interaction forces, including the vertical contact force and the contact frictional force. As expected, the actual interaction forces are usually controlled by various factors such as properties or characteristics of pavement and tire materials, speeds, acceleration and deceleration of vehicles, and damping properties at the interaction surface. This research emphasized motion features of vehicles including acceleration, deceleration, and steadily moving, as well as the material damping ratio at the interaction interface. In order to eliminate impacts from the other factors, this study utilized an idealized discrete element model, which consists of three parts: a smooth surface, a driving wheel, and a mass. The smooth surface was used to simulate the pavement surface while the driving wheel and mass represent a vehicle wheel and its corresponding mass, respectively. Obviously, both the actual pavement and vehicle loading conditions were idealized: variation of pavement roughness and vehicle loading conditions was eliminated for analyzing mechanism underlying the wheel-pavement interaction. Through this study, it was found that: 1) during wheel movement, the interaction forces were not constant but fluctuated around their averaged values; 2) the average frictional force was close to zero when the wheel is steadily moving, while it was non-zero during its acceleration and deceleration; 3) the observed vertical contact forces had similar trends to those obtained from the finite element modeling.

DOI: 10.6135/ijprt.org.tw/2013.6(6).689

***Key words**: Discrete element method; Frictional force; Pavement-wheel interaction; Vehicle motion.*

Introduction

Pavement is designed mainly to serve vehicles. When cars and trucks are travelling on the pavement, interaction forces at the wheel-pavement interface are directly relevant to pavement design, safety, and damage to both vehicles and the pavement. As mentioned by Hegmon [1], tire-pavement friction is important for traction and braking as well as directional stability of running vehicles. Under certain driving conditions, when the friction demand exceeds the available friction force, skidding, loss of vehicle control, and possibly an accident, can occur. However, it is difficult for one to predict the magnitude of tire-pavement friction, which depends on many variables. Mamlouk [2] performed both computer modeling and experimental tests to study the effect of vehicle-pavement interaction. It was observed that road roughness, truck speed, suspension type, tire pressure as well as many other factors could instantaneously influence the load applied by trucks on the pavement. Other researchers had similar observations. For instance, Liu et al. [3] observed that the surface roughness could significantly impact the dynamic responses of concrete slab. It was believed that the coupling action of vehicle acceleration, suspension deformations, tire forces, and pavement responses could not be neglected [4, 5]. Sun and Luo [6] studied nonstationary dynamic pavement loads that resulted from vibration of vehicles traveling at varying speeds using a quarter-vehicle and half-vehicle models. Time histories of dynamic coefficient corresponding to acceleration and deceleration were obtained numerically. The dynamic coefficient was defined as a ratio of the dynamic pavement load to the static load. It was found that: 1) When a vehicle accelerated, the dynamic coefficient fluctuated significantly at the beginning of the acceleration and then increased gradually. During the acceleration period, oscillation of dynamic coefficient was compressed to form a denser region near the end of acceleration period. The reversed phenomenon was observed when the vehicle decelerated. 2) During the acceleration and deceleration, the dynamic coefficient was distributed over a wide range of oscillation frequencies rather than concentrated at a particular frequency. Xia [7] proposed a full tire-pavement interaction finite element model that could effectively include the dynamic effect of tire rolling to the calculation of pavement response. The tire and the pavement were modeled as a finite strain hyperelastic material and elastic material, respectively. Commercial finite element code, ABAQUS, was utilized in his study to perform several representative simulations. It was concluded that the tire/pavement interaction model could be used to predict pavement response and pavement damage due to fatigue cracking and rutting in the field of pavement engineering. Yang et al. [5] presented a three-dimensional model based on Galerkin method and quick direct integral method to investigate the dynamic interaction between a heavy vehicle and road pavement. It was observed that the coupling action of vehicle body vertical acceleration, suspension deformations, tire forces, and pavement displacements could not be neglected even on a smooth road surface,

[1] School of Highway, Chang'an University, South Erhuan Middle Section, Xi'an City, Shanxi Province, 710064, China.

[2] Dept. of Civil and Environmental Engineering, Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931, USA.

[+] Corresponding Author: E-mail –yul@mtu.edu

Note: Submitted November 21, 2012; Revised April 6, 2013; Accepted April 25, 2013.

such as a highway. They pointed out that emphasis should be put on the dynamics of both vehicle and pavement simultaneously.

