Defence Science Journal, Vol. 74, No. 4, July 2024, pp. 469-481, DOI : 10.14429/dsj.74.19029

Terramechanics Models for Tracked Vehicle-Terrain Interaction Analysis: A Review

Pogula Nikhil Chakravarthy and Pankaj Kumar Sharma*

Department of Mechanical Engineering, Defence Institute of Advanced Technology, Pune - 411 025, India
**E-mail: pankaj_sharma@diat.ac.in*

ABSTRACT

Efficient manoeuvrability of off-road tracked vehicles such as military tanks and rovers is essential in ensuring the success of military/extra-terrestrial operations. To achieve this, in-depth research on vehicle-terrain interaction is crucial. This manuscript deals with reviewing the ways to study terramechanics viz. theoretical, empirical, and field tests, and proposing the merits and demerits of each method. Under the theoretical approach, empirical, numerical, and semi-empirical methods are discussed. Under the empirical approach, the method based onthe vehicle cone index for tracked and wheeled vehicles is discussed. Under the numerical approach, advantages and disadvantages of Finite Element Method (FEM) and Discrete Element Method (DEM) are discussed. Semi-empirical method, based upon a combination of the best features of numerical and empirical approaches discusses terrain response to normal repetitive loads and shear repetitive loads for tracked as well as wheeled vehicles. Pressure sinkage relationship for terrains at various loading conditions and shear stress displacement relationship for different terrains obtained through penetration and shear tests are discussed to determine the vehicle's mobility parameters under a semi-empirical approach. Further, the Super element model, multi-body simulation model, and ride and cornering vibration model are discussed under computer simulation models. A detailed review of various models customized towards tracked vehicle-terrain interaction discussed in this manuscript helps the authors set up a laboratory for terramechanics at DIAT. Preliminary analysis along with conceptual design of the experimental setup is also discussed. In a nutshell, this paper attempts to summarize the research that has been carried out in the field of tracked vehicle-terrain inter action comprising of VCI, MMP, FEM, DEM, Super element model, Multibody technique, and Semi-empirical methods helping the authors to establish a laboratory of terramechanics for their M. Tech. program on Armament and Combat Vehicles at DIAT Pune.

Keywords: Vehicle-terrain interaction; Vehicle cone index; MMP; FEM; DEM; Super element model; MBD

NOMENCLATURE

C_{Ia} : Cone index after remolding
C_{Ib} : Cone index before remolding
CP_f : Contact pressure factor
C_I : Cone index
w_T : Track width
L_{tG} : Length of track in contact with the ground
L_{cb} : Length of the belly of the vehicle
W_f : Weight factor
P_T : Track load
ξ : Total track length
G_f : Grouser factor
W_{Vh} : Vehicle weight
B_f : Bogie factor
N_a : Number of axles or road wheel stations
C_f : Clearance factor
p_f : Track link profile factor
p_T : Track pitch
d_R : Road wheel diameter
N_p : Normal pressure
E_f : Engine factor
T_f : Transmission factor
α_o : The angular relationship of the track element to the horizontal terrain
w_b : Width of vehicle's belly
α_{bo} : The angle between the belly and the terrain
N_{pb} : Normal stress on the belly–terrain interface
S_{sb} : Shear stress at the belly–terrain interface
I : Shear displacement
$C_k, C_ø, C_u$: Pressure sinkage parameters
Y : Sinkage
y_u : Sinkage during unloading
WES : U.S. Army Waterways Experiment Station
M_I : Mobility Index

Received : 27 July 2023, Revised : 19 December 2023
Accepted : 04 March 2024, Online published : 24 July 2024

1. INTRODUCTION

Off-road locomotion started in those days of history when man invented the wheel about 3500 B.C. and further the earliest transport system. As humanity evolved, people kept on shifting from off-road to on-road locomotion. In recent days, military, agriculture, and space requirements prompted scientists and engineers to design vehicles for their required performance on off-road terrain with the help of empirical, analytical, and computational tools.

The pioneer work in this area was done by Dr. M. G. Bekker who published Theory of Land Locomotion in

1956[1] and Introduction to Terrain-Vehicle Systems in 1969[2]. The foundation stone laid down by Dr. Bekker in this area established an independent discipline of "Terramechanics" under the domain of mechanical and civil engineering. Further, with the formation of the International Society for Terrain-Vehicle Systems (ISTVS), new developments took place in this area to bring Terramechanics to its present shape.

The terrain has a significant influence over the performance of vehicles in terms of engine power requirements, overall dimensions, ride comfort, obstacle crossing, water-wading, and other related aspects. The cross-country terrain in connection with military vehicles usually depends on several factors such as geography, meteorology, vegetation, soil type, moisture content, the ratio of sand, stone, and clay in addition to some personnel factors. Because of this, it is evident that the study of terrain is a crucial factor to be considered throughout the design and development of off-road vehicles.

Military operations are mainly off-road, in which military vehicles have to overcome a wide variety of terrains such as sandy terrain, snow terrain, clayey terrain, etc. Mobility, which is the efficiency with which the vehicle can travel in an unprepared terrain is an important aspect of military operations, space, and underwater or deep-sea explorations[3].

