

# Analysis of Off-road Performance for a Tracked Vehicle

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**Abstract:** Suspension system is one of the most important factors in provision of ride comfort and dynamic stability in any vehicle. However, the suspension system for the tracked vehicle has more particular specifications in compare with the other vehicles. Due to its continuous track, these specifications can help the tracked vehicles possess an improved dynamic stability in off-road maneuvers compared to the vehicles with discrete tiers. In this paper, off-road performance of the tracked vehicle has been thoroughly investigated. In this regard, firstly the mathematical model of a tracked vehicle suspension system with governing dynamic equations are derived and the state-space representation are represented. After on, the off-road inputs such as hill inputs, passing over Belgian block and irregular terrain are applied to the dynamic model and the system outputs, especially body hull vertical acceleration as one of the most important criteria of stability, are reviewed. The results show that the responses are in range of acceptable overshoot and there suggest the related critical speed of the vehicle. Furthermore, for model validation the results are compared with ACMP reference model in response to the standard off-road inputs and the results are satisfactory.

**Keywords:** Belgian block, Critical speed, Dynamic stability, Irregular terrain, Off-road performance, Suspension system, Tracked vehicle

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**Biographical notes:** **M. Reza Elhami** received his PhD in Mechanical Engineering from Liverpool University, UK, in 1997. He is currently Associate Professor at Mechanical Engineering Department of the Imam Hossein University (IHU), Tehran, Iran. He has been working on design and manufacturing of many industrial mechanisms in the field of control, dynamics and robotics. At present, his main research interest concern dynamic and vibration analysis in continuous media, advanced control strategies, intelligent mechanisms and advanced robotics.

## 1 INTRODUCTION

Dynamic stability of vehicle structure and ride comfort are two main criteria for performances priority of suspension system in any vehicle. In this regard, it is required to consider all various kinds of dynamic behavior known as “road performance” for system assessment. In the tracked vehicles, compare to vehicles with tires, there are multiple suspension systems with continuous tracks; and hence the related modeling and analysis are more complicated. In previous work [1], the performance of a tracked vehicle due to standard inputs has been investigated and the parameters of the suspension system were optimized. Usually, continuous suspension system shows better performance in irregular roads or gravel roads than the independent ones. However, from dynamic stability point of view, analysis and investigation of off-road performance of the tracked vehicles are studied in this article.

Early in year 2000, Balamurugan [3] studied the ride dynamic characteristics of a typical medium weight, high speed military-tracked vehicle for negotiating rough cross-country terrain and for optimization studies different types of suspensions used with finite element modeling and analysis. An eigenvalue analysis and implicit Newmark beta method carried out to estimate natural modes of vibration of the vehicle transient dynamic analysis. In 2005, Sandu and Freeman [4, 5] derived general dynamic equations for a tracked vehicle using “trailing-arm” suspension system and an independent compatible tracked model which is applicable to any kind of tracked vehicle [4]. In the next step, they conducted numerical simulation for a military tracked vehicle [5].

In this model, they investigated in more details chassis and suspension system elements such as driving sun gear, road tires and rollers with tension mechanism, and reviewed the effects of terrain geometry and profile, the soil specifications and the effects of vehicle speed on them. Gunter *et al.* [6] conducted the computer modeling and simulation of an unmanned tracked vehicle and performed some field tests and reviewed the dynamic response including impact and vibrations imposed to the system, as well as dynamic stability and off-road motion specifications. Ravishankar and Sujatha [7] investigated the ride vibrations of a high speed tracked vehicle as a “2+N” D.O.F. model, passing irregular terrain, modeled as a sinusoidal input with various amplitude and frequencies. They compared the system performance using torsion bar inactive suspension system and hydro-gas system. Giliomee [8] suggested a semi-active suspension system, in a detailed research for improvement of ride comfort in tracked vehicles. He demonstrated the performance improvement using experimental work

and field tests. Justin Madsen *et al.* [9] in 2010, reviewed different methods for tracked vehicle modeling and introduced a super-element models to create high-fidelity simulations of the interaction between the track chain and other running gear components. They also demonstrated the tracked vehicle modeling in the ATV toolkit and Chrono engine. More recently in 2013, Senatore *et al.* [10] studied experimentally performance of a single track device driving on three natural dry, granular materials. The test rig enables imposition of velocities or application of loads to interchangeable running gears within a confined soil bin. Finally, experimental measurements are compared against well-established semi-empirical models, to assess the predictive accuracy of these models.

In this article, off-road performances of continuous suspension system of a tracked vehicle, with torsion bar and torsional damper, optimized in the previous work [1] are investigated. The off-road performances are: the study of hill input, passing 6”×6” Belgian block and the effects of irregular terrain inputs on the vehicle body hull and suspension system. Furthermore, for additional validation of the present model the responses of standard inputs [1] are compared with the AMCP reference model [2].

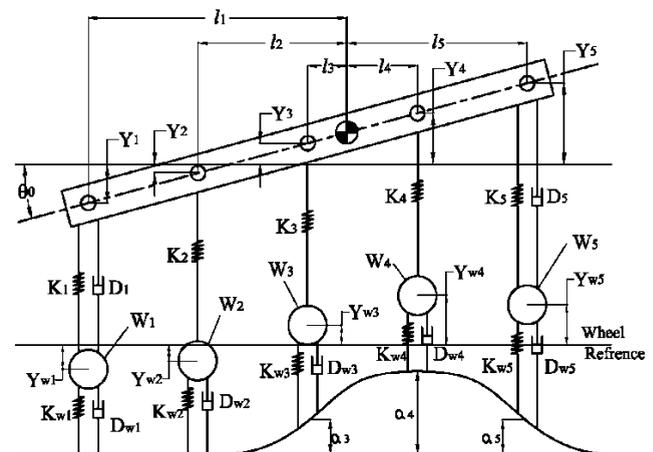


Fig. 1 The 1/2 dynamic model of vehicle

## 2 DYNAMIC MODEL OF THE SYSTEM

The proposed model for a tracked vehicle is a 7 degrees of freedom (D.O.F.) with linear time invariant (LTI) model, shown in Fig. 1. It is assumed that the vibrations in any point just effect on that point and then attenuated on that point. In this half-vehicle modeling, the body hull vertical movement (bounce), the angular movement of the body hull in vertical plane, and the vertical movement of tires and the effects of these movements on the vehicle have been considered.

