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The induced shock and impact force as affected by the obstacle geometric factors during tire-obstacle collision dynamics

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Abstract

The knowledge on vehicle stability, ride comfort and performance is critically significant on off-road vehicle traversing over irregular terrains. The subject of off-road vehicle analysis from the terrain-tire interaction perspective has always been from complex domains of engineering owing to the elasto-plastic behavior of deformable terrain and nonlinear vehicle dynamics. This paper is dedicated to synthesize the induced shock and impact force as affected by the obstacle geometric factors during tire-obstacle collision dynamics. To this end, various obstacle shapes were included at different depths to determine at which geometric configuration, the greatest and lowest impact forces are induced. Aiming this, the soil bin facility equipped with a single-wheel tester of Urmia University was adopted to carry out the needed experimental tests while the operational condition of the wheel traversing was absolutely controllable (i.e. slip, forward speed, wheel load, etc.). The developed model also was verified by the experimental data and the obtained results showed that the greatest impact force both at the longitudinally and vertically oriented directions were obtained by the triangular shaped obstacle at the greatest height while in contradictory to the expectations, the lowest values were obtained for the trapezoidal obstacle when compared with the Gaussian shaped obstacle. The findings will serve future studies as a functional source to develop improved vehicle designs to interact with differently shaped obstacles and various operational conditions for run-off-road vehicles traversing over irregularities.

Keywords: Tire; Off-road vehicle; Soil bin; Obstacle

1. Introduction

The industry of vehicle engineering is associated with diversity of domains from propulsion, vehicle engine, driveline system, power distribution among wheels, suspension system, etc. that drastically can affect the vehicle dynamics, performance, stability and ride comfort. These factors are all central issues for engineers, manufacturers and researchers from various points of view from modeling, analysis and optimization in design, mobility and performance. The components and subcomponents of vehicle system are harmoniously running to affect the three major aspects of ride comfort, handling and performance. The off-road vehicle analysis on rough irregular terrain has called significant attention due to the complex soil characteristic added with the nonlinear vehicle dynamics. If not more significant, at least equally important with the other influential vehicle components, the wheels play substantial role in vehicle mobility, handling, maneuvering, stability, performance and ride comfort of vehicles. Tire is the unique element of vehicle being in continuous contact with the surface and is subjected to all the moments and forces applied to the vehicle chassis from the ground [1-2]. There are numerous studies documented in the literature that correspond the kinetics and kinematics of wheel-ground interaction that have been investigated so far such as rolling resistance, traction and tire-obstacle impact force, etc. [3-7].

In the theorem of vehicle engineering, an impact is generated by a great force/shock applied over a short time period when wheel collides the obstacle. In this manner, the created force has a greater effect than an ordinary force applied over a longer period of time while it is pivotal on the relative velocity of the tire to the obstacle. Random road profile serves as road obstacles and influences the vehicle performance, handling and ride comfort while forming shocks/impact forces. This type of varying force is also closely concerned with the structural failure of the vehicle body and transport safety. A priori to optimize the vehicle design and describing the limitations of operational condition of the vehicle is to synthesize the physics and mechanics of the phenomenon particularly from the tire-obstacle shock analyzing perspective. The passenger safety, cargo protection, dynamic stress limit and vehicle structural dynamics directly depend on the amount of the impact forces and shock exerted to the wheel. Tire as a part of suspension system that deals with the transmissibility of an off-road vehicle in order to resist the bumps and jerks that randomly occur in an off-road track, takes an important role in negotiating with the impact force and shocks. In the process of route traversing, understanding the impact forces provides also realistic information required to assist in adjusting tire parameters such as tire pressure, wheel load, slip, etc.

The prediction of transient dynamic behavior of the tire in travelling obstacles under different operating conditions is a significant subject to provide tire designers and researchers with a understanding of aspects of tire behavior in ride comfort assessment and vehicle durability analysis [8]. Given the requisite on through investigation of wheel-obstacle collision dynamics, the following is to cover the relevant studies documented in literature.

An off-road vehicle stability traversing over obstacle has been a matter of concern reflected by the numerous studies [9-15]. Research about tractor stability and dynamics could be experimental, computer simulation or computer simulation and experimentation. The use of experimental methods to investigate tractor stability and dynamics is limited due to the fact that such experiments would be slow, very expensive and perilous and then it will be difficult to have such experiments repeated for numerous operating conditions [9]. In this regard, an explicit finite element analysis for tire-obstacle collision process was carried out by simplifying the vehicle as a single-freedom vibration model. A 3D finite element analysis (FEA) model of 11.00R20 TBR tire rolling on road was established by ABAQUS FEA software to simulate the tire-obstacle collision process while the results showed that the collision process had significant influence on the mechanical properties of the tire [19]. The effect of tire inflation pressure and tire velocity on the force of obstacle climbing were studied while the cleats were inserted in the traversing direction. It was indicated that there is a direct relationship between the forward speed and the induced force while there is a contradictory relationship between the tire pressure and the induced force [10-11].

The stability loss on rough ground is more likely than on smooth ground because the wheels of a tractor follow the bumps and hollows of the rough ground and cause steep local slopes [13]. To examine the effects of different geometries and mass specifications of a tractor operating across irregular sloping grounds on the lateral stability of this machine, a dynamic model was developed. In the proposed model, overturn and skid instabilities were studied and the tractor stability indexes were formulated [15]. However, this study did not cover the aspects of obstacle geometrical configurations on the tractor stability and the created impact forces. There are some other similar studies with the same objectives while not covering the role of different geometric configurations of obstacles in stability and overturning of the off-road vehicles [16-18].