The study of the analysis of the overall performance of the vehicle with consideration of the environment upon which it is operating i.e., terrain (soft soil, muskeg, snow, etc.) is called Terramechanics[4]. The primary goal is to offer guidelines on which decisions about off-road vehicle evaluation, design, development, and procurement are based[5].

The off-road vehicle's performance characteristics (Trafficability, Sinkage, Tractive effort, and Drawbar pull) are directly connected to normal and shear stress distributions upon the interaction of the vehicle's running gear and terrain (For tracked vehicles it is track and terrain interaction)[6]. To investigate the performance characteristics of a military vehicle, a study of the interaction of running gear (track for tracked vehicles) and terrain is necessary[7]. Theoretical modelling, soil bin experiments, and field test scan beutilized for the study of track and terrain interaction[8]. Carrying out experiments/ field tests for the design and development of an off-road vehicle is very expensive and time-consuming. Theoretical models provide an easy and cost-effective solution for performance evaluation, design, and development of off-road vehicles[6]. It is important to consider characteristics of terrain and vehicle design parameters in the theoretical models[6,4].

Factors affecting the vehicle's performance are strongly interconnected to ground pressure distribution. Traditionally vehicle mobility was assessed using Nominal Ground Pressure (NGP) (Eqn. 1) which does not account for other vehicle design parameters except the length and width of the track in contact with the terrain. Due to limitations of the NGP, new ways have been developed which we will go through further sections[9].

$$NGP = \frac{Normal\ Load}{Area\ of\ contact\ with\ the\ ground} \qquad (1)$$

Primary concerns in terramechanics include the measurement and characterization of terrain behavior and modelling of vehicle-terrain interaction.

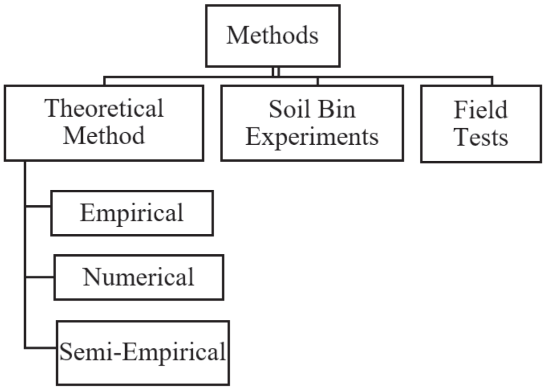

Figure 1. Classification of methods in terramechanics.

This paper provides a comprehensive review of various terramechanics models tailored towards tracked vehicle-terrain interaction. Referring to the classification shown in Fig. 1, the study examines the theoretical methods including empirical, numerical, and semi-empirical approaches[10] along with soil-bin experiments and field tests.

2. EMPIRICAL APPROACH

The empirical approach is based on the observations and measurements. Empirical relations are created based on the experiments for specific vehicle types and terrain/soil conditions because it is challenging to understand track (running gear) and its interaction with terrain. These relationships are applied to assess the manoeuvrability and trafficability of the vehicles[6].

The empirical method based on the cone index was developed initially by Waterways Experiment Station (WES) for the US Army to assess the vehicle's ability to traverse the off-trail track[4].The purpose of this technique was to equip personnel of the US Army by providing a simple means to assess vehicle mobility on a "Go/No-Go" basis for fineand coarse-grained soils. The type of soil was decided by the grain size. Accordingly, if, by weight, 50 % or more of the soil grains are smaller than 0.074 mm (in diameter) the silt or clays are called fine-grained whereas if this percentage is less than 7 %, the beach and desert soils in dry condition are called coarse-grained soils. With further improvements, this built the basis for the NATO Reference Mobility Model (NRMM). Off-road vehicle transverse capability is assessed using the Cone Index (C_I) i.e., soil's resistance to being penetrated which is analysed through a cone penetrometer devised by WES[4,11,12,13]. Generally, a 30^0 circular cone with a 0.5^2. base area fitted at one end of a long rod is used as a cone penetrometer. The other components of the cone penetrometer consist of a proving ring and a dial gauge fitted at the other end of the long rod. The dial gauge indicates the force required to penetrate the cone into the terrain about which one needs to know the mobility of the vehicle. The preferred force for penetration should develop a rate of penetration of about 1.2 in/s. This force when divided by the base area of the cone is referred to as cone index (C_I).

Repeated vehicle movement on an off-trail track can alter its characteristics and affect trafficability. To determine vehicle mobility on such terrain is determined by the Remoulding Index (R_I). The remolding process varies with the type of soil[13]. The ratio of the cone index of soil after remolding to that before remolding is called the Remoulding Index (Eqn. 2). The shear strength of the terrain is altered due to the process of remolding.