In addition to those research efforts discussed above, various approaches were developed or used to study tire-pavement interaction: Markow et al. [8] analyzed the interactions between dynamic vehicle loads and highway pavements by developing analytic models. Papagiannakis and Gujarathi [9] presented a roughness model to investigate the influences of the pavement roughness on the interactions between the pavement and heavy vehicles. Mamlouk [2] performed both computer modeling and experimental tests to study the effect of vehicle-pavement interaction. Saleh et al. [10] proposed a mechanistic roughness model based on the vehicle-pavement interaction. Kim and Tutumluer [11] performed finite element analysis to study the multiple wheel-load interaction in flexible pavement. Li and Yang [4] investigated dynamic interactions between heavy vehicle and road pavement with a three-dimensional finite element method. Shi and Cai [12] presented a three-dimensional (3D) vehicle-pavement coupled model to simulate the pavement dynamic loads induced by the vehicle-pavement interaction, where both the vehicle vibration and pavement deformation were considered. Details about those studies are not main focus of this study, but readers may refer to the references listed at the end of this paper for more information. By reviewing the existing research efforts, it was observed that three categories of methods were employed in the literature to study the pavement-vehicle interaction, namely experimental measurement, analytical analysis, and computer simulation. Computer modeling was the most popular approach in the existing studies. Experimental testing and analytical approaches were commonly used in conjunction with the computer modeling methods. Typical computer modeling approaches were developed on the basis of finite element codes, such as ANSYS and ABAQUS. Few research efforts were made only for interpreting the underlying mechanism of the interaction forces between pavement and a moving wheel.

Objective and Scopes

As mentioned in the background, even though many research efforts have been made in the past decades, it is still challenging to interpret the underlying mechanism of the pavement-vehicle interaction. First of all, even though the pavement-wheel interaction forces could be measured through experimental tests under some specific conditions (certain vehicles and pavements), the results could vary if the specific conditions are different. Secondly, comprehensive numerical models (full-truck or half-truck finite element models for instance) could represent most features of both vehicles and pavements. However, those models usually have the complexities similar to their counterparts. Therefore, instead of using comprehensive models, the main objective of this study is to simulate pavement-wheel interaction with an idealized model. Since the discrete element method (DEM) is an efficient tool to seek solutions for interaction problems of individual entities, the simulation of the pavement-wheel interaction was in a direct and intuitional manner. Additionally, instead of modeling a full-truck or half-truck, only a driving wheel was simulated with the idealized model. Through the DEM simulation, the wheel-pavement interactions were analyzed under various conditions, such as acceleration, deceleration, various damping, and various velocities. Experimental tests are not involved in this study due to the following reasons:

1) The accuracy of DEM in simulating contacting problems has been validated as demonstrated in the previous research [13-15].
2) Instead of exactly and fully predicting the actual pavement-wheel interaction for practical use, the goal of this research is to present a cross-section of the targeted problem. Compared with a complex model, the simple model of this research is easy to understand and the modeling results can be applied to not only the pavement-wheel interaction problem but also many other engineering problems.

Discrete Element Model for Pavement-wheel Interaction

Geometry of the Discrete Element Model

The idealized discrete element model consists of three parts as shown in Fig. 1: the pavement surface, the driving wheel, and the “vehicle mass” which is a part of the total vehicle mass distributed to the driving wheel. The Particle Flow Code in three-dimension (PFC3D) is one of the most powerful discrete element codes and was used in this research. With the PFC3D, the pavement surface was simulated with a standard infinite wall, while the driving wheel and the vehicle mass were simulated with two individual clumps. In the PFC3D, an infinite wall is absolutely smooth, with the infinite dimensions in both the transverse and longitudinal directions. Therefore, the influence of the pavement surface roughness was eliminated in this research and the interface frictional property was simulated through setting frictional coefficients of the infinite wall and the driving wheel. A clump in the PFC3D can be considered as a special element which is created through modifying a group of slaved discrete elements (balls). The slaved elements can be overlapped to any extent without causing larger internal contact forces. As shown in Fig. 1, the vehicle mass was overlapped to achieve its high density and smooth surface, while the center of the driving wheel was overlapped to ensure the smooth interaction between the mass and the wheel. In order to simulate the inertia force during the wheel acceleration or deceleration, a vehicle mass was included in the idealized model as shown in Fig. 1.The vehicle mass is concentrated into the center of the wheel and simulated with a special clump. The volume of the clump was much smaller than its counterpart (a part of the vehicle mass). As a result, the vehicle mass in the idealized model has a relative larger density than its normal value.