The literature concludes that there is an essential need to understand the effect of obstacle geometric factors on the impact force during tire-obstacle collision time. This is very momentous aspect in Terramechanics while the tire-obstacle collision occurs frequently with irregular obstacle shapes. An experimental step functionally contributed to the obtained results and conclusions drawn from the study. Therefore, the present study mainly follows to respond the following questions:

i. How does the geometric factors of the obstacle affect the impact force between the tire and the obstacle?

ii. What is the effect of operational condition of wheel traversing on irregular terrain?

iii. How are the peak values of impact forces obtained at three different obstacle shapes being compared?

2. Mathematical Considerations

An important topic of specialized interest in wheel kinetics is impact force. The principles of impulse and momentum have important use in describing the behavior of colliding bodies. Impact refers to the collision between two bodies and is characterized by the generation of relatively large contact forces which act over a very short interval of time. For the linear momentum, we may write the basic equation of motion by:

$$\sum F = m\dot{v} = \frac{d}{dt}(mv) \tag{1}$$

where the product of the mass and velocity is defined as the linear momentum $G = mv$ of the particle. Eq. 1 can be written in the three scalar components as:

$$\sum F_x = \dot{G}_x \qquad \sum F_y = \dot{G}_y \qquad \sum F_z = \dot{G}_z \tag{2}$$

the effect of the resultant force ΣF on the linear momentum of the over a finite period of time is described as:

$$\int_{t_1}^{t_2} \sum F dt = G_2 - G_1 = \Delta G \tag{3}$$

Which can be rewritten as:

$$\begin{aligned} m(v_1)_x + \int_{t_1}^{t_2} \sum F_x dt &= m(v_2)_x \\ m(v_1)_y + \int_{t_1}^{t_2} \sum F_y dt &= m(v_2)_y \end{aligned} \tag{4}$$

the third direction is removed since the longitudinal and vertical forces are more significant during wheel traversing on surfaces with no slope that causes no lateral force generation.

However, velocity should be presented as a vector in both vertical and longitudinal directions:

$$\vec{V} = \dot{x}i + \dot{y}j \tag{5}$$

The path of wheel is affected by the obstacle geometry as following:

$$y = sin\,\frac{2\pi}{l}x \qquad 0 < x < 2\pi \tag{6}$$

For the triangular shaped obstacle, the following equation is described:

$$y = \begin{cases} ax & x < \frac{l}{2} \\ -ax & x > \frac{l}{2} \end{cases} \tag{7}$$

Where *l* is the obstacle length and *a* is 0.4, 0.6, and 0.8 for the obstacles with the heights of 1, 2, and 3 cm, respectively.

$$trapezoid(x;a,b,c,d) = \begin{cases} 0, & x \le a \\ \frac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \frac{d-x}{d-c}, & c \le x \le d \\ 0, & d \le x \end{cases} \tag{8}$$

Now, the governing equation based on the Newtonian-Eulerian method can be presented for the problem of tire-obstacle collision as following (Fig. 1):

$$\begin{aligned} &\sum F_x = m_t a_x \\ &\sum F_y = m_t a_y \\ &\sum M = I\alpha = I\ddot{\theta} \end{aligned} \tag{9}$$

Where m_t, M, I and α are tire mass, moment, mass inertia of moment and angular acceleration, respectfully. From Eq. 9, the following equation can be derived:

$$\begin{aligned} &N_t - N\cos\theta - R_r = ma_x \\ &N\sin\theta - mg = ma_y \\ &N\cos\theta \times l\sin\theta + N\cos\theta \times l\cos\theta - T = \overline{I} + m_t r^2 \end{aligned} \tag{10}$$

Where N, N_t, R_r, *l* and T are the reaction force component normal to the contact surface, the net traction force, rolling resistance, length of contact between the tire and surface, and torque applied to the tire, respectively. In this condition, the longitudinal and lateral impact forces for the impact can be rewritten as following:

$$\begin{aligned} F_l &= N\cos\theta = N_t - ma_x - R_r \\ F_v &= N\sin\theta = m(a_y + g) \end{aligned} \qquad (11)$$

However, it should be also noted that due to the acceleration vector components at x and y directions that should follow the obstacle shapes, the obtained variations of force in the developed model varies in the domain of time.