$$R_I = \frac{C_{Ia}}{C_{Ib}} \qquad (2)$$

To enhance the accuracy of the procedure, the vehicle parameters must be taken into account along with the terrain/ soil characteristics, enabling better prediction of traffic conditions. To predict trafficability, a comparison between the Rating Cone Index (R_{CI}) and Vehicle Cone Index (V_{CI}) is to be made[4,11-12]. The multiplication of the cone index (measured before remolding) and the remolding index is called the Rating Cone Index (R_{CI}). The terrain strength under repeated vehicular traffic is represented by R_{CI}. Determination of R_{CI} and V_{CI} shown in Eqn. 3 to Eqn. 6 are given as follows:

$$R_{CI} = R_I \times C_I \qquad (3)$$

WES devised an empirical equation to calculate the mobility index (M_I) for tracked vehicles. M_I is a function of the track factor, grouser factor, engine factor, transmission factor, contact pressure factor, weight factor, bogie factor, and clearance factor. M_I is used to find the vehicle cone index (V_{CI}), which indicates the lowest value of soil strength in the critical layer to allow a particular vehicle to make a certain number of passes without any problem. V_{CI1} for single pass and V_{CI50} for 50 passes for tracked vehicles running on fine-grained soils can be calculated by Eqn. 4 and Eqn. 5.

For single pass:

$$V_{CI_1} = 7 + 0.2M_I - \left(\frac{39.2}{M_I + 5.6}\right) \qquad (4)$$

For 50 - passes:

$$V_{CI_{50}} = 19.27 + 0.43M_I - \left(\frac{125.79}{M_I + 7.08}\right) \qquad (5)$$

Where M_I is the mobility index given by

$$M_I = \left(\frac{CP_f \times W_f}{T_f \times G_f} + B_f - C_f\right) \times E_f \times T_f \qquad (6)$$

Further, tracked vehicle performance parameters such as maximum negotiable slope, the net maximum drawbar pull, and towed motion resistance can be empirically determined. In addition to the R_{CI} and V_{CI} indices, there is another index based on the Cone Index for rubber tracks that have been developed by Servadio[11,14], *et al.* Clay-rubber track numeric can be calculated from Eqn. 7:

$$CR_{TN} = \frac{C_I \times w_T \times \xi}{P_T \times \pi} \qquad (7)$$

A similar Empirical approach as explained above can be followed for predicting wheeled vehicle performance with the help of the mobility index of an off-road wheeled vehicle[15].

Given the limitations of NGP, Rowland has proposed Mean Maximum Pressure (MMP) - an average of the maximum under the tracked vehicle's road wheels[16-18] which considers few other vehicle parameters in the determination of Ground Pressure.

MMP of tracked vehicles is given by Eqn. 8

$$MMP = \frac{1.26 \times W_{Vh}}{2 \times N_a \times p_f \times w_T \times \sqrt{p_T \times d_R}} \qquad (8)$$

In a comparative study conducted by Wong[16], the predicted values of MMP obtained using Rowland's[17-18] and NTVPM-86 were compared. While Rowland's approach does not consider terrain parameters when determining MMP, the empirical approach has certain limitations, resulting in slight variations between the predicted and experimental MMP values[19-20]. Larminie[20] has presented modifications to the vehicle ground pressure criterion of Mean Maximum Pressure (MMP)for tracked and wheeled vehicles based on fine-grained soils (clays, cohesive soils) and coarse-grained soil (sands, frictional soils). The effect of the number of axels driven on MMP is also considered in his publication. MMP Formula for belt tracks with pneumatic tires, and wheels of different sizes in fine-grained soils along with special cases for trailers, articulated vehicles, and half-tracks is also presented[20].

To overcome the problem of soil compaction caused by vehicle traffic in agricultural soils, P. Servadio[11] applied this empirical approach in his research. However, since the empirical approach relies on experimental tests of vehicles in different terrains, its applicability may be limited when extrapolating results to different vehicles and terrains.

3. NUMERICAL APPROACH

It is difficult to solve the tracked vehicle-terrain interaction problems analytically where the shape of running gear and terrain characteristics change with the traffic[4,9,21]. So, the Numerical Approach can be used to solve such interaction problems. For modelling vehicle-terrain interaction, Finite Element Method (FEM) & Discrete Element Method (DEM) can be very promising for obtaining accurate results. The effectiveness of such methods depends on the accurate modelling of terrain behaviour and vehicle running gear[22]. Compared to experimental or field test results, numerical simulations can provide a good degree of accuracy along with cost and time savings in the vehicle design and development process[23].

3.1 Finite Element Method

Finite Element Method **(**FEM) is a numerical technique that sub divides a large and complex system into smaller and manageable parts called finite elements that are analyzed more effectively through a high-powered computer. The complex problems of terramechanics such as the deformation of terrain, having different grain sizes, moisture content, the interaction of wheel/ track with terrain, etc. can be modelled and simulated using this technique. Several factors, including grain shape, moisture content, vegetation, etc. impact the mechanical characteristics of the terrain[24]. This approach enables us to investigate the effect of various terrain parameters on vehicle performance, such as soil compaction and sinkage. Moreover, FEM has become increasingly practical as computational power has improved and material models have become more sophisticated.

Three crucial sections of FEM analysis of vehicle-terrain interaction are Vehicle Running Gear Modelling, Soil Modelling, and Interaction Modelling[25].