Mechanical Model

The mechanical model of the idealized model herein describes the force-displacement relations, frictional properties, and mechanical damping at contacting points of adjacent discrete elements. The force-displacement relationships were simulated with a linear elastic contact stiffness model which was defined with normal stiffness (K_n) and shear stiffness (K_s). The normal stiffness and shear stiffness are

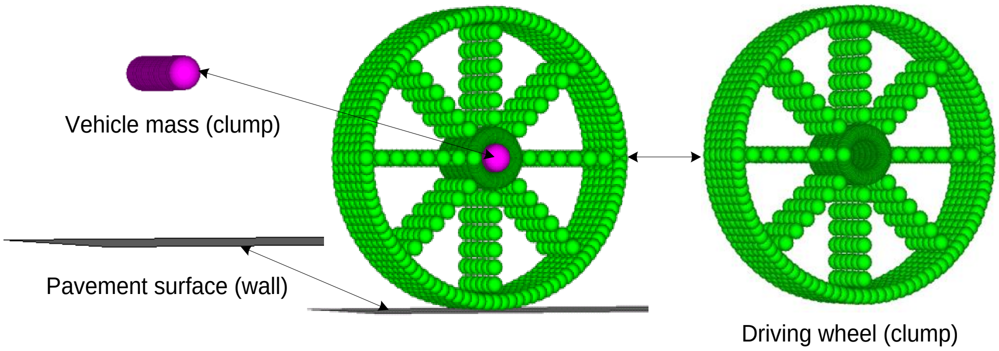


Fig. 1. Illustration of the Idealized Discrete Element Model.

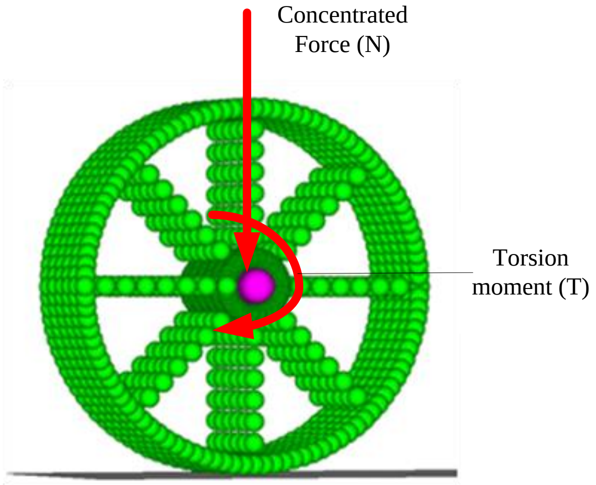


Fig. 2. Typical Motion Feature of the Rolling Wheel.

two constants for calculating the contact forces or the relative displacements between two contacting elements. The frictional properties between elements were simulated with a slip model, which is defined with a frictional coefficient. The previous research [16, 17] and the PFC3D manuals provide more details about the linear elastic contact stiffness model and the slip model. The viscoelastic contact damping model was used in this study to simulate the mechanical damping. Two key parameters were used in this research to define the viscoelastic damping model. They are *dmp_yvis* and *dmp_xvis,* which are critical damping ratios in the normal and shear directions, respectively. More details on the viscoelastic contact damping ratios are provided in the PFC3D manuals. It should be noted herein that both the pavement surface and the wheel were simulated with elastic contact models; therefore, the most suitable case of this research is the rigid pavement under a single wheel load.

Loading Conditions

A vehicle usually has two types of wheels, namely the driving wheels and the driven wheels. A driving wheel is a powered wheel on a steam locomotive. Similarly, the driving wheel of a truck is defined as a wheel powered by the truck engine while the driven wheel is defined as a wheel moving through the traction force or hauling force. As shown in Fig. 2, a concentrated force and a torsion moment were applied at the center of the driving wheel to simulate the vehicle weight and the engine powered torsion force.