3. Experimental Tests

As aforementioned, the provision of controlled testing environment is crucially significant for the reliability of the results. Hence, a single wheel-tester (SWT) inside a soil bin facility was used to conduct the required experiments. The soil bin channel with 24 m length, 2 m width and 1 m depth was filled with the soil texture of the test region. The holistic system is consisted of a soil bin channel, SWT and the carriage. The SWT was connected to the carriage to be able to traverse through the soil bin channel. The carriage was powered with a 22 kW electromotor which was connected to the inverter for the start/stop and velocity control procedures. The power transmission was carried out through the electromotor to the chain system that was linked to the carriage. The carriage was traversing in the channel by means of four ball bearings positioned on the sidewalls of the soil bin. The SWT was connected to the carriage through an L-shaped part and also four horizontal arms each accommodating one S-shaped Bongshin load cell with 500 kg capacity. It is worth to note that the horizontal load cells were used to measure the horizontal forces applied to the wheel. In order to measure the vertical force variations, one S-shaped Bongshin load cell with 2000 kg capacity was situated between the U-shaped and L-shaped parts of the SWT. This facility provided the ability to measure and monitor the vertical force variation online. One U-shaped frame was used to hold the tire and a three-phase electromotor of 5 kW was used to power the driving wheel. An appropriate inverter was also used to control the rotational velocity delivered to the wheel shaft and therefore; the linear velocity was adjustable. It is worth mentioning that the linear speed difference between the carriage and the SWT yielded different levels of adjustable slippage. Furthermore, the SWT was connected to the L-shaped frame by a power bolt rod (to adjust the applied wheel load) which was connected to a vertically situated S-shaped load cell responsible to measure the load variations while traversing over the obstacle and irregularities. The load cells were connected to Bongshin digital indicators which were in connection with a data logger with RS232 output signals. The data were subsequently sent to the laptop computer to be stored and processed with the frequency of 30 Hz. It is noteworthy that the utilized tire for experimentations was a 220/65R21 driven tire. The general soil bin facility along with the single-wheel tester is shown in Fig. 2. Fig. 3 provides a schematic insight into the research body with the major objectives to be covered.

For all the experiments the tire inflation pressure was maintained at 131 kPa as recommended by the manufacturer. Two shapes of triangular and curved obstacles were used in the study each at three heights of 1, 2 and 3 cm while the wheel load was adjusted at 3 kN which was the recommended level by the manufacturers at adjusted the tire pressure. Furthermore, tire slip was adjusted and kept constant at 10%. In order to remove the soil effect on the experiment outputs due to the soil nonhomogeneous properties, a wooden board with 2 m width and 3 m length was used. The obstacles situated in the traversing direction of the wheel are depicted in Fig. 4.

4. Results and discussion

Given the mathematical model background of impact force in Section. 2, an ODE solver code in MATLAB software was developed to assess the study objectives. The modeled system using the developed code for Gaussian-shaped obstacles were validated by the experimental results both in vertically and longitudinally oriented directions (Figs. 5 and 6). Fig. 5 shows the force variations in time domain while the tire collides and traverses over the Gaussian shaped obstacle in vertical direction at different obstacle heights. Also, validation process with experimental data has been performed (Fig.5). As appreciated from Fig. 5, after the collision the force disturbance occurs until the shock absorbs and damps after a period of time. The peak values depend on the obstacle height in a manner that increased obstacle height results in the increment of impact force. Furthermore, the vertical force is greatly affected by the impact force with greater range of amplitude variation (compressive/extensive loads). In the interest of a balanced vehicle traversing, the accuracy and reliability of the complete vehicle model has to produce rational relation to the performance of the applied tire model. For the effect of obstacle height, it can be said that due to the change of momentum in the vertical direction, a velocity change in the vertical direction of y (i.e. ΔVy) is formed which results in the formation of linear impact in the same direction. Hence, an acceleration component at the same vertical direction of y is created owing to the aforesaid velocity change (i.e. ΔVy) at the increased obstacle height leading to the increased vertically induced inertia forces. This process well describes the increase of vertical force with respect to the increase of obstacle height. Likewise, the increased obstacle height results in the reduction of the instant velocity of wheel at the horizontal direction which in turn, results in a significant change of the linear momentum and therefore greater linear impact in the horizontal direction is obtained. Fig. 6 is dedicated to present the longitudinal force variations in time domain for both model validation and the variations of the force at different obstacle heights versus time. It is expectable, with abovementioned justifications that increased obstacle height results in the increment of impact force. The greatest and lowest values of impact force in vertical direction corresponded to the obstacle heights of 4 and 2 cm with values about 5180 and

3871 N, respectfully. Similarly, the greatest and lowest values of impact force in longitudinal direction corresponded to the obstacle heights of 4 and 2 cm with values about 679 and 261 N, respectfully.

Fig. 7 demonstrates the impact force variations in both directions addressing the trapezoidal shaped obstacles at different depths. Owing to the change of momentum in the vertical direction, a velocity change in the vertical direction of y (i.e. ΔVy) is formed which results in the formation of linear impact in the same direction. Due to the decrease of the instant velocity of wheel at the longitudinal direction results in variation of the linear momentum and greater longitudinal impact force. The greatest and lowest values of impact force in vertical direction corresponded to the obstacle heights of 4 and 2 cm with values about 5597 and 4273 N, respectfully. Similarly, the greatest and lowest values of impact force in longitudinal direction corresponded to the obstacle heights of 4 and 2 cm with values about 492 and 187 N, respectfully. Finally, Fig. 8 illustrates the impact force variations in both directions addressing the triangular shaped obstacles at different depths. The variations justifications are previously covered for the other obstacle geometries. The greatest and lowest values of impact force in vertical direction corresponded to the obstacle heights of 4 and 2 cm with values about 5628 and 3788 N, respectfully. Also, the greatest and lowest values of impact force in longitudinal direction corresponded to the obstacle heights of 4 and 2 cm with values about 802 and 198 N, respectfully.

It is thus concluded that the trapezoidal shaped obstacles bring about the lowest values of longitudinally oriented impact force while the greatest values correspond to the triangular obstacles. While the greatest values of impact force in vertical direction correspond to the triangular obstacles, in contradictory to the longitudinal impact force, the lowest force corresponded to the Gaussian shaped obstacles. This can serve as an important step in vehicle suspension design and tire manufacturing industry. Further studies are needed to consider the effect of deformable obstacles from soil textures.