The Vehicle Running Gear Modelling section deals with how load or pressure is applied to the terrain. It is essential to accurately model the running gear shape and apply initial and boundary conditions. This modelling can be done in 2D or 3D using any CAD or modelling software, which then can be imported into the simulation software. Hall[26], *et al.* have used Hyper Mesh to model tires and LS-DYNA to solve the interaction problem. However, for analysis of tracked vehicle's interaction with terrain, the pressure distribution pattern must be known in advance to use the FEM approach accurately[27].

Soil modelling is the most critical aspect of FEM simulation in terramechanics. It is necessary to model the soil accurately to reflect its actual behaviour under pressure or load applied. The soil models available are Elastic, Nonlinear-elastic, Visco-elastic, Elastic-Viscoplastic, Drucker-Prager model, Cam-clay model, etc.[25]. It is essential to select appropriate mathematical parameters to get the closest soil model representing the actual soil in the approach. One can choose these parameters from literature or experimental tests such as the cone index, triaxial compression test, etc.[28]. To get a reasonable FEM solution, the mathematical model of the vehicle running gear and soil has to be accurate, and the results should be validated by experimental tests[21]. Once the modelling of soil and running gear is done, their interaction can be modelled by specifying initial and boundary conditions such as load being applied to the soil, speed of travel of track or tire, etc.

Various researchers in the field of Finite Element Method (FEM) have presented their studies with detailed soil models. For instance, Yong[29], *et al.* modelled a rigid wheel, and a nonlinear elastic terrain model to simulate the soil behaviour. The study revealed that the FEM results were in close agreement with experimental findings. Similarly, Karafiath[28], *et al.* utilized the Ramberg-Osgood model, typically used for describing the stress-strain relationships in metals, to incorporate the plastic behavior of soil in their study on soil deformation under a moving track. In another study, Omar[30], *et al.* employed the Extended Drucker Prager soil model to simulate soil compaction in agricultural soil, which exhibits elastoplastic behaviour. Additionally, Liu[21], *et al.* updated the critical state soil model by introducing a new nonlinear elastic relation, which resulted in findings that closely align with experimental results.

Despite the advantages of the FEM approach in accurately predicting sinkage and soil compaction, the limitations of the FEM approach are the boundary conditions such as interfacial stresses and loading conditions have to be experimentally determined[26] and fed into FEM simulations. FEM is based on continuum mechanics, and shear and soil flow characteristics are ineffectively modelled for moving vehicles[21]. In FEM, the soil is modelled as a continuous medium, which is not the actual case. The movement of interface sand particles during vehicle movement over the sandy terrain also influences mobility, which cannot be studied by FEM[31-33]. Most of the research in this approach is in the field of tire-soil interaction and compaction of soil and vehicle sinkage in the terrain of agriculture[30,34]. Where the central problem of soil compaction and ruts formation is due to heavy load vehicles[28]. Modelling a tracked vehicle and its interaction with soil is complex as the pressure distribution pattern under the track has to be known before FEM simulation. If pressure distribution is known, the determination of other performance parameters can be easily solved.

3.2 Discrete Element Method (DEM)

The discrete or Lagrangian approach models the soil as an assembly of idealized granular particles, where each particle is assumed to be a distinct entity in the computational domain. The interaction between these discrete granular particles produces bulk deformation in the soil (assembly of particles) when subjected to an external force[7,23,35-36]. Using this approach, one can investigate the shear deformation, frictional resistance, and dilatancy of the soil[23]. These three parameters are used to study the stability of the vehicle, the ability of soil to support the vehicle, and the relative movement of soil particles due to applied load.

In contrast to DEM, the limitations of the FEM approach in analyzing the vehicle-terrain interactions are due to the consideration of the soil as a continuous medium which is discontinuous in nature[7]. FEM assumes soil as a homogenous and continuous medium as that of metals, which leads to inaccurate prediction of vehicle-soil interaction.

In DEM modelling, similar steps to those used in FEM are followed, including vehicle running gear modelling, soil modelling, and interaction modelling. To model the soil in DEM, the main parameters that are required are the mechanical parameters of the soil and interaction coefficients which are given as input to the interaction model. The interaction model is the one that defines the interaction of the vehicle running gear element considering the track that interacts with the soil particle and this particle's interaction with another particle. EDEM software offers several pre-programmed interaction models, including Hertz Mindlin (no slip), Hertz Mindlin with RVD Rolling Friction, Hertz-Mindlin with JKR, Hertz-Mindlin with bonding and Linear Cohesion. These models vary in their ability to simulate different types of interactions between particles, such as adhesive or cohesive forces[7]. Table 1 shows the tests that are required to obtain different parameters used in the modelling of soil in DEM. These parameters are summarized in Table 1.

Table 1. Parameters required to model soil in DEM7

Parameters	Tests
Density of soil	Proctor test
Moisture content	
Avg. size of soil particles	Screening test
Young's modulus	Triaxial compression test
Poisson's ratio	
Internal friction angle	
Internal friction cohesion	
Coefficient of restitution	Repose angle test
Coefficient of static friction	
Coefficient of rolling friction	

Under DEM, the soil in the system is incorporated virtually and replicates the actual behaviour of the soil in the system and then simulates the interaction. The virtual creation of the soil has various advantages in the field of development of rovers which are sent to extra-terrestrial terrain for exploration where the vehicles shouldn't fail to move because of not producing adequate traction. Thus, the development of a virtual soil model for the study of the interaction of vehicles and terrain to obtain adequate mobility is necessary[37-39].

