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# Terrain Accessibility Prediction for a New Multi-axle Armoured Wheeled Vehicle

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**ABSTRACT**

Better terrain accessibility of military vehicle makes it possible to project force at desired points in a theatre of operation. The factors responsible for terrain accessibility are slope, obstacles and soil. Torque requirement for meeting vehicle speed and gradient requirement is understood and can be analytically arrived at. It can be met by appropriate choice of engine and transmission using. There is dearth of information as well as a common metric in quantification of terrain accessibility especially soft soil trafficability. Approach adopted in this study is that of characterisation of vehicle in terms of mobility characteristic and mobility limit parameters and comparing them with vehicle in-service worldwide. Simple empirical relation has been preferred over complex analytical approach for mobility prediction and gradient climbing capability in sand has been predicted and compared with other vehicles. parametric study for tyre sizes vis-a-vis mobility parameters have been obtained and results have been presented for chosen vehicle configuration. Second part of this study is obstacle crossing capability study for standard set of obstacles. Vehicle model has been built in multi-body environment and parameters of significance viz., wheel displacement to verify correctness of model and acceleration at CG for ride comfort and ground reactions for evaluation of dynamic loads on axles have been obtained. Vehicle drivetrain configuration to achieve desired terrain accessibility in terms of soft-soil trafficability and obstacle crossing has been demonstrated.

**Keywords:** Terrain accessibility; Soft soil trafficability; Mobility performance prediction; Mobility characteristic parameters; Mobility limit parameters

## 1. INTRODUCTION

Mobility is the ability to move freely and rapidly over the terrain of interest to accomplish varied combat objectives. Mobility is thus measured by a system's freedom of movement i.e. per cent of the terrain over which the vehicle is mobile and its average speed or travel time over that terrain[1]. A vehicle's mobility is impacted by its tractive ability over various soil types. The off-road mobility of military vehicles plays a key role in operation. The ability to reach the desired area in a theatre of war represents the most important condition for a successful accomplishment of the mission for military vehicles. The off-road vehicles face a broad spectrum of terrains to cross. The primary functional objective of a military vehicle suspension system is to improve mobility by permitting an increase in speed at which the vehicle may traverse in the speed at which the vehicle may traverse uneven terrain without detrimental or unacceptable impacts and vibrations to the vehicle and to the personnel, and without intolerable variations of traction with the terrain. The degree of attainment of the functional objective for a particular vehicle may be restricted by the suspension of that vehicle. However, for a given vehicle achieving best available mobility characteristics result from an approach in which due consideration is given to the significance of the factors viz., terrain contour, unsprung mass, sprung mass, elastic support system consisting of control linkage, springing and damping.

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Adequate information and understanding of all the power train elements of a vehicle such as engines, transmissions is available. Tractive performance of a vehicle based on power train elements can be predicted mathematically. Maximum tractive effort generated by the vehicle is theoretically limited by minimum of the (a) Power of the vehicle and (b) Maximum tractive force available from the soil. Power limitation of the vehicle is overcome by high power engines so largely terrain accessibility is governed by the tractive effort generated from the vehicle-soil interaction. In absence of recognised theories for soil vehicle interaction, vehicle concepts are developed empirically using basic principles of mechanics and land locomotion.

Accessibility of terrain by the vehicle gives military commander capability of projecting force to any point. A vehicle ideally has to have capability to access any terrain. There are two aspects to terrain accessibility - soft soil trafficability and obstacle crossing (Fig. 1). Vehicle sinks in a soft terrain leading to immobility. Another source of immobility is on account of obstacle which appear in many forms such as trench, step and triangular ditch. Water obstacle is another factor which results in immobility. However, scope of this study is limited to soft soil trafficability and obstacle crossing.