According to the model presented in Fig. 1, dynamic equations of the system are as follows:

1. Vehicle hull vertical movement equation

$$\ddot{Y}_o = -\frac{K_1}{M_o}(y_1 - y_{w1}) - \frac{K_2}{M_o}(y_2 - y_{w2}) - \frac{K_3}{M_o}(y_3 - y_{w3}) - \frac{K_4}{M_o}(y_4 - y_{w4}) - \frac{K_5}{M_o}(y_5 - y_{w5}) - \frac{D_1}{M_o}(\dot{y}_1 - \dot{y}_{w1}) - \frac{D_5}{M_o}(\dot{y}_5 - \dot{y}_{w5}) \quad (1)$$

1. Vehicle hull angular movement equation

$$\ddot{\theta}_o = -\frac{K_1 L_1}{J_o}(y_1 - y_{w1}) - \frac{K_2 L_2}{J_o}(y_2 - y_{w2}) + \frac{K_3 L_3}{J_o}(y_3 - y_{w3}) + \frac{K_4 L_4}{J_o}(y_4 - y_{w4}) + \frac{K_5 L_5}{J_o}(y_5 - y_{w5}) - \frac{D_1 L_1}{J_o}(\dot{y}_1 - \dot{y}_{w1}) + \frac{D_5 L_5}{J_o}(\dot{y}_5 - \dot{y}_{w5}) \quad (2)$$

1. Vehicle tires vertical movement equations

$$\ddot{y}_{wi} = \frac{K_{wi}}{M_{wi}}(y_{wi} - a_i) - \frac{D_{wi}}{M_{wi}}(\dot{y}_{wi} - \dot{a}_i) - \frac{K_i}{M_{wi}}(y_{wi} - y_i) - \frac{D_i}{M_{wi}}(\dot{y}_{wi} - \dot{y}_i) \quad i = 1 \dots 5 \quad (3)$$

In the presented model, it is assumed that all tires are in contact with the ground and no bounces in tires. The model parameters and assigned coefficients are listed in section 11, nomenclature.

3 STATE-SPACE REPRESENTATION

State-space representation is the most feasible model to analyze the dynamic stability of the vibration system and investigation of its responses to different inputs.

1. Representation of the system states

In dynamic systems, two states are usually considered for each D.O.F. Hence, for a 7 D.O.F. system there will be 14 states that are as follows:

$$\begin{aligned} Z_1 &= y_o & Z_3 &= \theta & Z_5 &= y_{w1} & Z_7 &= y_{w2} \\ Z_9 &= y_{w3} & Z_{11} &= y_{w4} & Z_{13} &= y_{w5} \\ Z_2 &= \dot{y}_o & Z_4 &= \dot{\theta} & Z_6 &= \dot{y}_{w1} & Z_8 &= \dot{y}_{w2} \\ Z_{10} &= \dot{y}_{w3} & Z_{12} &= \dot{y}_{w4} & Z_{14} &= \dot{y}_{w5} \end{aligned} \quad (4)$$

2. Representation of the system inputs

The road input comes through the tires and because of 5 pairs of tires are considered in this model, 10 inputs

will exist regarding the inputs speeds.

$$\begin{aligned} U_1 &= a_1 & U_3 &= a_2 & U_5 &= a_3 \\ U_7 &= a_4 & U_2 &= \dot{a}_1 & U_4 &= \dot{a}_2 & U_6 &= \dot{a}_3 \\ U_8 &= \dot{a}_4 & U_9 &= a_5 & U_{10} &= \dot{a}_5 \end{aligned} \quad (5)$$

3. State-space representation

Replacing the above states of Eq. (4) in dynamic equations and auxiliary equations of motion and arranging them with reference to the state-space model, 14 equations regarding the derivatives of the states will be obtained as follows:

$$\dot{Z}_1 = Z_2 \quad (6)$$

$$\begin{aligned} \dot{Z}_2 &= \frac{-1}{M_o} [k_1(Z_1 + 1_1 Z_3 - Z_5) + k_2(Z_1 + 1_2 Z_3 - Z_7) + k_3(Z_1 + 1_3 Z_3 - Z_9) \\ &+ k_4(Z_1 - 1_4 Z_3 - Z_{11}) + k_5(Z_1 - 1_5 Z_3 - Z_{13}) + D_1(Z_2 + 1_1 Z_4 - Z_6) + D_5(Z_2 - 1_5 Z_4 - Z_{14})] \\ \dot{Z}_3 &= Z_4 \end{aligned} \quad (7)$$

$$\begin{aligned} \dot{Z}_4 &= \frac{-1}{J_o} [k_1 l_1(Z_1 + 1_1 Z_3 - Z_5) + k_2 l_2(Z_1 + 1_2 Z_3 - Z_7) + k_3 l_3(Z_1 + 1_3 Z_3 - Z_9) \\ &- k_4 l_4(Z_1 - 1_4 Z_3 - Z_{11}) - k_5 l_5(Z_1 - 1_5 Z_3 - Z_{13}) + D_1 l_1(Z_2 + 1_1 Z_4 - Z_6) - D_5 l_5(Z_2 - 1_5 Z_4 - Z_{14})] \\ \dot{Z}_5 &= Z_6 \end{aligned} \quad (8)$$

$$\begin{aligned} \dot{Z}_6 &= \frac{1}{M_w} [-K_w(Z_5 - a_1) - D_w(Z_6 - \dot{a}_1) + K_1(Z_1 + 1_1 Z_3 - Z_5) + D_1(Z_2 + 1_1 Z_4 - Z_6)] \\ \dot{Z}_7 &= Z_8 \end{aligned} \quad (9)$$

$$\begin{aligned} \dot{Z}_8 &= \frac{1}{M_w} [-K_w(Z_7 - a_2) - D_w(Z_8 - \dot{a}_2) + K_1(Z_1 + 1_2 Z_3 - Z_7)] \\ \dot{Z}_9 &= Z_{10} \end{aligned} \quad (10)$$