The study of the applicability of the DEM to vehicle–terrain interaction was initially started by Odia[40], *et al.* where his research focused on how the track shoe interacted with cohesive soil. The work by Zhang[31], *et al.* has revealed that simulation results using DEM accurately replicate the results by experimental tests. In their study, a non-linear mechanical interaction model for soil particles has been implemented in DEM for the dynamic behaviour of the soil particles during bulldozing by plate. The work of high computations by DEM for vehicle terrain interaction to achieve a high degree of accuracy has been described by Nakashima[36]*, et. al.* Linxuan, Zhou[7], *et al.* has proposed a method using DEM that can be used to accurately model the interaction between sand and track element and obtain results very close to that of the experimental results.

Besides the advantages of the DEM approach, the limitations are large computing time. For accurate results, the input soil parameters should be accurate. To get accurate soil parameters, simultaneous tests and simulations for triaxial compression and repose angle are necessary[7]. To address these challenges, Nakashima[35], *et al.* have created a fast and efficient program that combines both the discrete element approach and finite element approach to examine how a vehicle interacts with the terrain. DEM is used in the top section of the terrain and FEM for the later part of the terrain.

4. SEMI-EMPIRICAL APPROACH

The semi-empirical approach is a hybrid technique to evaluate vehicle performance that combines both the empirical and numerical methods. Empirical relations based on experimental data on soil behaviour are used to derive a rational basis for assessing vehicle performance[9]. However, it is important to note that these empirical relations have limitations and may not hold beyond the range of conditions for which they were derived.

Numerical methods, on the other hand, offer their advantages and limitations. While they provide a more detailed and accurate analysis of vehicle performance, they can be computationally expensive and time-consuming. The semi-empirical approach combines the advantages of both methods to create a comprehensive and efficient method to evaluate vehicle performance.

By using empirical relations to provide a basic understanding of soil behaviour and numerical methods to refine and validate the analysis, the semi-empirical approach can provide a more accurate and reliable assessment of vehicle performance under a variety of conditions.

The path followed in this approach is to understand the behavior of the terrain at first then modeling the terrain behavior and further modeling of interaction between terrain and vehicle[4].The parameter that is to be determined for the evaluation of the performance of the vehicle is[4,15,41] resistance to motion which can be due to external factors such as obstacles or due to internal friction upon the interaction with the terrain. Resistance to motion can be due to the vehicle load where if pressure applied by the vehicle on the terrain is not in permissible limit of terrain, the vehicle sinks, and traversing over such terrain is difficult.

Relation to determine resistance offered by normal pressure is given by Eqn. 9:

$$R_{np} = 2w_T \int_0^{L_{tG}} N_p \sin\alpha_o dl_t \tag{9}$$

In some cases, the belly of the vehicle interacts with terrain and offers furthermore resistance which is given by Eqn. 10:

$$R_{bt} = w_b \left[\int_0^{L_{cb}} N_{pb} \sin\alpha_{bo} dl_t + \int_0^{L_{cb}} S_{sb} \cos\alpha_{bo} dl_t \right] \tag{10}$$

Tractive effort – the effort that a vehicle needs to put to move through the terrain is determined by the shear strength of the soil/terrain given by Eqn. 11.

$$T_{ef} = 2w_T \int_0^{L_{tG}} S_S \cos\alpha_o dl_t \tag{11}$$

Eqn. 12 defines the Drawbar pull which is the net load that the vehicle can pull through terrain.

$$D_P = T_{ef} + 2F_S - R_{np} - R_{bt} \tag{12}$$

where, shearing force is given by Eqn. 13

$$F_S = \int_0^{L_{tG}} S_S \sin\alpha_o dl_t \tag{13}$$

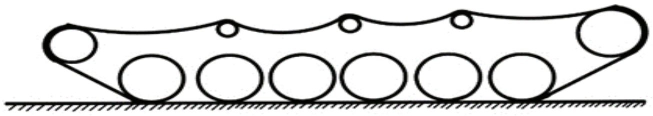

Figure 2. Schematic diagram of the shape of track on a flat and hard surface.

It can be seen that all the parameters are directly dependent on normal & shear loads, which depend upon the area of contact of the vehicle running gear with the terrain. In the determination of the area of contact, the length of the track varies with the type of terrain it is traversing. If the terrain is flat and hard surface (Fig. 2) for example, concrete or asphalt, the length of contact of the track with the terrain is less and the contact length of the track at sprocket, support rollers, and idler is more. Figure 3 shows the movement of the vehicle on soft terrain e.g., sandy, clayey, etc. where the length of the track in contact with the terrain is more and on the top run, it is less[9]. The 2D finite element model is employed by Doyle and Workman[42] to study the variation of track tension when the vehicle transverses through the obstacle and analyzes the parameters that influence the track tension.

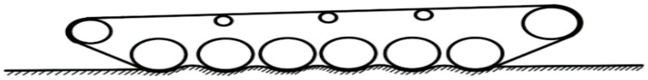

Figure 3. Schematic diagram of the shape of track on soft/ deformable terrain.