5. Conclusions

An optimal control design method based on the use of the correlation between different suspension systems is pivotal on the studies and researches on off-road vehicle traversing over irregular terrains. The subject of off-road vehicle analysis from the terrain-tire interaction perspective has always been from complex domains of engineering owing to the elasto-plastic behavior of deformable terrain and nonlinear vehicle dynamics. This paper is dedicated to synthesize the induced shock and impact force as affected by the obstacle geometric factors during tire-obstacle collision dynamics. To this end, various obstacle shapes were included at different depths to determine at which geometric configuration, the greatest and lowest impact forces are induced. Aiming this, the soil bin facility equipped with a single-wheel tester of Urmia University was adopted to carry out the needed experimental tests while the operational condition of the wheel traversing was absolutely controllable (i.e. slip, forward speed, wheel load, etc.). The developed model also was verified by the experimental data and the obtained results showed that the greatest impact force both at the longitudinally and vertically oriented directions were obtained by the triangular shaped obstacle at the greatest height while in contradictory to the expectations, the lowest values were obtained for the trapezoidal obstacle when compared with the Gaussian shaped obstacle. The findings will serve future studies as a functional source to develop improved vehicle designs to interact with differently shaped obstacles and various operational conditions for run-off-road vehicles traversing over irregularities. Furthermore, the optimal suspension design can be a good solution if one intends to do further research in the domain of ride comfort analysis.

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Figure Captions:

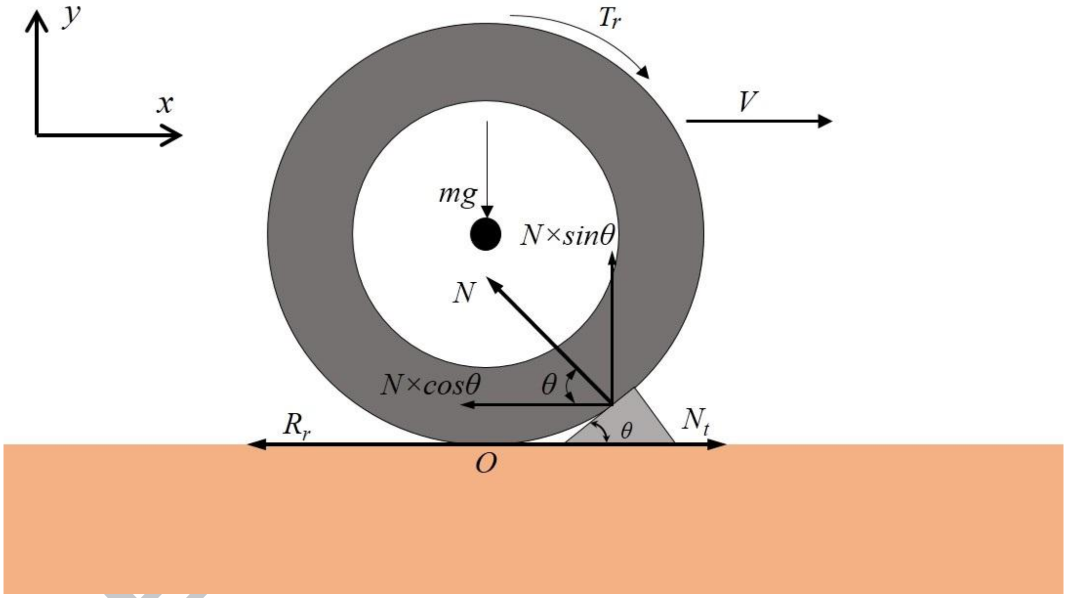


Figure 1- The free-body diagram of the tire-obstacle impact

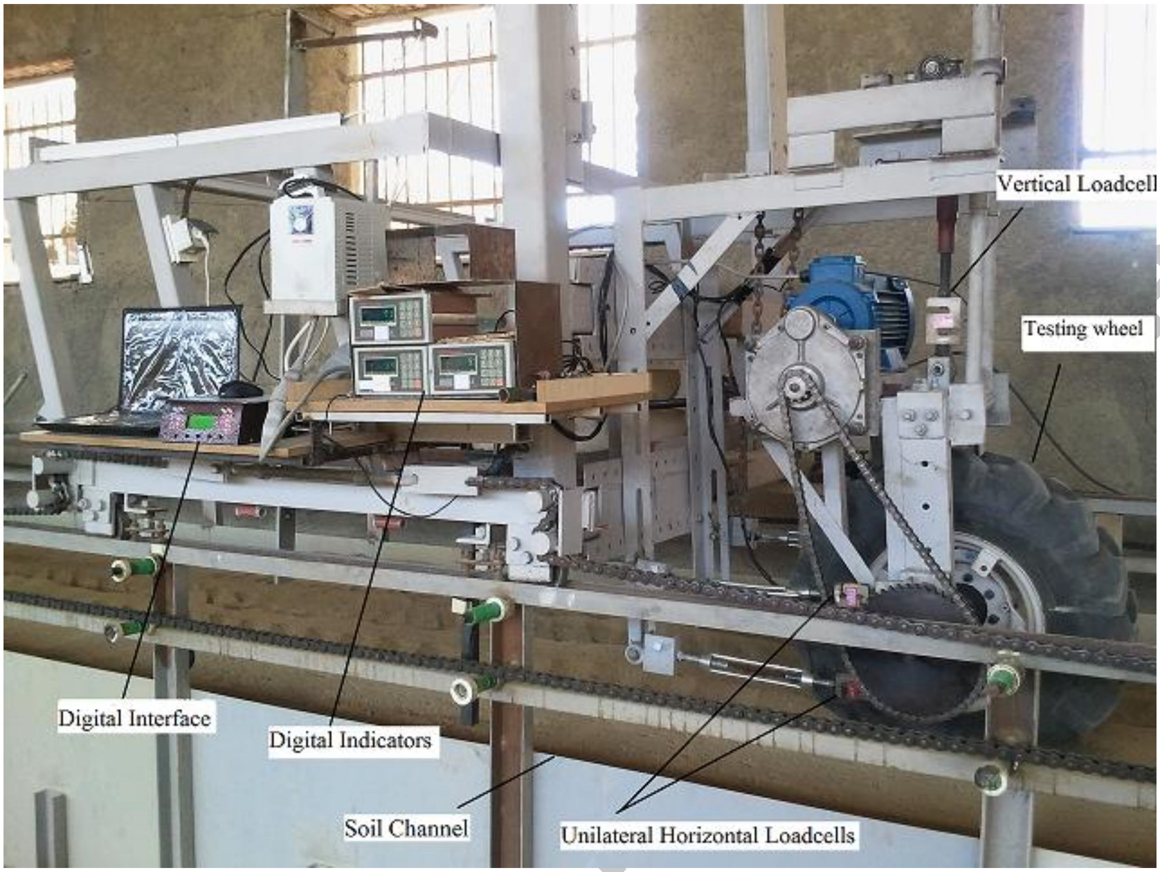


Figure 2- Soil bin testing facility and the components

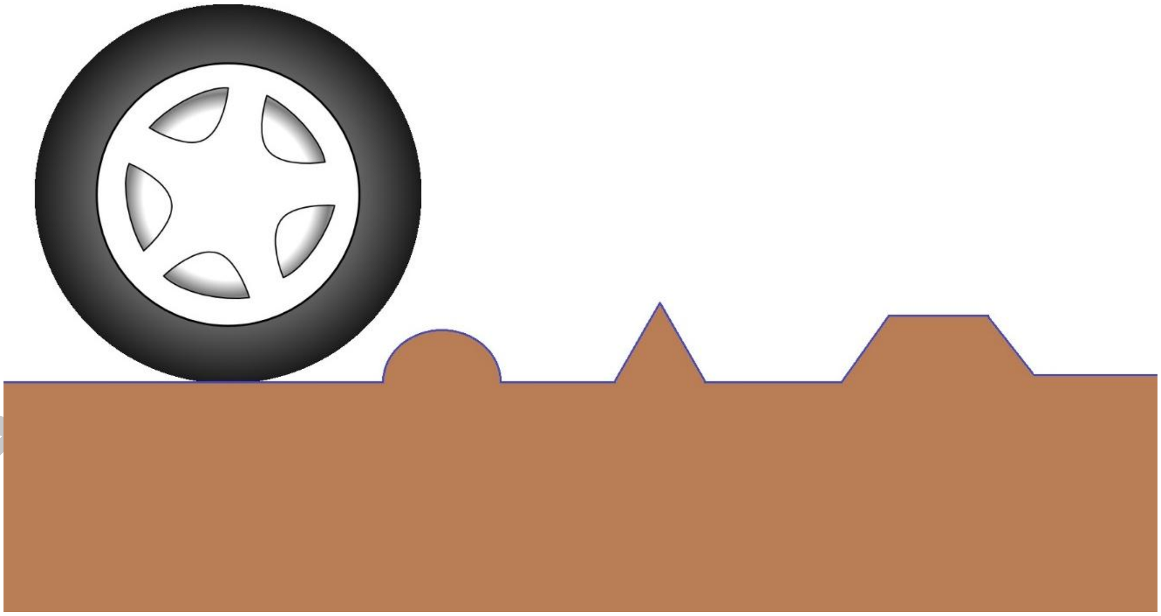
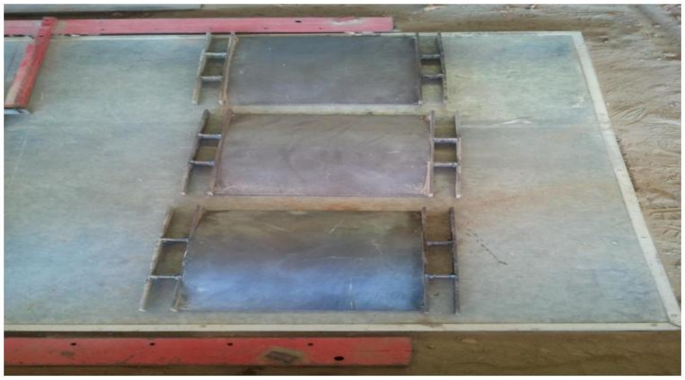


Figure 3- Schematic representation of the tire traversing over different obstacles

