Modelling of Tire Response for the Study of Speed Bump Profiles

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Abstract

A speed bump is a device commonly used as traffic calming measures in the inhabited zones where a large number of pedestrians and other vulnerable road users are expected. Most of current speed bumps in Thailand were installed without any standard; therefore, they may cause damages to the vehicles passing over them and may also result in injuries to the passengers. The ultimate goal of this work is to give guideline for the establishment of a standard for speed bump installations in Thailand. This paper introduces the development of a static tire model to represent the tire longitudinal response to road unevenness. The model is validated using the experimental data of a static tire on uneven road. The change in tire shape is used to find the force acting on the hub. In the paper, the developed tire model is implemented in order to evaluate an effect of a speed bump profile. Numerical results of the impact force in longitudinal and vertical axes from the basic speed bump profile are presented and used to show the performance of the developed tire model.

Keywords*:* Tire Model, Ground Vehicle Modelling and Simulation, Speed Bump Evaluation.

1. Introduction

A speed bump is a raised pavement area across a roadway. It is a device commonly used as traffic calming measures in the inhabited zones where a large number of pedestrians and other vulnerable road users are expected, i.e., school area and private housing area. Speed bumps typically cause significant discomfort to the driver and passenger and can be effectively used to impose a speed reduction to vehicles passing over them.

In Thailand, current speed bumps generally installed on private/public roadways and parking lots are poorly standardized and constructed without the proper engineering study regarding their profile and placement. The standard from the Department of Public Works and Town & Country Planning only limited speed bumps to be constructed in the travel range between 0.30 and 0.90 meters and with a height smaller than 0.075 meters [1]. If speed bumps were installed without any standard, they could 1) decrease the level of vehicle safety by causing damages to the vehicle steering and suspension systems; 2) increase risk of Spinal cord injury due to impact shock from the bumps; 3) increase the degree of noise disturbance to the surrounding area [2–4]. Despite the increasing number of vehicles on the road and the expanding of new housing and school areas which will require the installation of speed bumps on their road ways, the impact of the speed bump profiles on road safety, passenger comfort, or deterioration of vehicles were little studied [5–8].

In the evaluation of the effect of speed bump profiles on the passing vehicle, the tire response plays an important role in transferring the ground force from the road surface to the vehicle. Most of the tire model developed previously were either developed for a driven tire on flat road or very complicated and specific to a unique (physical) model of tire [9, 10]. Therefore, most researches on vehicle responses due to road roughness commonly assumed rigid tire models [10, 11]. This presents the need of a simple physical model capable of representing general distributed ground force from road unevenness.

The ultimate goal of this work is to give guideline for the establishment of a standard for speed bump installations in Thailand. The current work focuses on the development of tools which can be utilized to evaluate design characteristics and effectiveness of the profiles of speed bump and achieve a specific limitation on vehicle operations without imposing unreasonable or unacceptable safety risks and disturbances. This paper presents the development of a generic model to represent tire responses in the longitudinal-vertical plane due to uneven road surface and the incorporation of the developed tire model in the road-bump evaluating tools.

In this paper, the development of the tire model is presented in Section 2. In Section 3, the developed tire model is implemented in the simulation tool in order to obtain the road-to-vehicle dynamic responses. The results of using the developed system to evaluate a basic profile of speed bumps are presented in Section 4. Finally, the conclusion of current work and ideas for future work are presented in Section 5.

2. Model Development

In order to study the impact of speed bump profiles on the passenger comfort and on the deterioration of the vehicle, mathematical models representing dynamics of vehicle, i.e., tire, suspension, chassis, and passenger seat must be utilized to obtain the response at the passenger location from the road profile. These models can be built as a multi-body system connected by a spring-damp system. Fig 1 illustrates the diagram of model connection for investigating effects of speed bump profiles.