## 2. SOFT SOIL TRAFFICABILITY

A vehicle is said to be able to be trafficable on a particular soil if the vehicle is able to develop positive drawbar pull. Generally, it is assumed that sufficient torque available from

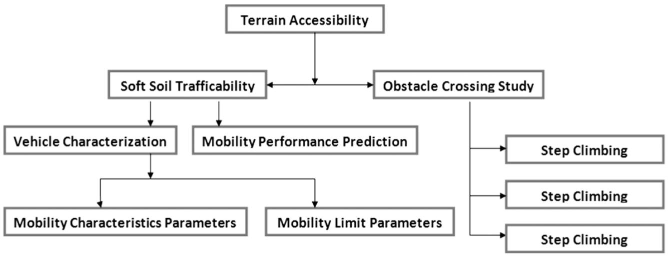


**Figure 1. Terrain accessibility.**

the power train to rotate the wheels. In other words mobility is not limited on account of less power train based thrust. This part of study is concerned with soil vehicle interaction.

## 3. APPROACH

There is plethora of ways of quantifying mobility. Broadly, there are two ways viz., vehicle characterisation[2] and mobility performance prediction[3]. Mobility characteristic parameters are a function of vehicle parameters and soil parameter as such have no influence on these parameters. These mobility characteristic parameters help in making comparisons with existing vehicles worldwide. Minimum strength of soil on which the vehicle can be expected to remain mobile is given by mobility limit parameter. This parameter is used in the field where soil conditions are mapped using devices such as cone penetrometer. In the present work, a comparison is made between the vehicles available worldwide and the newly developed vehicle. The vehicles considered for comparison vary in terms of gross vehicle weight (GVW), No. of axles, Provision of centralised tyre inflation system (CTIS) and country of origin. Details of vehicle and their information along with the new vehicle under consideration are as shown in Table 1.

### 3.1 Mobility Characteristic Parameters

*Mean Maximum Pressure*

Mean maximum pressure (MMP) has come to be accepted as a useful tool for comparing the mobility of different wheeled vehicles. Maclaurin approach for MMP for wheeled vehicles was proposed for all-wheel drive vehicles of approximately uniform weight distribution which was claimed to offer a better correlation[4,5,6]. This approach was incorporated in the statement of requirement for the multi-role armoured vehicle programme of US.

Mean Maximum Pressure (MMP)

$$MMP_w = \frac{1.14 \times W}{2mb^{0.85} d^{1.15} \sqrt{\delta/d}} \quad (kPa)$$

where $w$ is gross vehicle weight (kgs), $m$ is number of axles, $b$ is tire section width (m), $d$ is tire unladen carcass diameter (without tread) (m) = (overall dia - 2 x tread depth), δ is tire static deflection (with CTIS) (m), and $h$ is tire section height (edge of rim to bottom of tread) (m)

If differential locks are fitted the MMP may be considered to improve as follows:

| | |
|---|---|
| 4 x 2 vehicles | 0.98 MMP |
| 8 x 8 or 6 x 6 vehicles | 0.97 MMP |

It can be seen from Figure 2 MMP vs Mass, MMP values of the vehicle are comparable to the world-class vehicles. Lesser value of MMP indicates better mobility.

### 3.2 Mobility Limit Parameters

Mobility limit parameter predict the value of cone index which immobilises the vehicle. It may be noted that the results obtained by this method are not very consistent[7,8]. In general the trends suggest that vehicles with centralised tyre inflation system (CTIS), bigger tyres and less weight tend to do better.

*Mobility Index*

$$= \left[ \frac{CPF \times WF}{TF \times GF} + WLF - CF \right] \times EF \times TRF$$

where

$$CPF \ (Contact\ Pressure\ Factor\ ) \ = \ \frac{gross\ vehicle\ weight\,(lbf\,)}{B \times R \times \ number\ of\ tyres}$$

where $B$ is tyre width (in) and $R$ is tyre radius (in)

$$WF\,(Weight\ Factor) \ = \ 0.533X \quad ................(X < \ 2)$$

$$= \ 0.033\,X + 1.05 \quad ...........(2 \ < \ X \ < \ 13.5).$$

$$= \ 0.142\,X \ - \ 0.42 \quad .............(13.5 \ < \ X \ < \ 20)$$

$$= \ 0.278\,X \ - \ 3.115 \quad .............(X \ > \ 20)$$

where $X$ is average axle load = gross vehicle weight (lbf)/(1000 x no of axles)