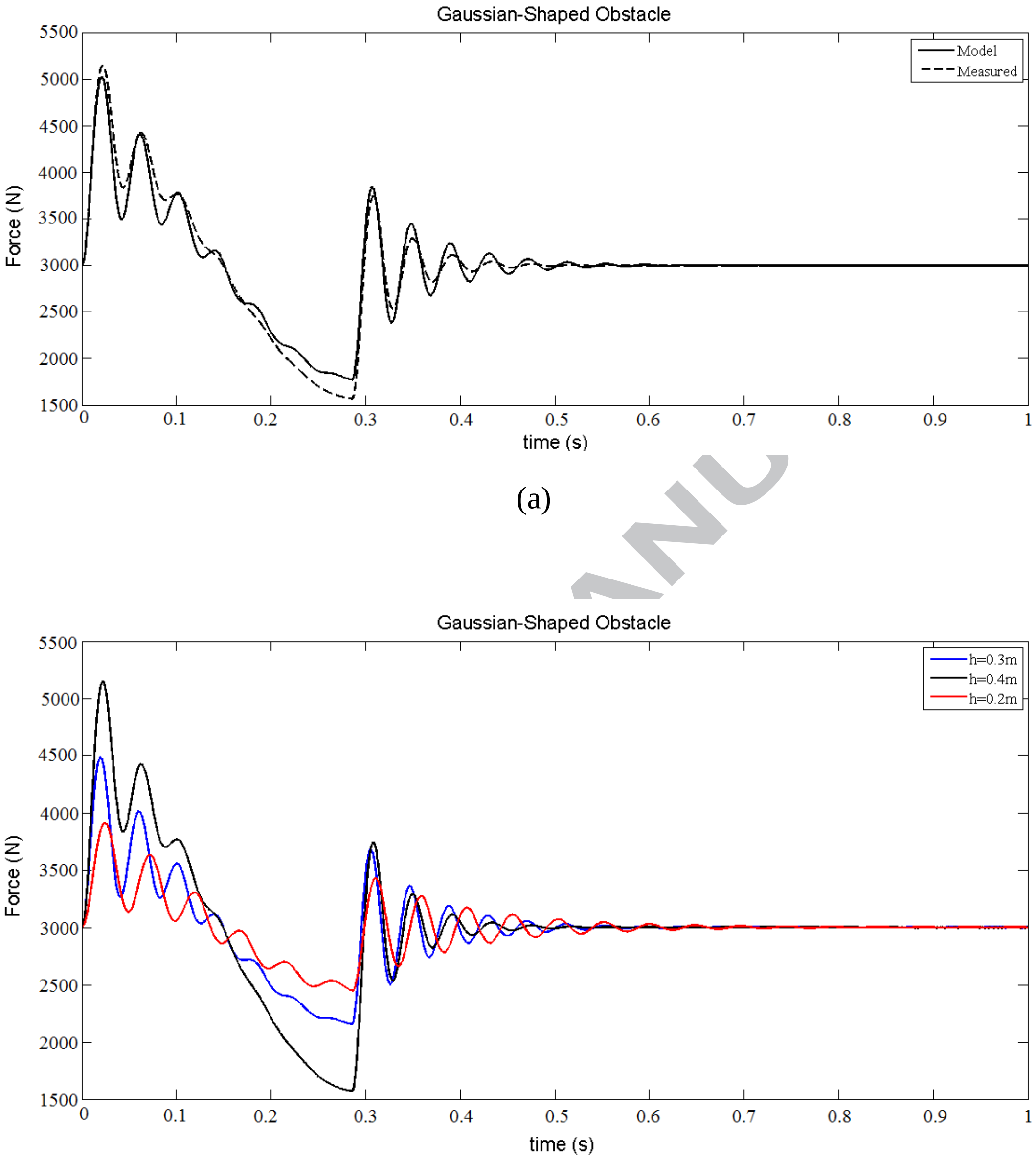


(a)

(b)

(c)