$$\begin{aligned} \dot{Z}_{10} &= \frac{1}{M_w} [-K_w(Z_9 - a_3) - D_w(Z_{10} - \dot{a}_3) + K_3(Z_1 + 1_3 Z_3 - Z_9)] \\ \dot{Z}_{11} &= Z_{12} \end{aligned} \quad (11)$$

$$\begin{aligned} \dot{Z}_{12} &= \frac{1}{M_w} [-K_w(Z_{11} - a_4) - D_w(Z_{12} - \dot{a}_4) + k_4(Z_1 + 1_4 Z_3 - Z_{11})] \\ \dot{Z}_{13} &= Z_{14} \end{aligned} \quad (12)$$

$$\dot{Z}_{14} = \frac{1}{M_w} [-K_w(Z_{13} - a_5) - D_w(Z_{14} - \dot{a}_5) + k_5(Z_1 - 1_5 Z_3 - Z_{13}) + D_5(Z_2 - 1_5 Z_4 - Z_{14})]$$

It is notable that the magnitudes of  $a_1$  to  $a_5$  and  $\dot{a}_1$  to  $\dot{a}_5$ , represent the displacement and the related velocity of road inputs to each tire, respectively.

4. Representation of system outputs

The second part of state-space equations are output equations which are functions of states and inputs in terms of time. In this model, the 4 outputs are considered that can be obtained as follows:

$$Y_1 = Z_1 \quad (13)$$

$$\begin{aligned} Y_2 &= \frac{-1}{M_o} [k_1(Z_1 + 1_1 Z_3 - Z_5) + k_2(Z_1 + 1_2 Z_3 - Z_7) + k_3(Z_1 + 1_3 Z_3 - Z_9) \\ &+ k_4(Z_1 - 1_4 Z_3 - Z_{11}) + k_5(Z_1 - 1_5 Z_3 - Z_{13}) + D_1(Z_2 + 1_1 Z_4 - Z_6) + D_5(Z_2 - 1_5 Z_4 - Z_{14})] \\ Y_3 &= Z_3 \end{aligned} \quad (14)$$

$$\begin{aligned} Y_4 &= \frac{-1}{J_o} [k_1 l_1(Z_1 + 1_1 Z_3 - Z_5) + k_2 l_2(Z_1 + 1_2 Z_3 - Z_7) + k_3 l_3(Z_1 + 1_3 Z_3 - Z_9) \\ &- k_4 l_4(Z_1 - 1_4 Z_3 - Z_{11}) - k_5 l_5(Z_1 - 1_5 Z_3 - Z_{13}) + D_1 l_1(Z_2 + 1_1 Z_4 - Z_6) - D_5 l_5(Z_2 - 1_5 Z_4 - Z_{14})] \end{aligned}$$

The physical concept of above outputs will be explained in the next section. However, among these output,  $y_2$  is related to the vehicle vertical acceleration that has been considered as dynamic stability criterion of the vehicle body hull structure.

For body hull vertical acceleration criteria, based on Table 8 in reference [14], the allowable vertical acceleration imposed to the tracked vehicle body hull is equal to  $4g$  at high speeds in cold asphalt roads,  $2.3g$  at medium speeds in suburban gravel roads and  $8g$  at low speeds in irregular terrains. For ease of analysis and based on medium size of the tracked vehicle, the allowable body hull vertical acceleration for dynamic stability of the desired system is determined as  $4g$ .

#### 4 SYSTEM PARAMETERS AND COEFFICIENTS

According to optimization results in the previous work [1], the optimized values for spring and damper coefficients of the desired system have been determined as  $k_i=110$  KN/m and  $D_i=20$  KN.S/m. Since a torsion spring is applied in suspension system and for modeling simplifications, the springs have been assumed linear, the variations from linear to torsion behavior must be considered in the actual application of spring coefficients. The procedure of transformation from linear to torsion equations has been presented in [14].

#### 5 SYSTEM RESPONSE

To investigate the system response, motion equations must be transformed from parametric to numerical form. Continuing the research, the system responses are optimized and then investigated against various off-road inputs with using MATLAB software.

##### 1. The system inputs are

- a) Passing Belgian block bumps (hill input).
- b) Irregular road input.

##### 2. The system outputs are

- a) Vertical displacement of body hull centroid ( $y_1$ ) in term of  $m$ .
- b) Vertical acceleration of body hull centroid ( $y_2$ ) in terms of  $m/s^2$ .
- c) Angular displacement of body hull ( $y_3$ ) in term of  $rad$ .
- d) Angular acceleration of body hull ( $y_4$ ) in terms of  $rad/s^2$ .

#### 6 BELGIAN BLOCK BUMP INPUT

One of the main off-road tests for the tracked vehicle is passing  $6'' \times 6''$  Belgian block bump that is shown in Fig. 2. In fact, this is a step input test that has been

practically transformed to a ramp profile input. When the tires of tracked vehicle pass this block, the tires form a trapezoidal hill profile with the height of 6 inches in Fig. 2 (a). Fig. 2 (b) shows the parametric model that is considered as hill input.

In order to investigate the effects of factors such as vehicle speed and bump figure on performance of suspension system, firstly, the parameters should be defined; then a relation derived between vehicle speed and system input; and finally the effect of excitation on the first tire and the other tires. All of these relations have been coded in MATLAB and the results plotted accordingly. The parametric relations are as follows:

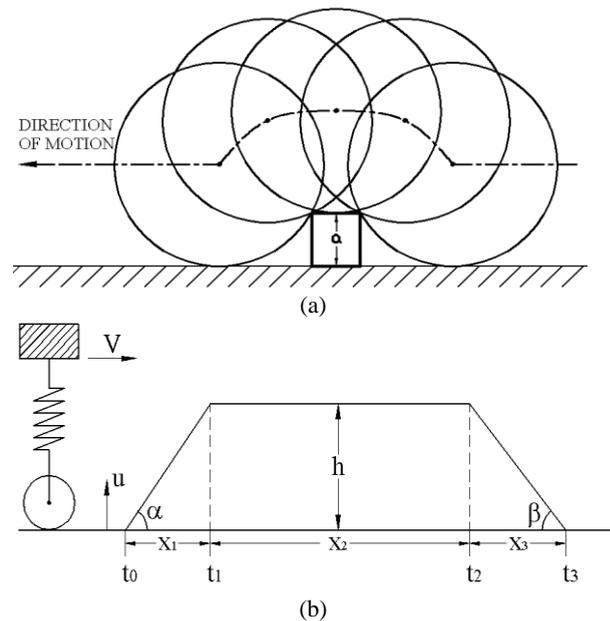
$$U = x.tg\alpha \quad \Rightarrow \quad U = V.t.tg\alpha \quad (15)$$

$$x = V.t$$

$$t_1 - t_0 = \frac{x_1}{V} \quad , \quad tg\alpha = \frac{h}{x_1} \quad (16)$$

$$t_2 - t_1 = \frac{x_2}{v} \quad , \quad tg\beta = \frac{h}{x_3} \quad (17)$$

$$t_3 - t_2 = \frac{x_3}{v} \quad (18)$$



**Fig. 2**  $6'' \times 6''$  Belgian block bump, (a) locus profile of the wheels; (b) parametric model of the ramp

In order to define the sequence of tires input, the following equations are derived

$$ad_1 = |L_1 - L_2| \quad \Delta T_1 = \frac{ad_1}{V} \quad (19)$$

$$ad_2 = |L_2 - L_3| \quad \Delta T_2 = \frac{ad_2}{V} \quad (20)$$

$$ad_3 = |L_3 - L_4| \quad \Delta T_3 = \frac{ad_3}{V} \quad (21)$$

$$ad_4 = |L_4 - L_5| \quad \Delta T_4 = \frac{ad_4}{V} \quad (22)$$

$$\Delta U = \Delta t \cdot V \cdot \tan \alpha \quad (23)$$

The model parameters have been considered as  $h = a = 6 \text{ in.} = 15 \text{ cm}$ ,  $X_2 = X_1 = 0.15 \text{ m}$ ,  $X_3 = 0.375 \text{ m}$  and  $\beta = \alpha = 45^\circ$ .

Depend on which tire firstly passes the block, the output response will be different. Moreover, the response of other tires will be along with a time delay proportional to the vehicle speed ( $V$ ) passing the bump. Therefore, to study the response of passing Belgian block bump or hill input, three parameters must be considered: 1) the number of tire where the block or step input begins; 2) the related input of other tires; 3) the speed of passing the block. The hill input for the first tire has been considered at two standard speeds of 5 and 15 Mph, that are equal to 8 and 24 Km/h, respectively [2, 12]. These two speeds are considered as values of 10 and 24 Km/h for simplicity.

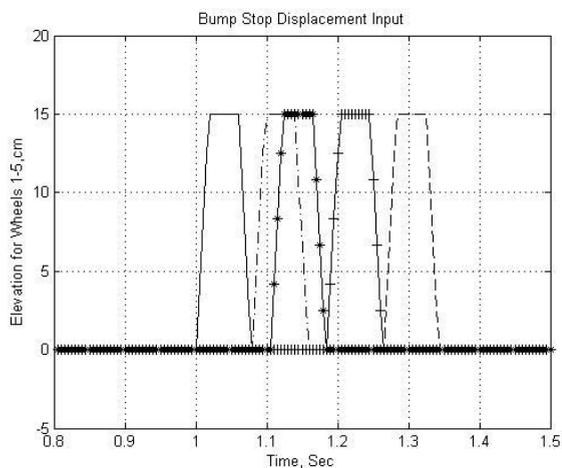


Fig. 3 The vertical displacement of 5 tires in response to the step input (passing Belgian block)

Figs. 3 and 4 show the diagrams of vertical displacement and velocity imposed to tires 1 to 5, by passing the Belgian block at the speed of 10 Km/h. Notice that the group of 5 curves are related to tires 1 to 5, respectively. To show the accurate tracking of tire interactions, the displacement and velocity of the first tire at two standards speed values have been compared along with its input.

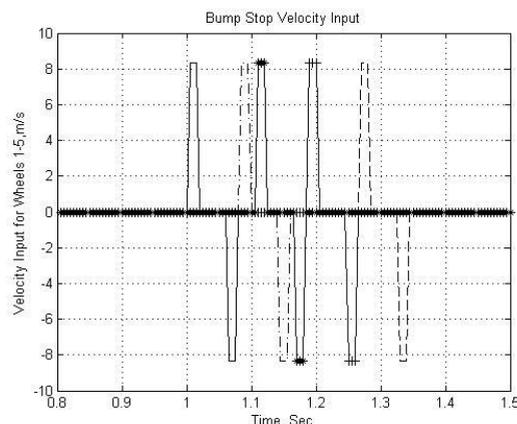
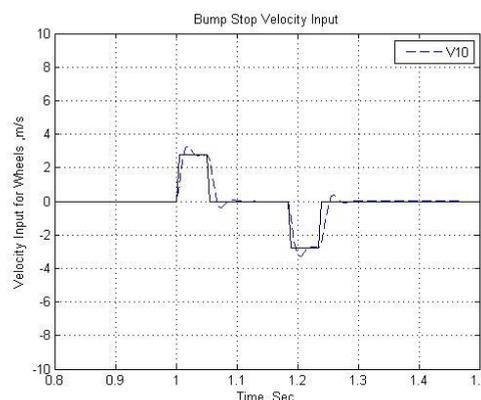
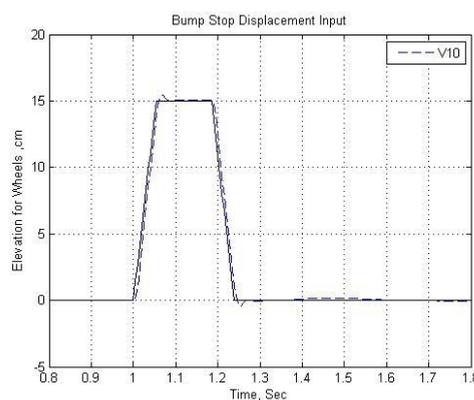