Also,

$$TF(\ Tyre\ Factor\ ) \ = \ \frac{10 + tyre\ section\ width\ (in)}{100}$$

**Table 1. Vehicle parameters worldwide**

| No of wheels (M) | Name of vehicle | Country of origin | Weight (tons) | Tyre width (m) | Tyre diameter (m) | Tyre deflection (m) | Tyre section height (m) | Ground clearance (m) | CTIS |
|---|---|---|---|---|---|---|---|---|---|
| 6 | Pandur | Austria | 13.5 | 0.338 | 1.033 | 0.084 | 0.263 | 0.43 | Yes |
| 8 | BTR-80 | Russia | 13.6 | 0.33 | 1.117 | 0.105 | 0.33 | 0.475 | Yes |
| 4 | Panther | UK | 14 | 0.438 | 1.343 | 0.133 | 0.418 | 0.55 | Yes |
| 6 | AMX-10RC | France | 15.88 | 0.366 | 1.254 | 0.119 | 0.373 | 0.35 | Yes |
| 6 | Grizzly | Canada | 10.5 | 0.287 | 0.984 | 0.037 | 0.289 | 0.5 | No |
| 4 | Saxon | UK | 11.66 | 0.366 | 1.254 | 0.062 | 0.373 | 0.29 | No |
| 8 | LAV-25 | Canada | 12.79 | 0.287 | 0.984 | 0.037 | 0.289 | 0.5 | No |
| 6 | Fuchs | Germany | 19 | 0.366 | 1.254 | 0.062 | 0.373 | 0.406 | No |
| 6 | WAPC (6x6) | India | 15 | 0.384 | 1.258 | 0.119 | 0.373 | 0.45 | Yes |

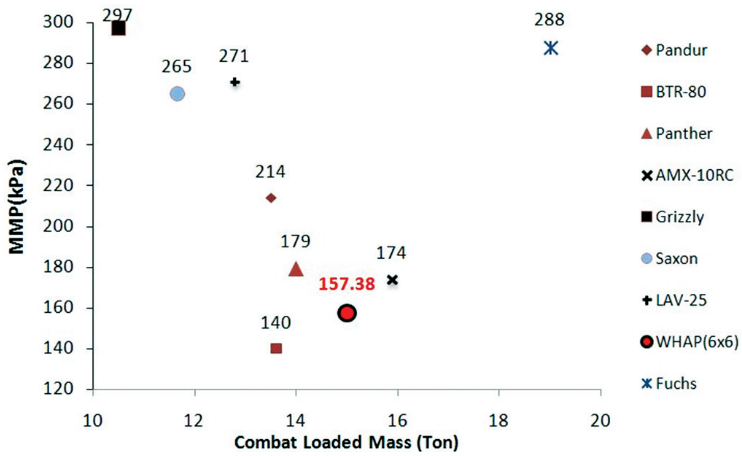


**Figure 2. MMP vs Mass.**

$$GF\left(Grouser\ Factor\right)=1.05\left(with\ chains\right),1.0(withoutchains)$$

$$CF\left(Clearance\ \ Factor\right)\ =\ ground\ clearance\ (in)/10$$

$$EF\left(Engine\ \ Factor\right)=1.0\ (power\ mass\ ratio\ >10\ hp/ton)$$

$$TRF\left(Transmission\ \ Factor\right)\ =1.0\ (automatic\ transmission)$$

$$=\ 1.05\ (manual\ transmission)$$

Using above values, Mobility Index can be calculated as:

$$MI_w=\left[\frac{CPF\times WF}{TF\times GF}+WLF\text{ - }CF\right]\times EF\times TRF$$

**(a) Vehicle Cone Index ($VCI_w$)**

The vehicle cone index is based on mobility index (MI). It may be noted that mobility Index is not influenced by tyre inflation pressure even though this has a very significant effect on mobility. A correction factor takes care of the tire static deflection term. Figure 3 VCI vs mass shows the comparison of world-class vehicles with WhAP (6x6) with respect to combat mass. VCI of 195.5 kPa is obtained for WhAP (6x6).