The study of the comprehensive behavior of the terrain is crucial to analyzing the vehicle-terrain interaction. Different soils have different behaviours based on the vehicular loads there for e-developed model should incorporate such variations to give accurate outputs. The terrain response against the normal and shear loads that a moving vehicle exerts[41] are described in the following sections.

4.1 Terrain Response to Normal Repetitive Loads

Consider the tracked vehicle moving on an unprepared terrain as shown in Fig. 4. A terrain element is considered where it is subjected to loading by the track under the roadwheel. When this roadwheel is passed the terrain element is now not loaded and as the second roadwheel approaches the respective terrain element the terrain element is being subjected to loading again. This procedure is repeated until all of the tracked vehicle's roadwheels have crossed the terrain element. For the analytical study to anticipate the distribution of normal & shear stresses, the reaction of the terrain to repeated loading has to be considered. The pressure sinkage relation for the repetitive loading has to be considered and all the types of soils have to be measured.

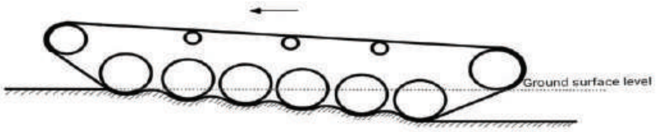

Figure 4. Schematic diagram of moving tank with deflected track in deformable terrain.

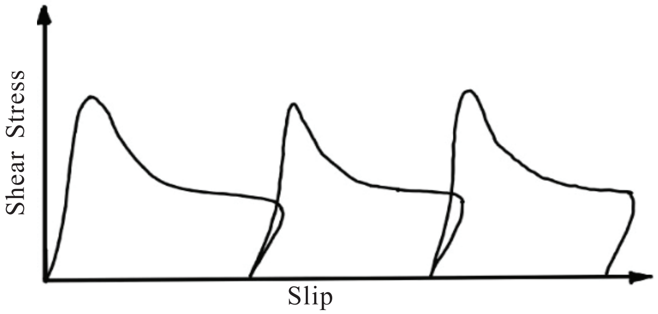

Figure 5. Response of a dry sand terrain to repetitive shear load[41].

4.2 Terrain Response to Shear Repetitive Loads

When a vehicle transverses through the terrain the terrain not only experiences the normal pressure due to normal load by the vehicle but also experiences repetitive shear load due to the non-uniform distribution of normal pressure over the terrain. Figure 5 depicts how the terrain reacts to a shear load. When the next roadwheel causes re-shearing, the shear stress doesn't reach its maximum value at the instant.

Table 2 shows the pressure sinkage relationship for different terrains (sandy, snowy, and muskeg) at different loading conditions which are continuously increasing, unloading, reloading, and continuously increasing before and after breaking crust.

Table 3 shows the shear stress displacement relationship for different terrains which are sand, peat, rubber-muskeg, muskeg-mat, loam, and snow.

4.3 Measurement and Characterization

Terrain response is different for different soil conditions, so measurement and characterization to normal and shear loads for terrain is a must which can be done by Bevameter. Bevameter is an equipment developed by Bekker[1] that is used to measure the mechanical properties of soil to assess a vehicle's mobility. To measure the mechanical properties, penetration and shear tests are performed[43].

Table 2. Pressure sinkage relation for different terrain at various loading conditions[41]

Type of terrain	Loading condition	Pressure sinkage relation
Sandy	Continuously increasing load	$N_p = \left(\frac{C_k}{w_T} + C_\phi\right) y^n$ $= cz^n$
	Unloading and reloading	$N_p = C y_u^n$ $-C_u\left(y_u - y\right)$ $C_u = C_O + A_u y_u$
Snow	Continuously increasing load before and after breaking the crust	$y = y_w(1-$ $\exp\left(\frac{-N_p}{N_{pw}}\right)$
	Unloading and reloading	$N_p = C y_u^n$ $-C_u\left(y_u - y\right)$ $C_u = C_O + A_u y_u$
Muskeg	Continuously increasing load	$N_p = C_m y + \frac{2M_m y^2}{w_T}$
	Unloading and reloading	$N_p = C y_u^n$ $-C_u\left(y_u - y\right)$ $C_u = C_O + A_u y_u$

Table 3. Shear stress displacement relationship for different terrain[44]

Terrain	Relation
Sand, peat and rubber-muskeg	$\frac{S_s}{S_{s\max}} = 1 - e^{\frac{-i}{c}}$
Muskeg mat	$\frac{S_s}{S_{s\max}} = \frac{i}{C_w} \exp\left(1 - \frac{i}{C_w}\right)$
Loam and snow	$\frac{S_s}{S_{s\max}} =$ $C_r[1 + \left(\frac{1}{C_r\left[1 - \exp(-1)\right]} - 1\right)$ $\exp\left(1 - \frac{i}{C_w}\right)]\left[1 - \exp\left(-\frac{j}{C_w}\right)\right]$

4.3.1 Penetration Test

The track/tire sinkage is measured in this test for the application of vertical load by the track/tire on the ground. Penetration test is performed by applying normal load through a hydraulic ram on a circular plate (sinkage plate) of adequate size which simulates the contact area of the vehicle running gear. For this purpose, a Bevameter is generally mounted in front of the vehicle. This test yields the pressure-sinkage relationship for a given terrain. The general trend of the relationship considering repetitive loading is shown in Fig. 6.