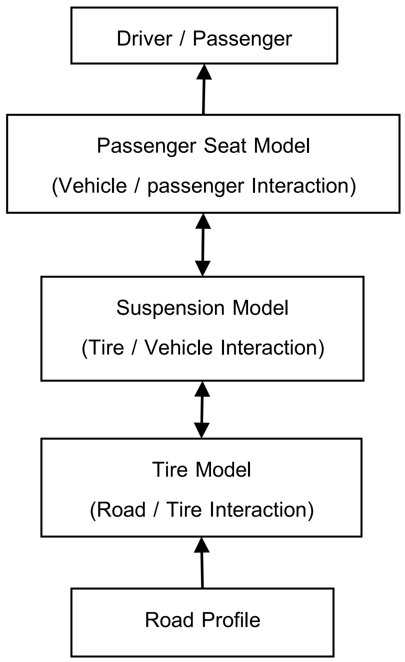


Fig. 1 Diagram of road-to-passenger interaction

For the sake of simplicity, this paper considers only simplified motion dynamics of a quarter-vehicle. The full motion of vehicle including the full longitudinal / lateral motions and combined longitudinal-lateral dynamics as well as the vehicle-to-passenger responses are neglected and left for future investigation.

The traditional quarter-vehicle model was adopted and modified to represent the vehicle dynamics for road profile inputs. The tire model was separately formulated to calculate the resultant force due to road profiles acting on the wheel in the inertial frame.

2.1 Vehicle Model

In this paper the simplified motion dynamics of a quarter-vehicle model is considered. The three-degree of freedom lumped model as shown in Fig. 2 is utilized. The model allows vehicle's longitudinal and vertical motions (x_v and z_v) as well as the vertical motion of the front wheel (z_f). The system equations of motion can be written as

$$m_v \ddot{z}_v = F_{s,z} - m_v g \quad (1)$$

$$(m_v + m_f)\ddot{x}_v = -F_{f,x} \quad (2)$$

$$m_f \ddot{z}_f = F_{f,z} - F_{s,z} - m_f g \quad (3)$$

where m_v *and* m_f are the mass of the vehicle's body and the wheel, $F_{f,x}$ and $F_{f,z}$ are the horizontal and vertical components of the resultant force from the ground (tire model), and $F_{s,z}$ is the vertical force components in the front suspension given by the following equations:

$$F_{s,z} = c_s(\dot{z}_v - \dot{z}_f) - k_s(\Delta z_v - \Delta z_f) \quad (4)$$

where k_s and c_s are the spring and damping characteristics of the vehicle suspensions.

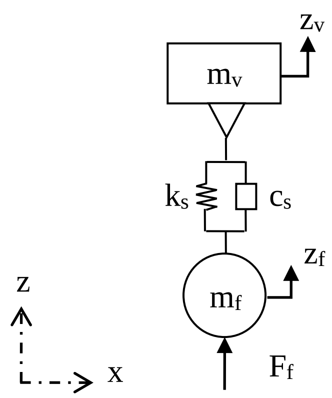


Fig. 2 Quarter-vehicle model

2.2 Tire Model

To obtain the resultant force on the wheel from the road roughness, a static tire model is developed. The simple physical model considers a tire as a deflectable, circumscribing belt with radial support strings. Fig. 3 illustrates the tire model. In the ground interaction, the force from the ground presses on the belt and results an elastic change in its shape. With the knowledge in the elastic properties of the tire, the distribution of ground force can be obtained.

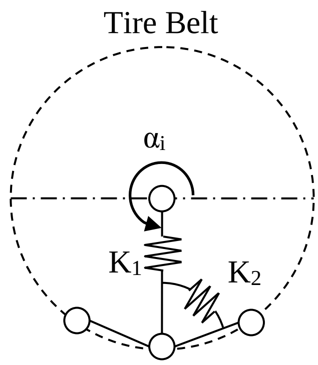


Fig. 3 Tire model

In this model, the ground profile and the hub position are the inputs. The tire belt is represented using a finite number of nodes. The driven force is not considered. The force distribution on any node *i* can be obtained by

$$F_i = F_{r,i} + K_2\left(\frac{(r_{i-1} - r_i)}{r \cdot d\theta_{i-1}} + \frac{(r_{i-1} - r_i)}{r \cdot d\theta_{i+1}}\right) \quad (5)$$

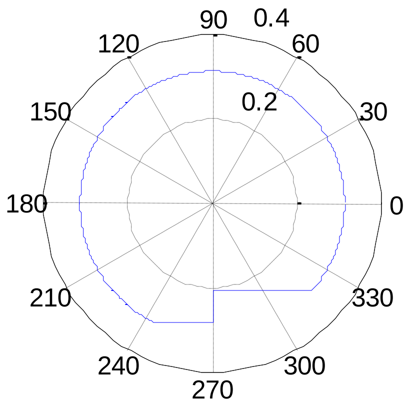
where r_i and F_i are the radial position of and the external force at the node *i*, K_2 represents the elastic property of the tire belt, the term $r \cdot d\theta_{i-1}$ and $r \cdot d\theta_{i+1}$ represent the distance to the previous and the next nodes, respectively.