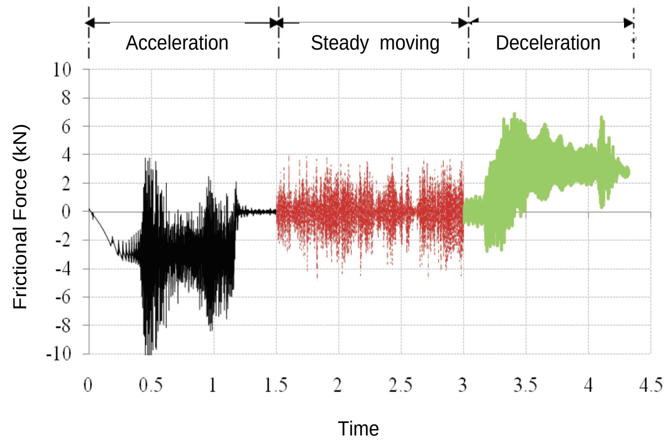
In reality, wheels of a running vehicle encounter not only the concentrated force and the torsion moment but also an inertia force during the wheel accelerating or decelerating. Therefore, not only traffic weight (the concentrated force) but also masses of the wheel and vehicle are important to correctly simulate the loading conditions of the wheel. As discussed in the next section of this paper, the inertia force was directly related to the frictional force at the pavement-wheel interaction surface.

Discrete Element Simulation

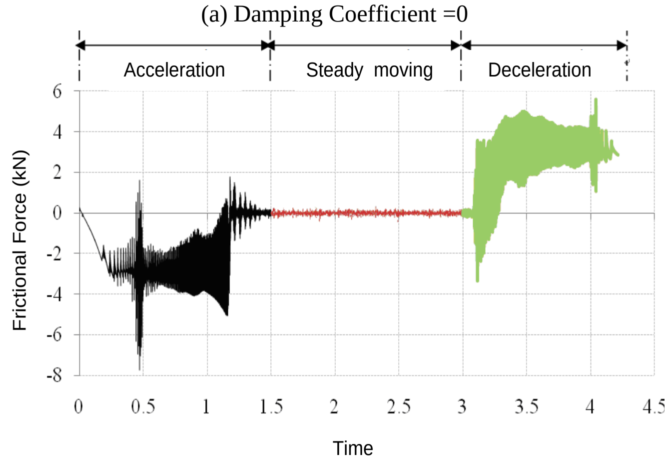
In order to investigate rigid pavement reaction under various wheel loading conditions and materials properties, virtual tests were performed with the following inputs: 1) the geometry of the discrete element model was defined with a wheel radius of150 mm, a wheel width of 120 mm, and a discrete element radius of 15 mm; 2) modulus of the rigid pavement surface and the rigid wheel were 66 and 55 GPa, respectively; 3) the shear critical damping ratio was 0.0, and the normal critical damping ratio was set to 0, 0.1, 0.2, 0.3, 0.5, 0.6, 0.7, 0.8, and 0.9 for nine discrete element virtual tests, respectively; 4) the loading conditions were defined by the vertical concentrated force of 100 kN and the controlled angular velocity of 10 rad/s. It should be noted that there may be different inputs for solving pavement-wheel interaction problems. However, the above inputs were selected in this research as the primary factors, which may significantly impact pavement-wheel interaction. Additionally, the wheel has no skidding problems, which means that there was no relative displacement between the wheel and pavement. Therefore, a larger value was given to the friction coefficient in this search. At the beginning of the virtual tests, a gradually increasing torsion moment was applied until the angular velocity of the wheel is close to 10 rad/s. The angular velocity of 10 rad/s was controlled and kept constant for 2 seconds before the torsion moment was removed and the wheel started to decelerate. During the simulation, the contact forces at the interaction surface between the wheel and pavement were recorded and analyzed as discussed below:

Contact Frictional Forces under Various Values of the Critical Damping Ratio

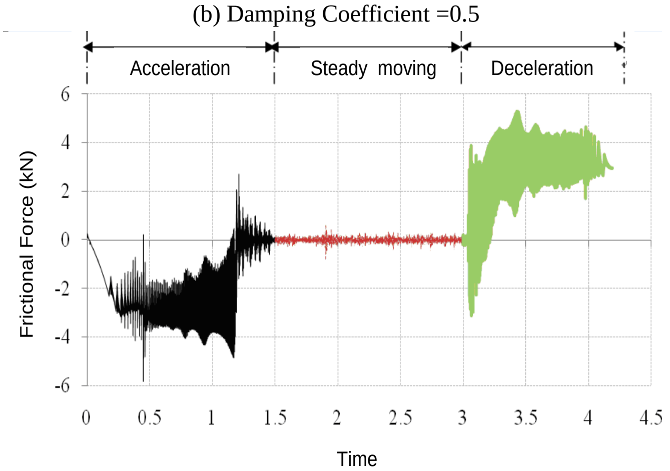
As mentioned in the previous sections, the contact frictional forces



(a) Damping Coefficient =0



(b) Damping Coefficient =0.5



(c) Damping Coefficient=1.0

Fig. 3. Frictional Force vs. Loading Time when the Wheel Rolling Along Pavement Surface (Peak Rotational Velocity = 10 rad/s).

are very important in impacting pavement performances and safe driving. This section herein presents analysis and discussion of the discrete element simulation results in order to interpret the underlying mechanism of the frictional behaviors during the driving wheel rolling on the pavement surface. Fig. 3 shows three representative results of the discrete element simulation. From this figure, the following findings were observed:

1) The average frictional force was zero while the wheel was steadily moving along the pavement surface; it was non-zero value due to the inertia force during the wheel acceleration or deceleration. The frictional force under acceleration was opposite to that under deceleration.
2) While the wheel was moving on the pavement surface, the frictional force was not constant, but fluctuating around its average values. The fluctuant amplitude depended on values of the critical damping ratio and wheel motion features as discussed subsequently.

In order to analyze the fluctuant amplitudes of the predicted frictional force, its maximum, average, minimum values were calculated from the simulation data and plotted in Fig. 4. The following findings were observed:

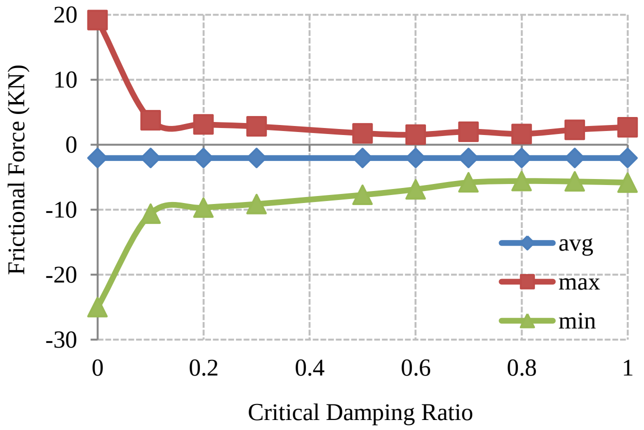
1) The findings above were further validated: the average values of the frictional force were varying when the wheel motion features were different. As shown in the figure, the average frictional force was -2.86kN, zero, and 2.83kN during the wheel accelerating, steadily moving, and decelerating.
2) When the damping ratio had a small value (equal to zero for acceleration or deceleration and less than 0.1 for the steadily moving), the frictional force fluctuated significantly. When the damping ratio had a relatively lager value (larger than 0.2, for instance), both the maximum and minimum values of the frictional force received the negligible impacts from the damping ratio.

Vertical Compressive Forces under Various Values of the Critical Damping Ratio

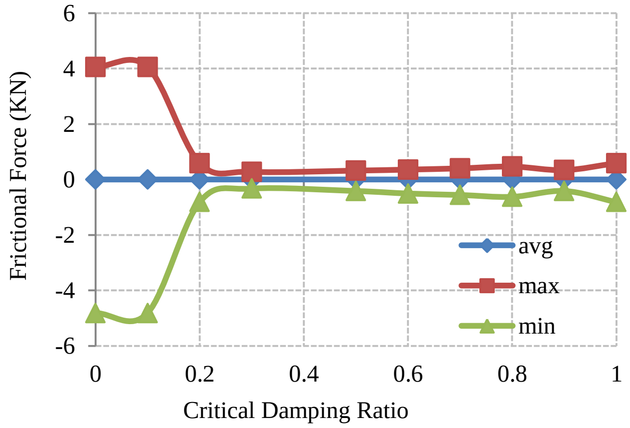
Fig. 5 shows representative examples of recorded normal compressive forces along the pavement surface during the wheel acceleration, steady movement, and deceleration. From this figure, the vertical compressive force was not constant, but fluctuating around its average value. The fluctuant amplitudes were varying from time to time and dependent on damping ratios as well as wheel motion features:

1) Increasing the damping ratio decreased the fluctuant amplitudes of the compressive force for all the simulations.
2) The fluctuant amplitude had a clear trend: a) while the wheel was accelerating, the fluctuant amplitude gradually increased to its peak value, then decreased to a certain value, and then increased at the end of the acceleration; b) while the wheel was decelerating, the reverse phenomenon was observed; c) while the wheel was steadily moving, the oscillating amplitude was constant.
3) The wheel motion features gave apparent impacts on the compressive force. In other words, the wheel accelerating, steadily moving, and decelerating resulted in significant differences of the compressive force curves, which were plotted in three different colors in Fig. 5:

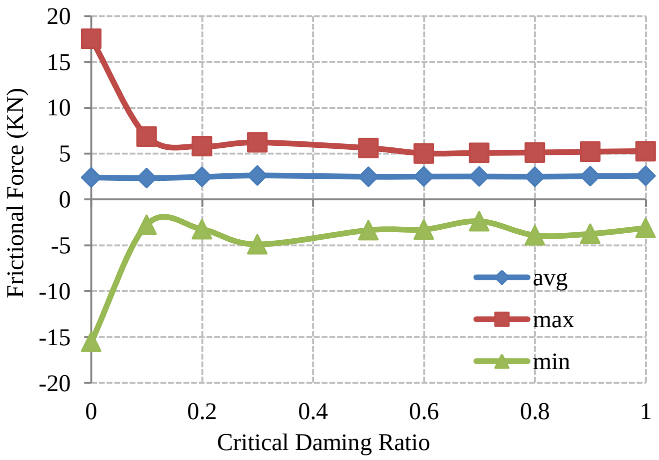
a) The compressive force fluctuated around its average values under all the three different motion conditions, but the fluctuant amplitudes while the wheel was steadily moving and decelerating were significantly smaller than those during the wheel accelerating.



(a) Acceleration



(b) Steady Moving

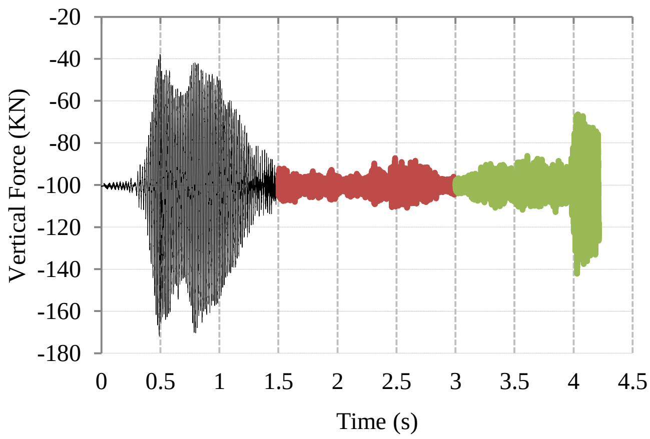


(c) Deceleration

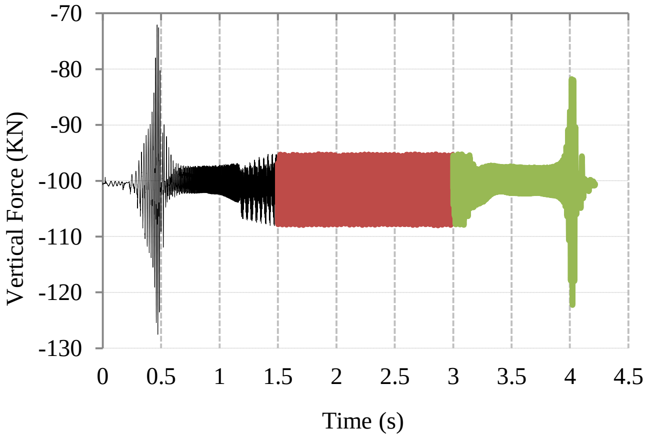
Fig. 4. Average, Maximum, and Minimum Values of the Frictional Force vs. Critical Damping Coefficient.

b) While the wheel was accelerating or decelerating, the fluctuant amplitude varied significantly during the simulation, but it was constant while the wheel was steadily moving.