Fig. 4 The vertical velocity of 5 tires in response to the step input (passing Belgian block)



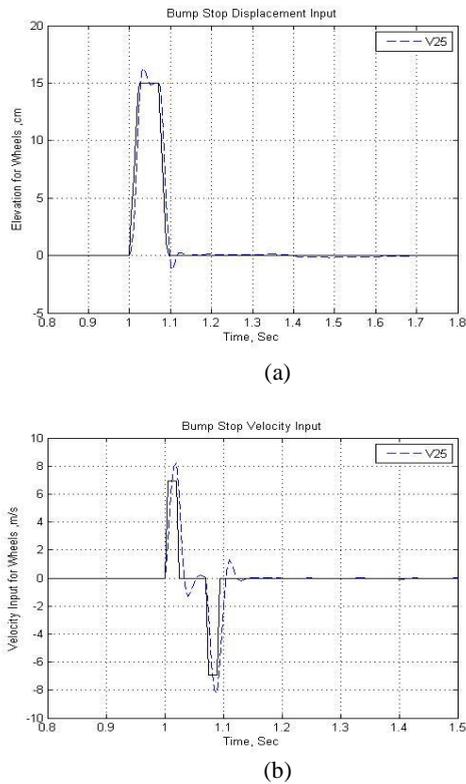
(a)



(b)

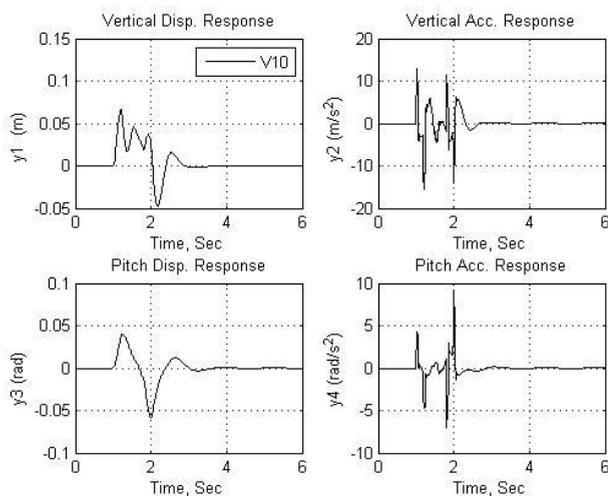
Fig. 5 The response of vertical (a) displacement and (b) speed of the first tire against the hill input (at the vehicle speed of 10 km/h)

Figs. 5 and 6 show inputs related to speeds of 10 and 25 Km/h, respectively. These diagrams clearly show the inputs accompanied by suspension system.

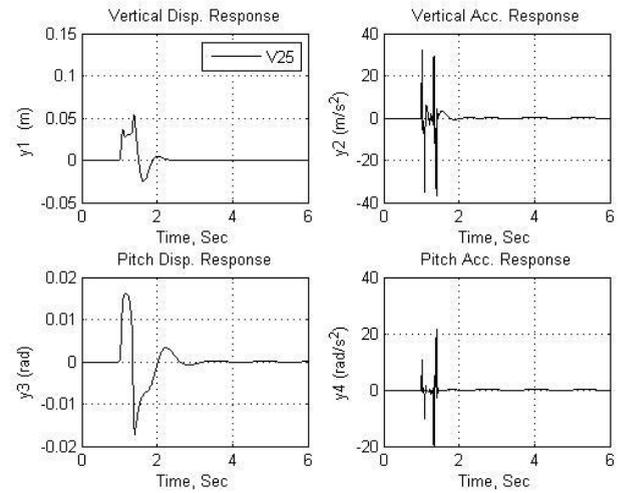


**Fig. 6** The response of vertical (a) displacement and (b) speed of the first tire against the hill input (at the vehicle speed of 25 km/h)

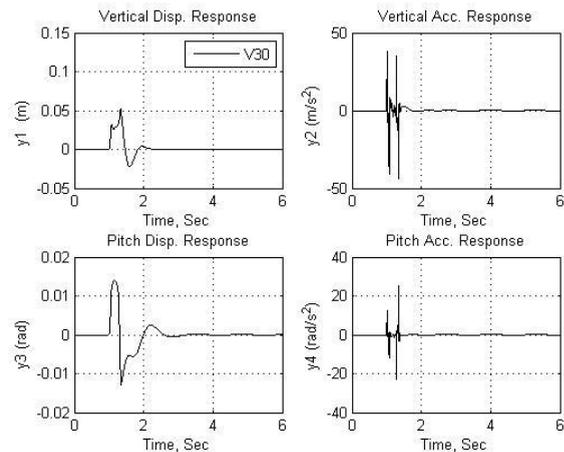
Furthermore, all of the system responses including displacement, linear acceleration, vertical acceleration, and angular acceleration due to these two standard speeds have been shown in Figs. 7 and 8, respectively.



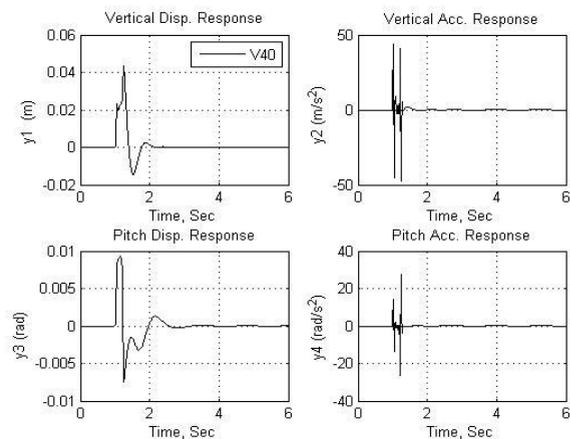
**Fig. 7** The all system response to hill input (at speed of 10 km/h)