*Vehicle Cone Index*

Clay soils:

For single pass:

$$VCI_w=11.48+0.2\ MI_w\text{ - }\frac{392.2}{MI_w+3.74}\quad\left(lb/in^2\right)...if\quad MI_w\le 115$$

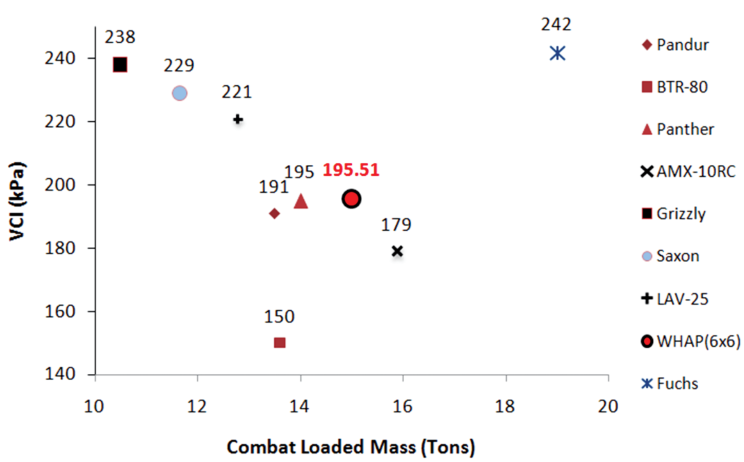


**Figure 3. VCI vs mass.**

or

$$VCI_w\ =\ 4.1MI_w^{\ 0.446}\ \left(lb/in^2\right)...if\ \ MI_w>115$$

so,

For 50 passes:

$$VCI_w\ =\ \ 28.23+0.43\ MI_w\text{ - }\frac{92.67}{MI_w+3.74}\qquad\left(lb/in^2\right)$$

### 3.3 Mobility Performance Predictions

They are designed to predict the performance of vehicles on different types of soil in terms of the rolling resistance, gross traction and net traction (or drawbar pull), often as a function of longitudinal slip. There are three methods deployed for mobility performance prediction. Analytical, empirical and hybrid. Analytical approach relies on soil data gathered experimentally using shear-penetrometer hence more laborious than empirical approach without delivering any better accuracy. Hybrid method such as NATO reference mobility model (NRMM) is far more elaborate and not just soft soil trafficability model. In NRMM, net traction for soft soil is obtained from excess of the VCI over the terrain. In present study the mobility performance is predicted using drawbar pull derived by WES on sand under field conditions at 20 per cent slip. In this a comparison of mobility is done for two penetration resistance gradient values[2] 1750 and 6500 kPa/m. Gradient climbing capability of other vehicles using same equations is available for these penetration resistance gradient values.

*Mobility on Sand*

Various mobility parameters for the proposed vehicle can be worked out using following empirical relationships for theoretical assessment of the mobility of the vehicle on sand.

$$Mobility\ Numeric\ (N_S)=\left[\frac{G\ (bd)^{2/3}}{W\times(\delta/h)}\right]$$

where $G$ is penetration resistance gradient of sand patch [MN/m$^3$ or kPa/m], $b$ is pneumatic tire width [m], $d$ is outer diameter of pneumatic tyre [m], $W$ is weight of each wheel [$kN$], $\delta/h$ is ratio of tyre deflection to tyre section height .