The force on the radial string at node *i* ($F_{r,i}$) is obtained from:

$$F_{r,i} = K_1(r_f - r_i) \quad (6)$$

where r_f is the load-free radius of the tire and K_1 represents the elastic property of the tire radial strings.

To obtain the force resultant from the ground, the force equation of every node must be solved. A numerical method can be used to solve this set of equations [12]. The generated nodes are categorized into two groups: 1) unknown nodes that are needed to be solved for; 2) known nodes that can be used as boundary conditions in the solving process. The known nodes are obtained from the tire-ground contact nodes. The intersection between the ground and the tire space is used to specify the ground nodes. The ground contact is assumed (the radial position of the node is known to be at the ground level) if the radial distance of the ground node is relatively close to the hub. The ground node that is relatively far away from the hub is considered an unknown node. Fig.4 illustrates an example of the shape of tire belt before and after solving process.



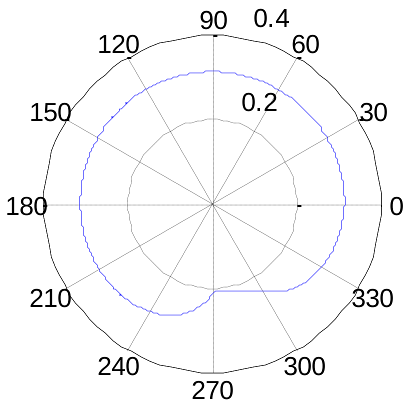


Fig. 4 The belt shape due to a ground profile.

After the tire belt shape is found, the vertical and horizontal components of the resultant force are then obtained by:

$$F_{f,z} = \sum F_{r,i} \sin \alpha_i \tag{7}$$

$$F_{f,x} = \sum F_{r,i} \cos \alpha_i \tag{8}$$

The developed tire mode is validated by comparing it against experimental data of tire response over a trapezium cleat and over an upward step at very low speed in [10]. Fig. 5 represents tire responses from the developed model that shows an agreement with the experimental data.

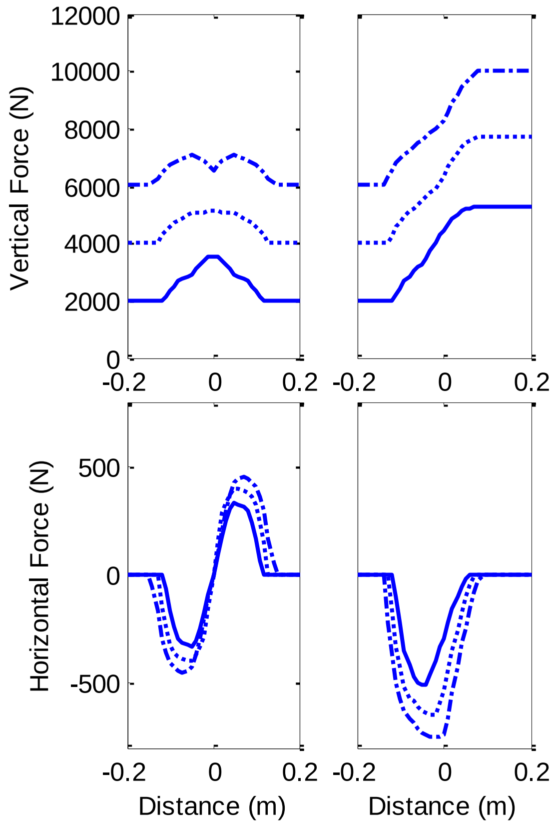


Fig. 5 Rolling-over-a-trapezium-cleat and rolling-over-an-upward-step responses from the developed tire model.

3. Simulation Model for Speed Bump Analysis

To study the effect of speed bump profiles, the developed vehicle and tire model are implemented in a simulation model. Fig. 6 illustrates the simulation diagram for the study of speed bump profiles. The road profile is the input to the simulation model. From the hub position, the tire model determines the ground-contact nodes and finds the resultant force from the deflected belt shape. The tire resultant force is the input for the vehicle dynamic model which determines the vehicle responses and the new position of the hub for the next simulation time step.