**Fig. 8** The all system response to hill input (at speed of 25 km/h)



**Fig. 9** The all system response to hill input (at speed of 30 km/h)

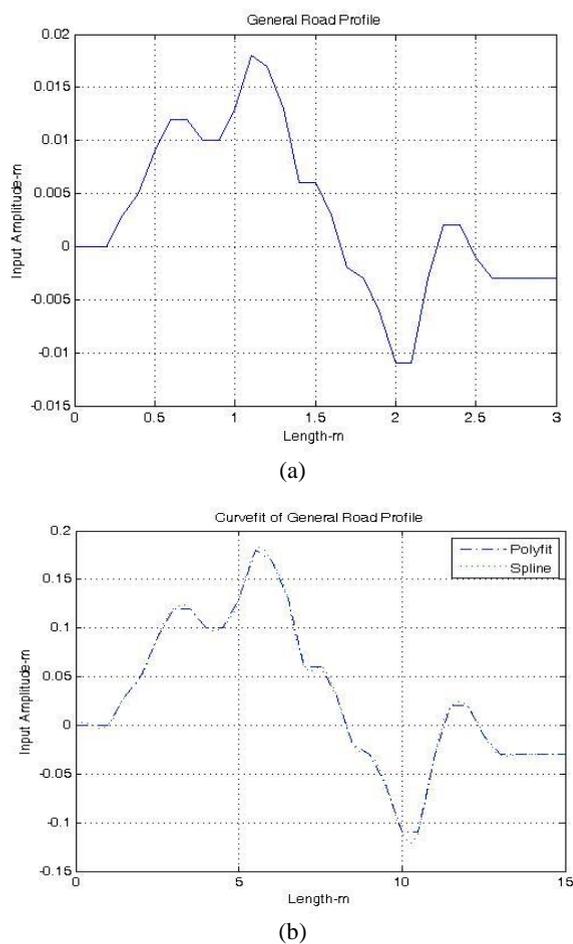


**Fig. 10** The all system response to hill input (at speed of 40 km/h)

In order to investigate the ultimate speed, the system responses at speeds of 30 and 40 Km/h have been obtained that shown in Figs. 9 and 10. Finally, the maximum and minimum amplitudes of vertical acceleration and settling time subject to the hill input are compared together at different speeds and the results are shown in Table 1.

**Table 1** The maximum and minimum responses of vertical acceleration and settling time for hill input at different speeds

Speed for passing Belgian block, km/h	10		25		30		40	
	Min	Max	Min	Max	Min	Max	Min	Max
Body hull acceleration, m/s <sup>2</sup>	-15.79	13.69	-35.79	32.64	-44.60	39.19	-48.65	45.95
Settling time ,sec	3.53		2.0		1.69		1.54	

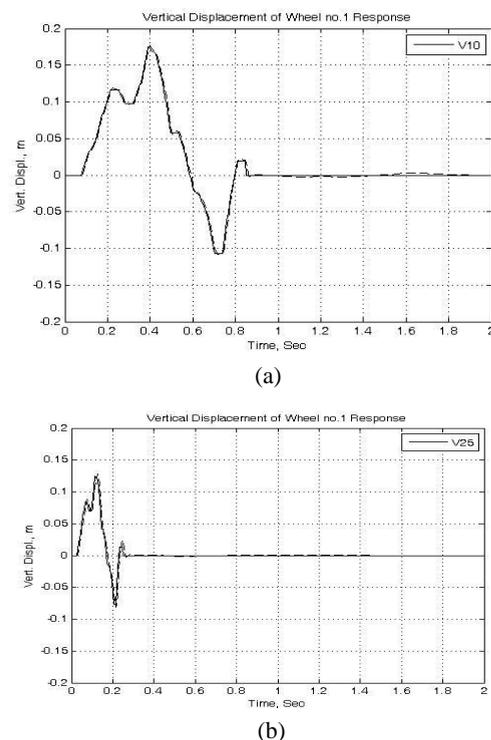


**Fig. 11** The diagrams of (a) irregular terrain profile and (b) the related fitted curve

### 7 IRREGULAR TERRAIN INPUT

For analyzing irregular terrain input so called “General non-periodic input” and its transient response, the analysis method of [13] has been used. The polynomial relations like cubic spline curve could be fitted over input data shown in Fig. 11. For the transient response, rectangular pulse series approach has been applied. In this approach, the input data in each time period is divided as a rectangular impulse and the related system response in each period is calculated; then added to the response for the latter time period as initial condition. This procedure continues until the system response for the whole desired time is obtained.

In this article, a model of an arbitrary irregular terrain has been used as a general non-periodical input by using impulse series response model. In this manner, the road data inputs have been entered separately and then the related spline fitting curve obtained by MATLAB software. Afterwards, the input are imported to the state-space model and the system outputs are obtained. The related passing speed has been considered as 10 and 25 km/h respectively. The initial profile and fitted curve of irregular terrain input is shown Figs. 11 (a and b). The response of the first tire related to the irregular terrain input, at two standard speeds of 5 and 15 Mph shown in Figs. 12 (a and b), respectively.



**Fig. 12** The reaction of the first tire to irregular terrain input at speeds of (a) 10 and (b) 25 km/h

The all system responses relative to the irregular terrain input, at two speeds of 10 and 25 km/h, have been shown in Figs.13 and 14, respectively.

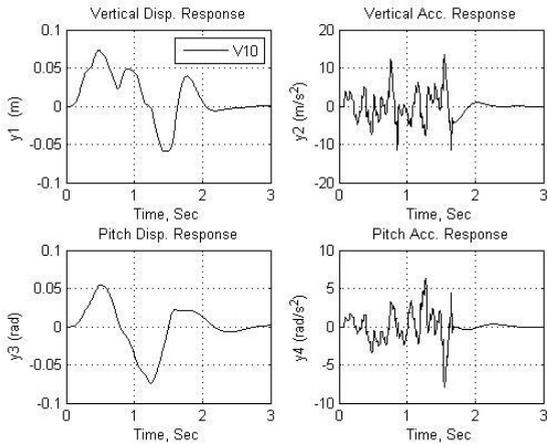


Fig. 13 All system responses to irregular terrain input (at speed of 10 km/h)