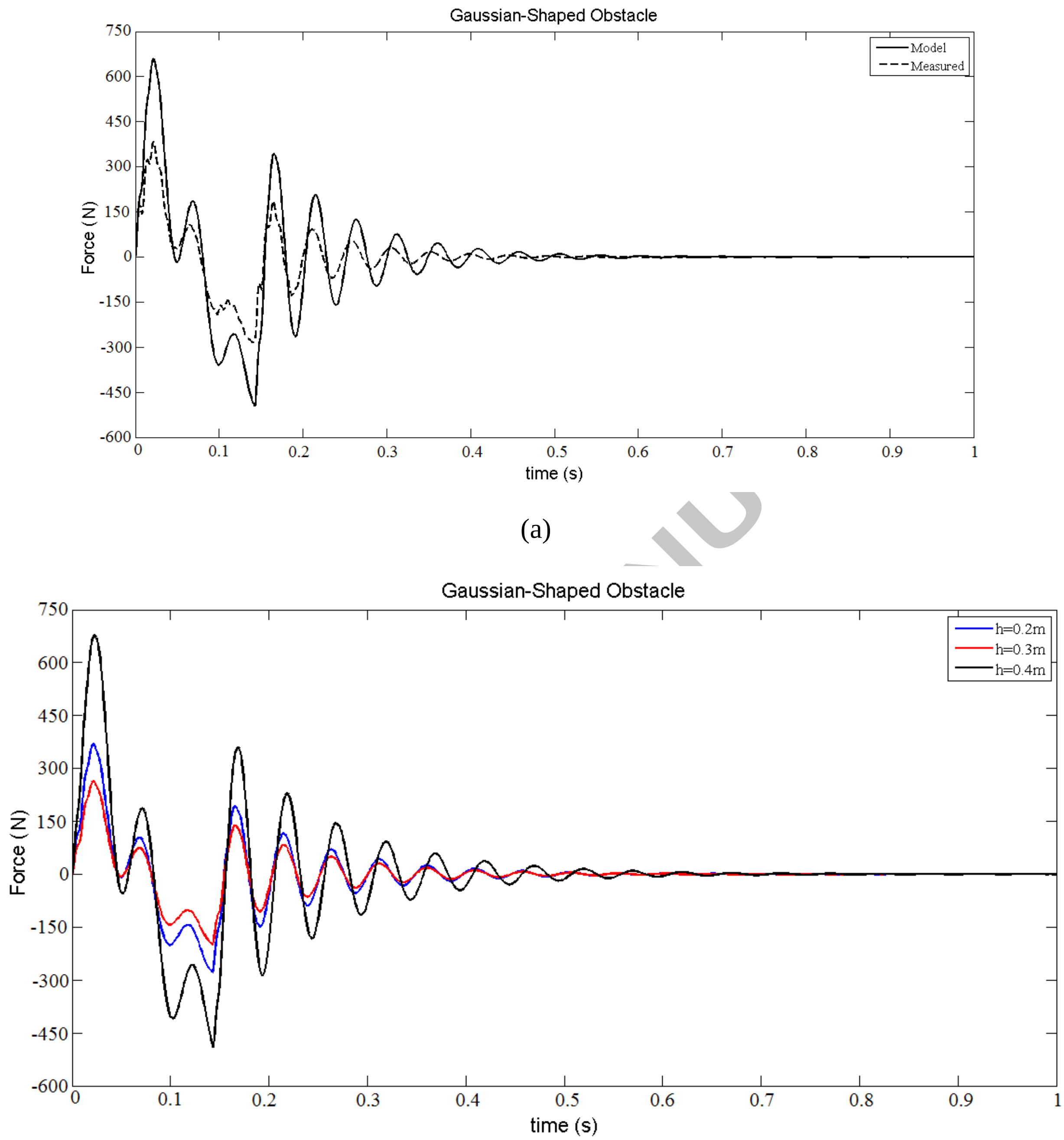
Fig. 4- An overview on the obstacles used in the experiments; a) Gaussian, b) Triangular and c) tire traversing over Gaussian obstacle



(a)

(b)

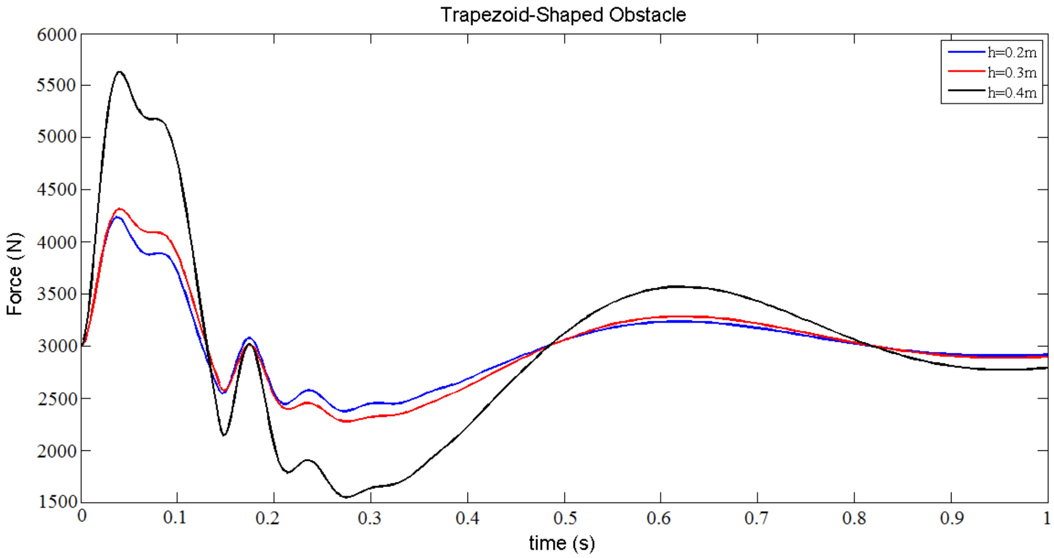
Figure 5- Force variations in time domain while the tire collides and traverses over the Gaussian shaped obstacle in vertical direction at different obstacle heights; a) model validation, b) obtained results at different depths



(a)

(b)

Figure 6- Force variations in time domain while the tire collides and traverses over the Gaussian shaped obstacle in longitudinal direction at different obstacle heights; a) model validation, b) obtained results at different depths