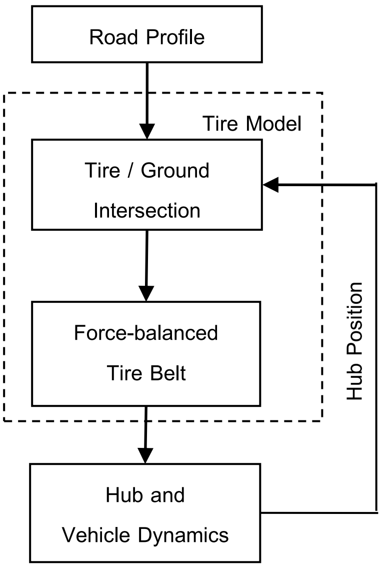


Fig. 6 Diagram of road-to-passenger interaction

4. Numerical Results

In this section, the vehicle model developed in previous section is used to find the effect of a general speed bump profile. The simulation model is developed for a typical medium sized passenger vehicle. Table 1 shows the properties of the medium sized passenger car [10, 11].

Table. 1 Properties of the vehicle model.

Parameters	Value
Vehicle mass	750 kg
Tire and hub mass	30 kg
Suspension spring	18250 N/m
Suspension damping	912.5 Ns/m
Tire free-load radius	0.3135 m

The speed bump profile considered in this paper is a circular curve with the travel range of 0.9 m and the highest point of 0.075 m above the ground. Fig.7 illustrates the speed bump profile.

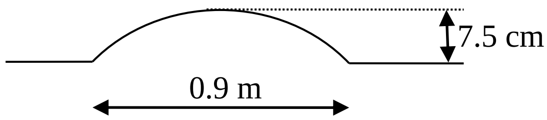


Fig. 7 Example of speed bump profiles

Figure 8 presents the vehicle responses due to the passing over the speed bump profile at different travel speed (8, 25, and 40 km/h). The simulation time step was less than 0.001 seconds. The impact force in longitudinal and vertical axes are represented in the term of acceleration components of vehicle and different traveling position over the speed bump. The results indicates that the front side of the vehicle part experiences the negative acceleration in all tested vehicle speed. However, the information on the positions of the passenger and the vehicle center of gravity is required in order to determine the passenger motions.

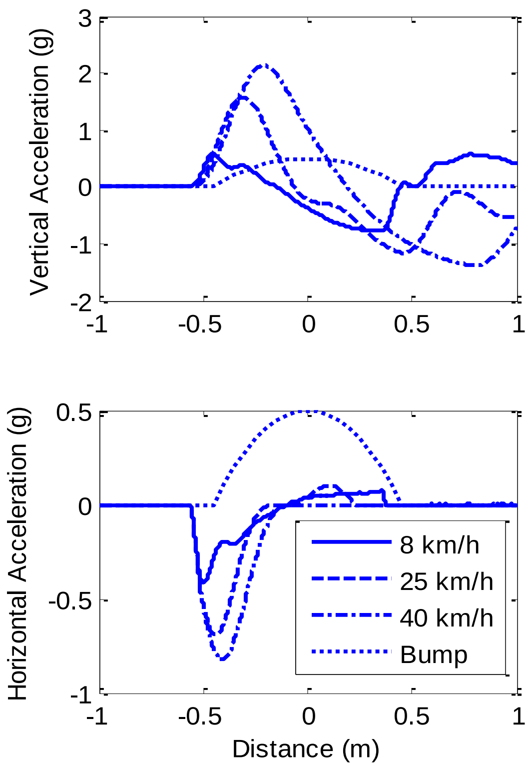


Fig. 8 Vehicle response to the example speed bump.

5. Conclusions

In this paper, the development of a simplified tire-model is presented. The tire model was developed using the concept of deflectable tire belt with supporting radial strings. The model responses were compared against the experimental data and an agreement was found.

The developed tire model were implemented in a simulation system of quarter-vehicle to study the effect of speed bump profile. The detail of implementation and the evaluation of a basic-profile speed bump are also presented.

Future work will be the improvement of vehicle dynamics model which will also include the dynamics of passenger seat. It is expected that the developed model will be useful both for simulation purposes and for the study of speed bump profiles for a guideline in the installation of safety speed bumps in Thailand in the future.

6. Acknowledgement

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7. References

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