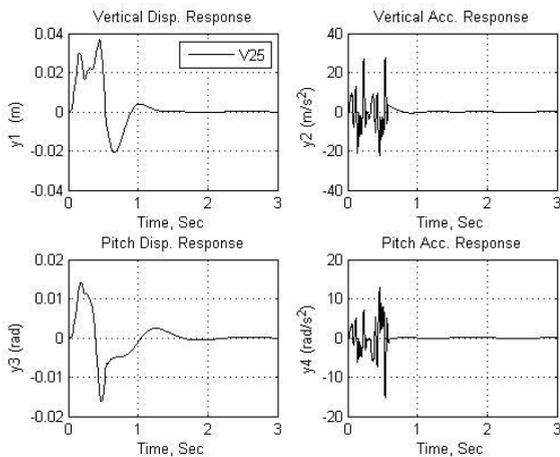
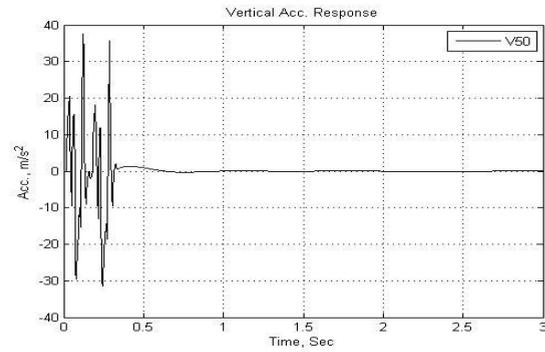


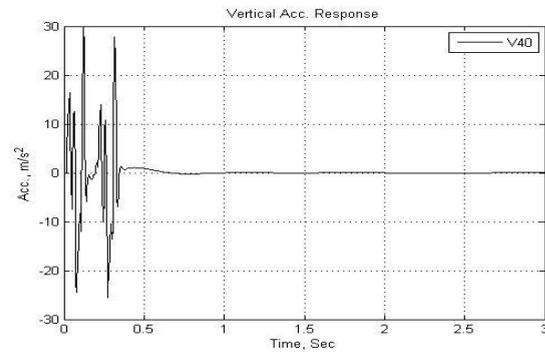
Fig. 14 All system responses to irregular terrain input (at speed of 25 km/h)

Table 2 The maximum and minimum responses of vertical acceleration and settling time against irregular terrain input at different speeds

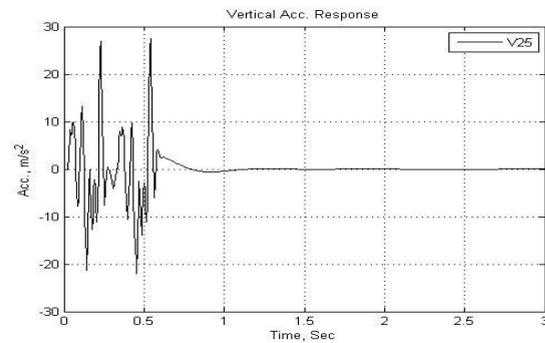
speed passing irregular terrain ,km/h	10		25		30		40	
	Min	Max	Min	Max	Min	Max	Min	Max
Body hull acceleration, m/s <sup>2</sup>	-15.79	13.69	-35.79	32.64	-44.60	39.19	-48.65	45.95
Settling time, sec	3.53		2.0		1.69		1.54	



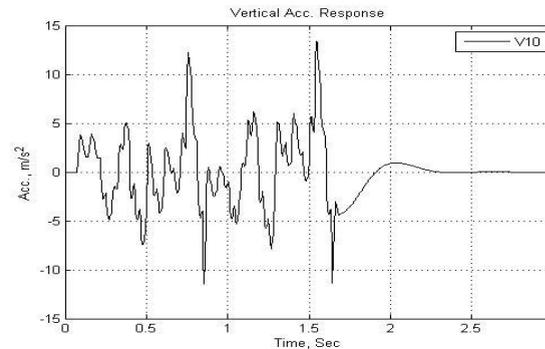
(a)



(b)



(c)



(d)

Fig. 15 The system response of vertical acceleration of body hull for irregular terrain input at speed of (a) 50 km/h, (b) 40 km/h, (c) 25 km/h, and (d) 10 km/h

Furthermore, to study the behavior of the tracked vehicle at higher speeds, the system response for 40 and 50 km/h have also been obtained. However, as a dynamic stability criteria only the results of vertical acceleration of body hull are shown in Fig. 15 (a and b). For the ease of comparison, the related vertical accelerations of other two speeds of 10 and 25 km/h are also shown in Fig. 15(c and d). Finally, the maximum and minimum magnitude of vertical acceleration and the related settling times for the irregular terrain input at various speeds have been compared together and the results shown in Table 2.

### 8 VALIDATION OF DYNAMIC MODEL

In this section, to validate the presented model (TOSAN), the behavior of the designed suspension system will be compared to the referenced ACMP model [2]. The exact comparison of the two models shows that a kind of innovation has been occurred in the way of calculation of spring and damper forces. Furthermore, in the referenced ACMP model, the term of gravitational acceleration was wrongly added that is modified for the comparison. For this purpose, the following procedure was carried out:

1. Deriving dynamic equations for AMCP model
2. Importing the inputs of TOSAN model to AMCP model
3. Importing the standard and road inputs to AMCP model
4. Considering 6 outputs for both two models, for more unification

**Table 3** The comparison of maximum and minimum vertical acceleration in the 2 models TOSAN and ACMP at speed of 5 and 15 Mph

Body hull acceleration m/s <sup>2</sup>	5 Mph		15Mph		Difference percentage			
	Min	Max	Min	Max	Min	Max	Min	Max
New model (TOSAN)	-12.34	10.37	-35.5	31.1	5 Mph	15 Mph	5 Mph	15 Mph
Reference model (AMCP)	-12.56	10.29	-35.08	31.01	~2%	~1.2%	~1%	~0.3%

The outputs are body hull vertical displacement, velocity and acceleration as well as body hull angular displacement, velocity and acceleration. To compare the outputs of two models, system responses versus

initial inputs, unit step response, response to the hill or Belgian block at speeds of 10 and 25 km/h and finally both systems responses to an irregular terrain have been obtained in form of diagram groups.