An equation for drawbar pull derived by WES on sand under field conditions at 20 per cent wheel slip is:

$$\frac{D_{20}}{W}\ =\ 0.52\ \text{-}\ \frac{12.97}{N_S+19.4}$$

Positive value of gradient on soil with penetration resistance gradient of 1750 kPa/m indicates good mobility over soft terrain. Second plot gives information on gradient climbing capability of the vehicle under consideration with other vehicles available worldwide. It can be seen that vehicle under consideration will have a maximum gradient climbing capability of 14.46°. This value is comparable with other world class vehicles. Figures 4 and 5 show the gradients achieved on different penetration resistance gradients of 1750 kPa and 6500 kPa.

## 4. OBSTACLE CROSSING CAPABILITY

Wheeled armoured personnel carriers need to overcome natural and artificial obstacles, or engineered

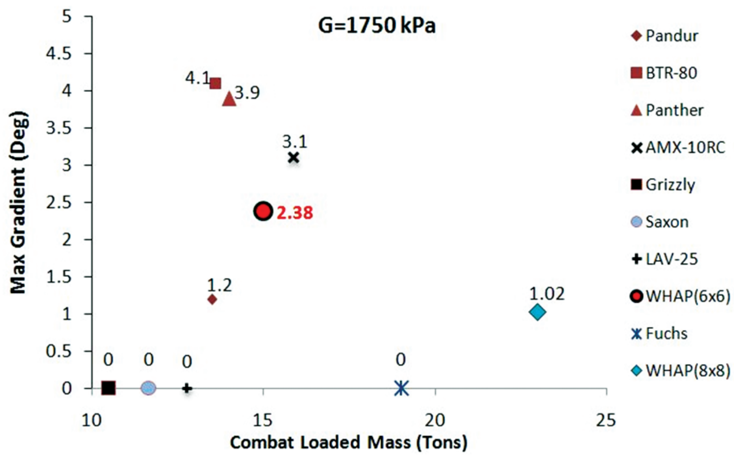


**Figure 4. Max gradient vs mass.**

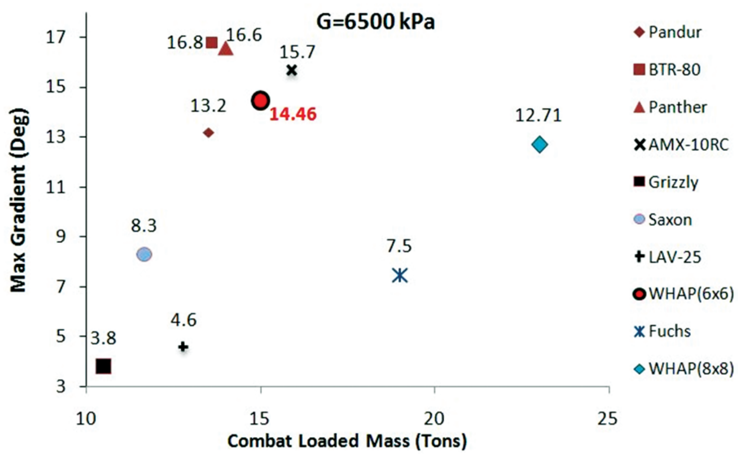


**Figure 5. Max gradient vs mass.**

roadblocks that reduce traffic ability. There are two part of this study, first part is assessment of capability of vehicle to overcome a particular obstacle and second part is determination of dynamic loads acting on the vehicle during this exercise. A full vehicle model is built in Multi-body environment using commercially available software and the obstacle crossing is simulated. Three standard obstacles trench, step and triangular ditch have been considered. It may be noted these obstacles are a part of vehicle performance requirements and hence need to assessed before going for actual development of vehicle. Parameters have been considered for assessing are wheel displacement, ground reaction and acceleration at centre of gravity. The developed model has been validated by comparing it with the results of a wheeled military vehicle having similar configuration and specification. Close correlation has been found between the published results and the performance predicted for the subject vehicle model[11].