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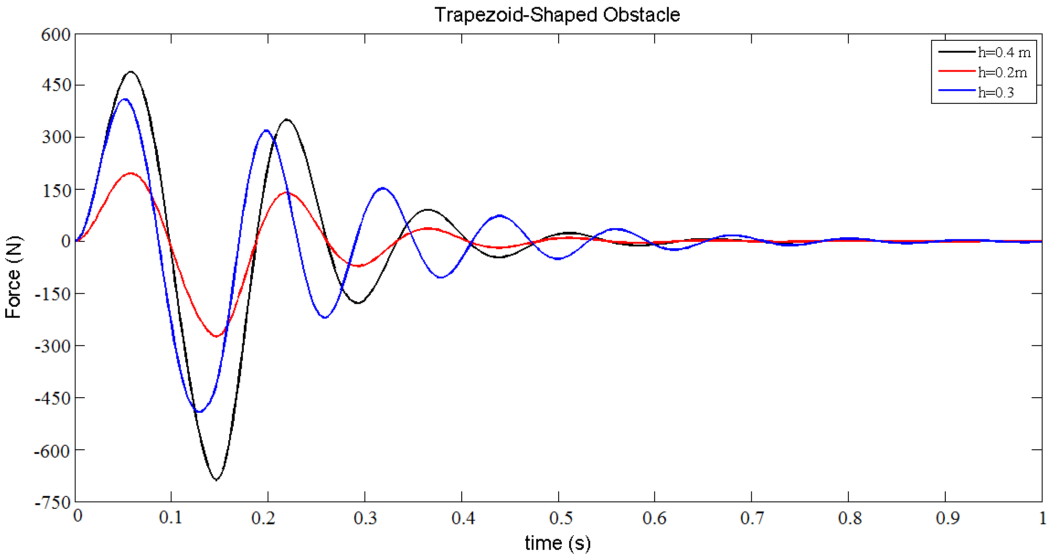
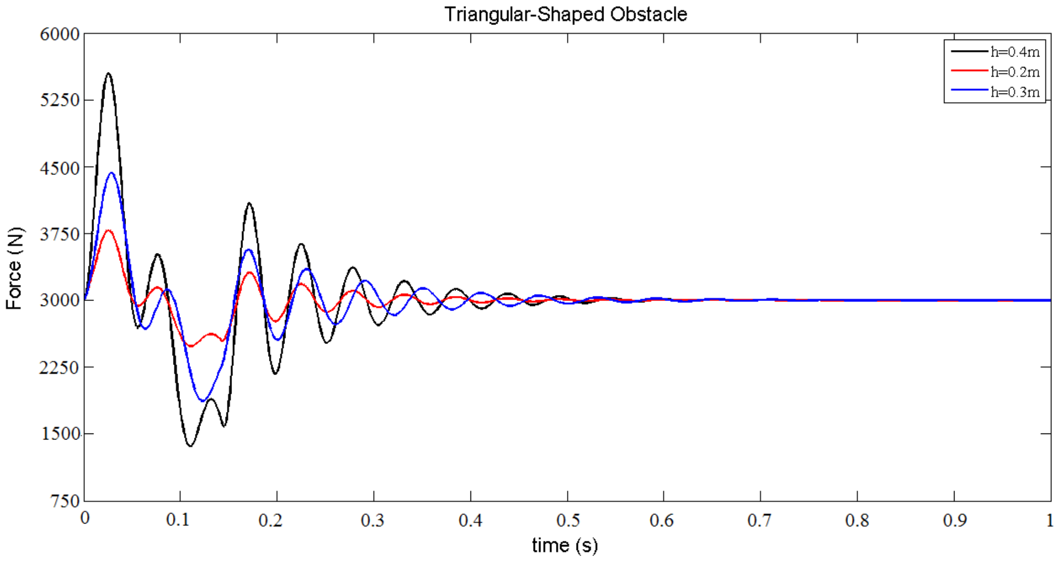
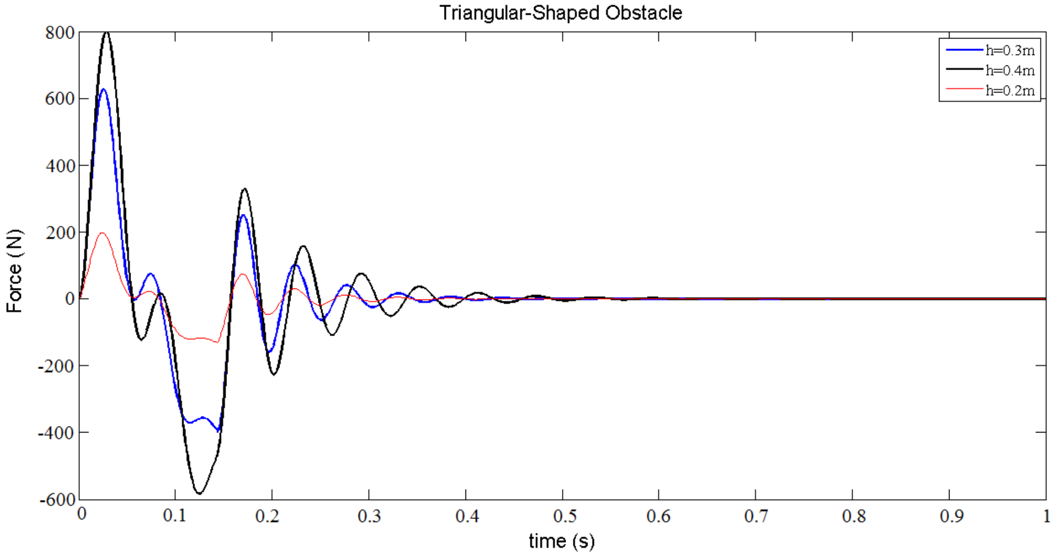


(b)

Figure 7- Force variations in time domain while the tire collides and traverses over the Trapezoidal shaped obstacle in a) vertical and b) longitudinal directions at different obstacle heights



(a)



(b)

Figure 8- Force variations in time domain while the tire collides and traverses over the Triangular shaped obstacle in a) vertical and b) longitudinal directions at different obstacle heights

Highlights:

- Experimental investigation of horizontal and vertical induced forces occurred for wheel traversing over obstacles.
- Effect of geometrical configurations were investigated.
- The longitudinal and vertical impact forces rely on the obstacle shape and size.