However, to summarize, just the acceleration responses of body hull due to passing the Belgian block (hill input) at two speeds of 5 and 15 Mph have been presented. The compared results are shown in Table 3. It can be seen that not only vertical acceleration responses in both models are close together, but also displacement, velocity, linear/angular responses in both models are close together. Therefore, with this procedure the proposed model was validated and approved.

### 9 RESULTS DISCUSSION

As mentioned earlier, in previous work [1] the standard inputs of initial condition and unit step were investigated. In this article however, the state-space model of the system has been completely presented and off-road inputs are reviewed. The first off-road input is passing Belgian block bump test. It can be seen in Fig. 2, after modeling and linearization the input becomes like a trapezoid which is also named “trapezoidal hill input”. The Belgian block test is one of the most common test that implemented for heavy vehicle such as trucks, tractor trailers, tracked vehicles and tracked vehicles such as tanks. The Belgian block test for the armored vehicle has been described in details in [2]. In Figs. 3 and 4, the diagrams of vertical displacement and speed of tracked vehicle tires while passing Belgian block bump have been shown. These diagrams show the situation of any tire with accurate time delay. As it can be seen in Figs. 5 and 6, the response of the first tire, follows the inputs of displacement and related velocity at two standard speeds with a small overshoot within a short time. These diagrams show the validation of inputs and tire interactions. Figs. 7 to 10 show the system responses at speeds of 10, 25, 30 and 40 km/h to hill input. It can be observed that:

1. All of the vertical displacements have amplitude of 1/3 relative to the input amplitude and become stable in less than 3 seconds.
2. All of the body hull vertical acceleration amplitudes are in allowable range and become stable within average time of 2 seconds. It is important to note that, as stated earlier, the admissible value of vertical acceleration in off-road performance of these tracked vehicles is less than 4g [11].
3. According to dynamic analysis, the maximum amplitude or overshoot of vertical acceleration increases with increase of vehicle speed, but the

settling time decreases, on the contrary. Table 1 shows this problem.

- The maximum speed for passing the bump is less than 30 km/h. However, if the maximum acceleration is considered as 3.2g (with 20% less than permissible limit), the safety limit for maximum speed will be suggested equal to 25 km/h. In the next step, system response to irregular terrain has been investigated. The irregular terrain was modeled by rectangular pulse series as a selected numerical method. In Fig. 11, the diagram of irregular terrain and the related fitted curve has been shown. In order to demonstrate that the tires are following the irregular terrain input, the first tire response at two speed values of 10 and 25 km/h have been shown in Figs. 12-a and 12-b, respectively. These diagrams show the tracking of inputs with minimum overshoots and time delays. System responses to this input at two standard speeds have been presented in Figs. 13 and 14. As a design criterion for suspension system, body hull vertical acceleration amplitudes of the system are very desirable and attenuated in less than 1.5 seconds. This response also studied for irregular terrain input at speeds of 10, 25, 40 and 50 km/h and the results shown in four diagrams of Fig. 15. Table 2 shows the maximum and minimum amplitudes of vertical acceleration along with settling time. As it can be seen, the increase of speed causes the increase of acceleration and decrease of settling time, but in all cases acceleration amplitudes are less than 4g. In order to obtain the optimum speed limit for passing the terrain with the acceleration limit of 3.2g (with 20% less than permissible limit), also for more safety the critical speed limit is suggested as 40 km/h. Finally, for validation of the presented model various inputs are examined for both TOSAN and AMCP models. However, for brevity only trapezoidal hill input (Belgian block) has been considered. For measureable and more clarification of this comparison, vertical accelerations of both models at both speeds of 5 and 15 Mph have been compared. The numerical results of minimum and maximum amplitudes of acceleration and discrepancy have been presented in Table 3. The minimum and maximum of discrepancy are 0.3% and 2%, respectively.

## 10 CONCLUSION

In this article, firstly a linear 7 D.O.F. model for analysis and investigation of suspension system of a tracked vehicle was derived. Then dynamic and state-space equations and system responses versus various

inputs have been obtained. The most important off-road performances are passing Belgian block bump test or "trapezoidal hill input" and riding on irregular gravel road or "irregular terrain input". The results shown that due to shocks imposed by hill and irregular terrain inputs caused a reasonable vertical acceleration of the system and it becomes stable in less than 2 seconds. Furthermore, the critical speed limit has been obtained to stipulate the dynamic stability limit and vehicle handling instruction in tactical maneuvers. The allowable speed of tracked vehicle to pass Belgian block bump is suggested in range of 25 to 30 km/h; whilst for irregular terrain would be in range of 40 to 45 km/h. These values are very reasonable and are practical for the drivers of the same tracked vehicles. Finally, to validate the present model, it was compared with the reference AMCP model and satisfactory results are achieved.

## 11 NOMENCLATURE

$a_i$	Road input over tracked tires (m)
$D_i$	Damping coefficients of suspension system (N.s/m)
$D_{wi}$	Damping coefficients of tracked tires (N.s/m)
$i$	The $i$ th tracked tire/wheel no. ( $i=1 \dots 5$ )
$J_0$	$\frac{1}{2}$ of torsion moment (kg.m <sup>2</sup> )
$K_i$	Spring coefficient of suspension system (N/m)
$K_{wi}$	Spring coefficients of tracked tires (N/m)
$L_i$	Distance between the center of the $i$ th tires to the centroid (m)
$M_0$	$\frac{1}{2}$ of sprung mass (kg)
$M_{wi}$	$\frac{1}{10}$ of un-sprung mass (kg)
$U_i$	The $i$ th input System
$Y_i$	Vertical displacement over the center of tires (m)
$y_{wi}$	vertical displacement of wheel $i$ (m)
$\ddot{Y}_o$	Vehicle hull vertical acceleration (m/s <sup>2</sup> )
$\ddot{y}_{wi}$	Vehicle wheel $i$ vertical acceleration (m/s <sup>2</sup> )
$Z_i$	The $i$ th state variable
$\dot{Z}_i$	The derivative of the $i$ th state variable
$\Theta_0$	Body hull torsion displacement (rad)
$\ddot{\Theta}_o$	Body hull angular acceleration (rad/s <sup>2</sup> )

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