### 4.1 Trench Crossing

Width of trench that vehicle can cross is mostly depends upon the number axles, their position along the length of the vehicle and the tyre diameter. The vehicle under consideration has three axles and its trench crossing capability is same as two axle vehicle i.e. Trench width = dw where dw is diameter of the wheel. This is considering that the vehicle approaches the trench in a direction perpendicular to its edge. In this study the trench width is considered is 1.2 m and depth is 1 m. Vehicle speed is kept constant during simulation.

It can be seen from the wheel displacement plot that the displacements are more in first and third axles and less second axle. This can be attributed to vehicle pitch down while crossing the obstacle. As for the second axle is concerned the displacement is limited by the rebound travel of the suspension. Displacement in the third axle is more indicates that the CG is behind the second axle resulting in higher pitch movement. This data corroborates possible physical phenomenon. Vehicle body acceleration in vertical direction is biggest contributor to ride comfort. It was found that peak acceleration value is close to 6 m/s$^2$. This is considered comfortable for human comfort.

### 4.2 Step Climbing

Ability of vehicle to climb the step mostly depends upon the ground clearance, number of axle and spacing between the axles. Once the front axle overcomes the step there is the possibility that the hull will hang up on the obstacle. If the step is sufficiently high, the geometry may prevent the vehicle centre of gravity moving sufficiently far forward to pass the edge of the step. In this situation the vehicle cannot tip over onto the top surface of the step. A centre of gravity forward of the mid wheelbase position is advantageous. For most of the vehicles examined, the quoted maximum step height is close to 50 per cent of the tire diameter. The ratio of step to ground clearance in most cases is greater than unity so hang-up does not appear even with uneven axle spacing.

The Figs. 6 and 7 show that the vehicle is able to overcome the obstacle of 600 mm step as per the design requirement. Vertical accelerations at CG are less than 5 m/s$^2$ g. Ground reaction is maximum on second axle, this is for a small duration wherein the second axle touches the step and other two axles are lifted off in the air during the transit.

### 4.3 Triangular Ditch Crossing

The length of ditch is 4000 mm with a 1000 mm. Obstacle crossing for performance analysis is carried out with constant speed of 5 km/h. While crossing the obstacle different results like hull acceleration, tire force and wheel displacements are plotted. While crossing the triangular ditch vehicle pitching takes place and first axle wheels strikes the obstacle in the perpendicular direction. At the striking of wheels maximum wheel displacement is observed. When the first axle climbs the obstacle the second axle wheels are in full rebound condition. Second axle wheels shows the maximum displacement of 620 mm. Figure 8 shows the time chart of wheel displacement during triangular ditch crossing.

## 5. CONCLUSIONS

A vehicle ideally has to have capability to access any terrain. There are two aspects to terrain accessibility - soft soil trafficability and obstacle crossing. Soft soil trafficability of the new vehicle under consideration Wheeled APC 6x6 with proposed specifications has been calculated and compared