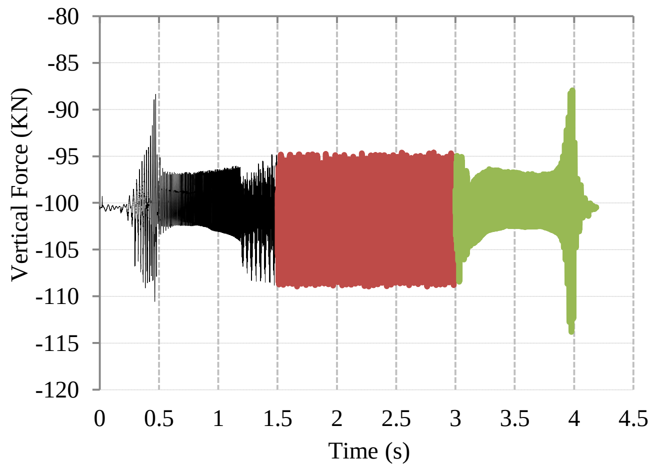
Sun and Lu observed similar research findings from the finite element modeling [6]. In their research, the “dynamic coefficient” was used to characterize the fluctuation of the compressive force at the wheel-pavement surface. A dynamic coefficient of the vertical compressive force is defined as the ratio of its oscillating amplitude



(a) Critical Damping ratio = 0



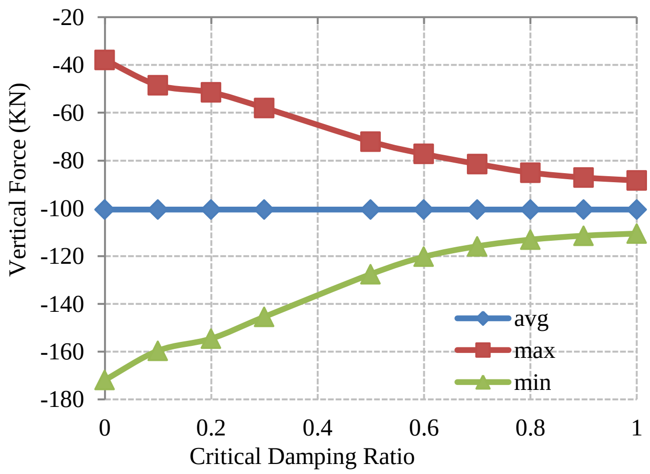
(b) Critical Damping ratio = 0.5



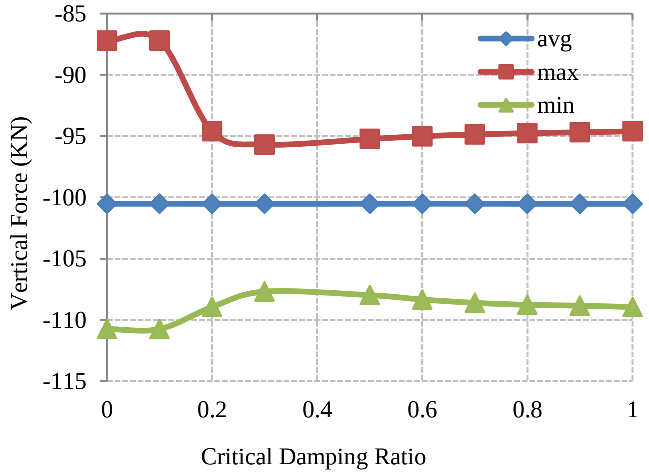
(c) Critical Damping ratio = 1.0

Fig. 5. Vertical Compressive Force vs. Loading Time When the Wheel Rolling along Pavement Surface (Peak Rotational Velocity = 10 rad/s; the Different Colors of the Curves Indicate That Different Motion Features: Acceleration, Steadily Moving, and Deceleration)