4.3.2 Shear Test

In this test, the shear stress and displacement relation

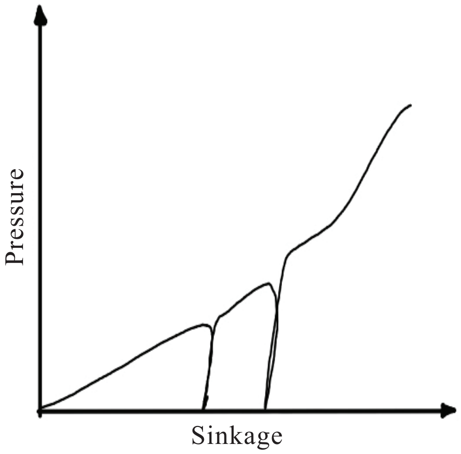

Figure 6. Pressure-sinkage relation of sandy terrain[41].

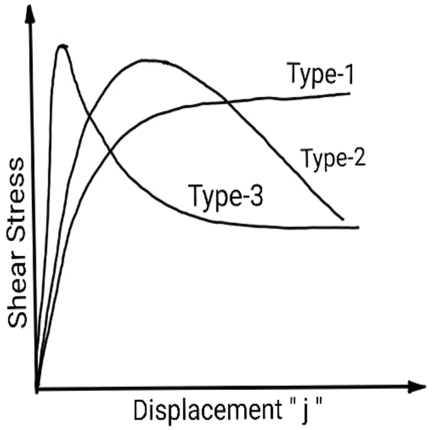

Figure 7. Shear stress versus displacement of different types[44].

is obtained by determining the angular displacement of the annular shear ring for torque applied while the terrain surface is subjected to normal stress. Different terrains exhibit different shear stress–displacement relationships which are summarised in Table 3 and Fig. 7.

The experimental parameters that are utilized in further procedures in determining the performance of tracked vehicles have to perfectly replicate the terrain[45].

4.4 Procedure for Determining the Normal Pressure and Shear Stress Distribution

The procedure to determine the normal pressure and shear stress distribution considering all the factors such as terrain behavior, and vehicle behavior to different terrains by Wong[41], *et al.* The steps in this process are as follows:

4.4.1 Step-1: Shape of the Track

The track is modeled as a flexible belt for numerical simulations. This seems appropriate for the tracks with rubber belts and link tracks having smaller track pitches. When the vehicle stays on a plane's rigid surface, the tracks take a flat shape on the ground. Figure 8 shows track-roadwheel arrangement on a deformable terrain operating under steady-state conditions. When a tracked vehicle rests on a hard surface, the track lies flat on that surface however it gets deformed taking a curved shape on soft terrain.

To determine track shape for a moving vehicle, consider it is moving on a deformable terrain (such as sandy) and the track is flexible and inextensible[9,15]. Figure 8 shows four sections of the full track: Section 1 is the track in the top run, Section 2 is between the sprocket and road wheel, Section 3 lies between the idler and road wheel, and Section 4 is the one in contact with the terrain[46-49]. Section 4 has two subsections, first in contact with both terrain and road-wheel Fig. 9(A) and second in contact with the terrain only Fig. 9(B). Determination of the shape of the track becomes easy by dividing the track into sections under equilibrium conditions. The complete procedure for determining the shape of the track that has been deflected due to a vehicle moving in the deformable terrain for the no-slip condition is explained by Garber[9]*, et. al.* and Wong[41]*, et. al.*

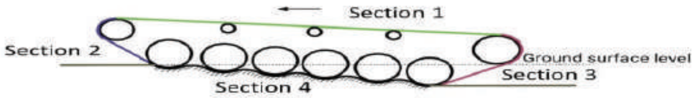

Figure 8. Moving tank with the deflected track in deformable terrain and sections of track to be considered in determining the shape of the track.

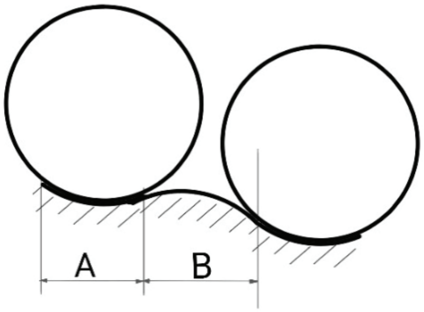

Figure 9. Schematic diagram of track element between two road wheels and under road wheels (Section-4) (A) in contact with road wheel and terrain (B) in contact with terrain only.

4.4.2 Step 2: Determining the Normal Pressure Distribution for No-Slip

Equations for various sections of the track for the track's shape and tension, along with vertical, horizontal, and momentum equilibrium and conservation of the track's length & normal pressure distribution are found utilising the terrain response to repetitive loading equations.