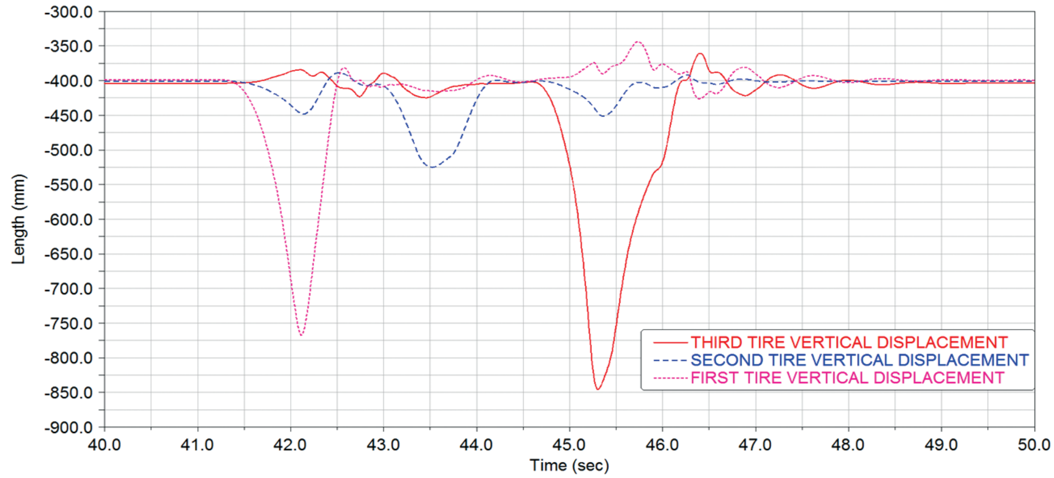


**Figure 6. Time chart of wheels vertical displacement 6 x 6.**

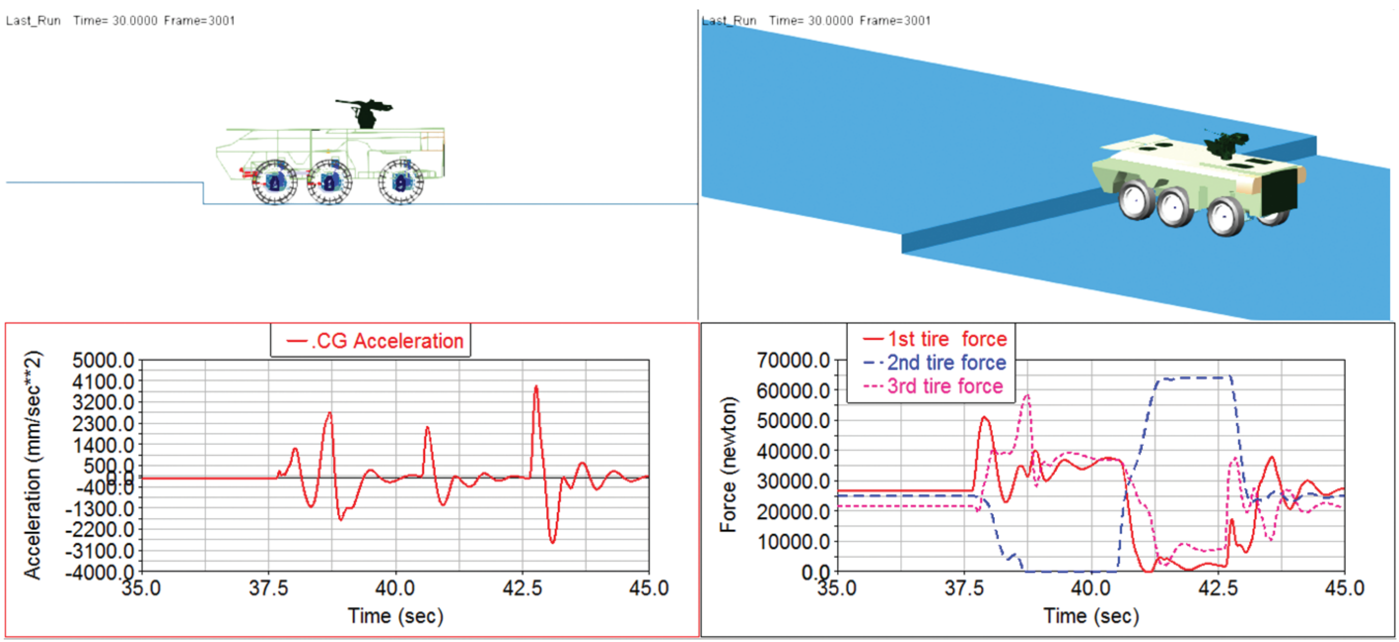


**Figure 7. Time chart of vertical body acceleration and dynamic ground reactions 6 x 6.**

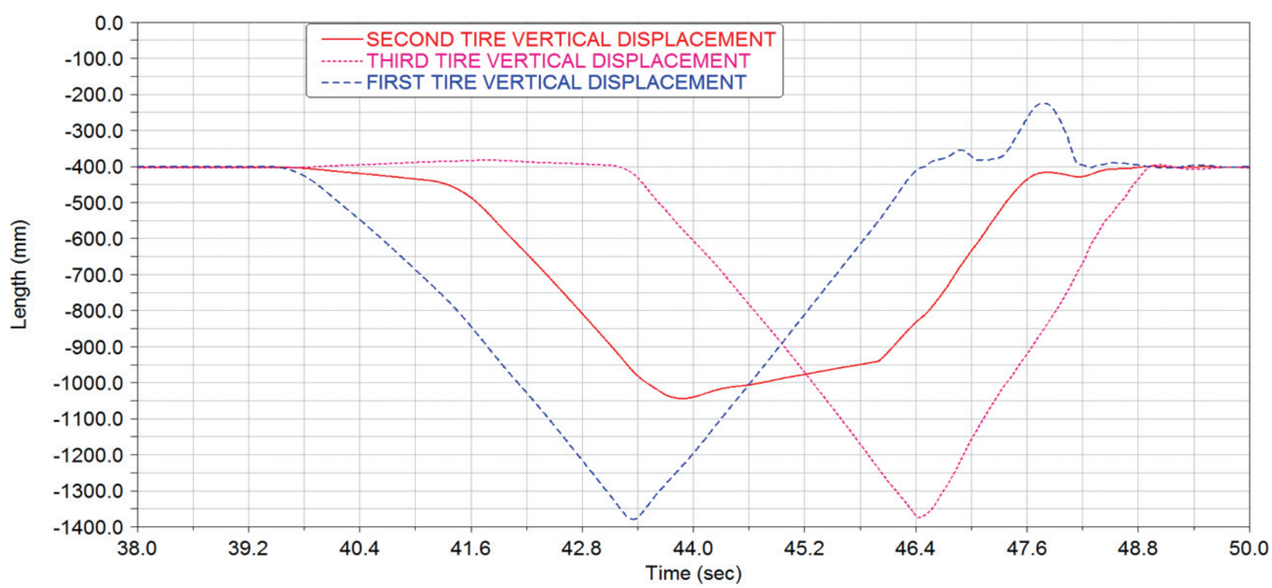


**Figure 8. Time chart of wheels vertical displacement 6 x 6.**

with vehicles used worldwide. Comparison has been done in two parts first being mobility characteristic numbers and other being mobility limit parameter. The world wide vehicle chosen for comparison varied in GVW, no. of axles, country of origin. These vehicles have been used by active military and the results so achieved with specifications of the proposed vehicle are comparable with these world-class vehicle and in some instances better than these vehicles. For mobility prediction empirical method proposed by WES used by US Army has been used. Analytical approach required lot of soil data and this empirical approach gives an idea of the mobility. This was done for soft soils with different penetration resistance gradients. It was found that, the gradient climbing capability values obtained are comparable with other world class vehicles. Though results of one particular configuration of the proposed vehicle are presented in this study, alternative tyre sizes, ground clearance etc were also studied.

A model in Multi body environment has been developed used for predicting the vehicle's obstacle crossing capability. The obstacle crossing capability of vehicle model has been verified for four type of obstacles namely Trench, step and triangular ditch. Vehicle dynamic parameters such as vertical acceleration at CG of the vehicle, tire deflection and ground reaction forces have been captured using the model developed. It is inferred that the factors such as number of axles, diameter of wheel, spacing between the axles, location of CG, suspension characteristics largely influence the obstacle crossing ability of wheeled combat vehicle. The obstacle crossing simulation has been done at constant speed. The vertical acceleration has been found to increase with the vehicle speed considerably in this case of trench, triangular ditch and step climbing. It could be possibly due to striking of wheel to the obstacle. The striking of wheel with the obstacle also has been found to cause increase in tire forces. It has been observed that increase in step height causes increase in vertical acceleration in case of step climbing simulation.

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In the current study, he has carried out mobility assessment of the vehicle using analytical and empirical approach and compared it with other world-class vehicles. Prediction for obstacle crossing was carried out using simulation.

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In the current study, he has contributed in development of approach of the current study.