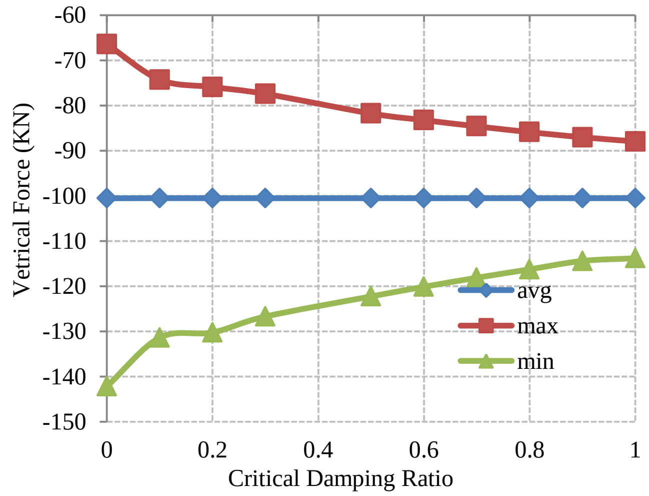
to its average value. In order to further analyze the vertical compressive force as demonstrated in Fig. 5, the discrete element simulation data was divided into three portions based on the wheel motion features. From each portion of the data, the maximum, minimum, and average values were calculated and plotted in Fig. 6.



(a) Accelerating



(b) Steadily moving



(c) Decelerating

Fig. 6. Average, Maximum, and Minimum Values of the Vertical Force vs. Critical Damping Ratio during the Wheel Accelerating, Steadily Moving, and Decelerating.

At the critical damping ratio of 0.0, the maximum and average values of the compressive forces in Fig. 6(a) are -40 kN and -100 kN, respectively. The oscillation amplitude is the difference between the average and the maximum or minimum: –40 – (–100) = 60 kN, or -172 – (–100) = –72 kN. Thus, the dynamic coefficient is (60kN)/(-100kN) = –60% or (–72kN)/(–100kN) = 72%. From Fig. 6, it was found that:

1) As the damping ratio was varying from 0.0 to 1.0, the average vertical compressive force kept the same value of -100kN which was equal to the applied concentrated force. In other words, the discrete element simulation under various damping ratios resulted in the identical average value of the compressive force.
2) As the damping ratio was varying from 0.0 to 1.0, the maximum and minimum values were not constant but dependent on the damping ratio and the wheel motion features.

a) While the wheel was accelerating, as shown in Fig. 6(a), the maximum value decreased and the minimum value increased as the damping ratio increased. Increasing the damping ratio from 0.0 to 1.0 resulted in a decline of the dynamic coefficient from 72% to 10%. The similar findings were found during the wheel decelerating as shown in Fig. 6(c).
b) While the wheel was steadily moving, as shown in Fig. 6(b), the dynamic coefficient fluctuated from 10% to 5% at the critical damping ratio ranging from 0.0 to 0.2. When the damping ratio was larger than 0.2, the dynamic coefficient was about 5%.

Summary and Conclusions

Dynamic forces under the vehicular wheels are important in the pavement design. It is well-known that the dynamic forces come from the pavement-wheel interaction. This paper presents a discrete element modeling approach for analyzing impacts of vehicle motion features and damping ratio on the pavement-wheel interaction forces. Following are the main findings from this research:

1) Both the critical damping ratios and the wheel motion features impacted the simulation results. The wheel-pavement frictional force was zero while the wheel was steadily moving along the pavement surface and non-zero when the wheel was accelerating or decelerating. Damping coefficients larger than 0.2 gave insignificant impact on the frictional forces, while those smaller than 0.2 gave relatively larger impacts.
2) Both the critical damping ratio and the wheel motion features impacted the compressive force. With the damping ratio increasing, the compressive force was less fluctuant. Acceleration or deceleration resulted in larger fluctuations.

It should be noted that even though both pavement and vehicle wheel loading conditions were simplified in the idealized model, the findings of this research are very important for further development of research methods. The on-going joint research efforts between Chang'an University and Michigan Technological University will develop more complex and realistic modeling approaches through consideration of more realistic pavement surface roughness, contact models, and wheel configuration. In the future work, the pavement structure will be simulated with a layered system, a viscoelastic model will be used to simulate asphalt materials, and so on.

Acknowledgements

This material is based in part upon work supported by the National Natural Science Foundation of China under Project No. 51208048 and Project No. 51178056. Additionally, this material is in part upon work supported by the China Postdoctoral Science Foundation under Project No. 2012M521730.

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