4.4.3 Step 3: Determining the Shear Stress Distribution for the Given Slip

By utilising the Mohr-Coulomb formulae as given by Equation[4,48,50] i.e.

$$S_{s\max} = c_c + N_p(x)\tan\phi_o \tag{14}$$

along with shear stress and displacement relation of the terrain for a given slip, shear stress is determined.

4.4.5 Step 4: Calculate Tractive Effort and Average Tension

From the above-determined Eqn., the tractive effort and average tension between adjacent roadwheels in each track segment can be calculated.

4.4.6 Step-5: Determination of Normal Pressure Distribution

From the above-determined tractive effort and average tension, normal pressure distribution is recalculated at the given slip. The recalculated normal pressure is now verified with the vertical, horizontal, and momentum equilibrium of the track along with length conservation. This step is repeated till the error between the assigned and determined value is minimized below a certain threshold.

With the above procedure, Wong[6,41,51], *et al.* has developed the computer models by which the performance evaluation can be determined. The comparison of the developed model with experimental results shows a good degree of accuracy[41]. The initial works of Wong[15], *et al.* in the development of the computer model based on the semi-empirical approach were with assumptions of the impact of belly drag and suspension, both of which significantly affect a vehicle's performance. This has been considered again and an advanced version of the previous model in terms of algorithm in programming, suspension, and belly drag is developed. The model developed is employed to examine how the vehicle's performance is influenced by its suspension parameters. In this analysis, five sets of suspension configurations in snowy and clayey terrain were considered[51].

For Tracks with rigid links, Gao[52], *et al.* used a semi-empirical approach, and above procedure, a computer simulation model is developed. The tracks with rigid links are mainly used in agriculture and construction vehicles.

The semi-empirical approach has combined advantages of Empirical and Numerical Approaches such as less computational time, and can be used to study various types of vehicles and terrains.

5. COMPUTER SIMULATION MODELS

Based on the above two approaches i.e. Empirical and Semi-Empirical, the solution algorithm is developed and programmed into the computer.

The empirical relation-based computer simulation model is called NRMM (NATO Reference Mobility Model), the Semi-Empirical computer simulation model for short pitch track is called NTVPM (Nepean Tracked Vehicle Performance Model), and the model for rigid link with long pitch track is called RTVPM.

The comparative study of both models has been done by Wong[3], *et al.* in which it is concluded that the performance predicted by NTVPM is close to experimental/field tests. Studies of both models have been completely compared in aspects of inputs and outputs, approach, and user friendliness[3].

Empirical-based Bekker model[1] does not apply to light vehicles. The extrapolation of the model to light vehicles yields large errors, Gariffithand Spenko[53] have experimentally (in soil bin) studied the applicability of Bekker's model to light weight Omni directional Vehicle at the Illinois Institute of Technology and found that it has resulted in large errors.

For extra-terrestrial exploration, the small robotic tracked vehicles find a wide range of applications. Computer simulation model scan be very helpful in evaluating these small robotic tracked vehicles' performance sunder adverse conditions occurring during exploration. Senatore[54]*, et al.* have made an experimental study of small tracked vehicles for different soils in soil bin tests. The applicability of the analytically developed NTVPM model to small vehicles has been studied by Wong[55]*, et al.* and found that results from NTVPM are in good agreement with soil bin experimental results obtained by Senatore[54]*, et al.*

5.1 Super Element Model

Super Element Model is a computational approach used to analyze the dynamics of tracked vehicles. In this approach with kinematic constraints track is considered to be a single body as a flexible belt & remaining bodies (road wheels, suspensions, etc.) as discrete rigid bodies. This makes the problem to be solved with less time.

One of the main advantages of this approach is that it takes much lesser computational time compared to DEM, making it a more efficient and cost-effective approach. However, it is important to note that this approach is primarily applicable to straight roads and may not accurately analyze vehicle dynamics during turning[56].

For analysis of tracked vehicle dynamics, recent research using Super Element has focused on improving the accuracy of track-roadwheel-terrain interaction models[56-58]. Ma and Perkins[58] have developed a mathematical model using the super element model while relaxing the assumptions for track-roadwheel-terrain interaction. In this study, the developed model is solved using the finite element approach. In their research, the non-linear finite element portrayal of the track is modelled by super element special force, improving the results than earlier ones.

This model is a promising computational approach for analyzing the dynamics of tracked vehicles. Its efficiency and ability to incorporate non-linear elements make it a valuable tool in developing more accurate models of track-roadwheel-terrain interactions. Additional research has to be done in this field on a variety of terrains and curved road tracks.

5.2 Multi-Body Simulation Model

It is a tool used to simulate and model the dynamics and kinematics of intricate mechanical systems. MBS is used in particular to model the interaction of vehicles and terrain accurately. While traditional modelling approaches have not been able to accurately capture this interaction, MBS has proven to be a more effective method. This model depends upon how well the constraints of links are given while modelling the running gear of the tracked vehicle.

Three-dimensional multibody models can be implemented in different ways by considering each track shoe an individual rigid body. Such models include a detailed description of the vehicle suspension system, the track system, and dynamic interaction among its components. The kinematic revolute joint constraint is applied at every link connecting with the neighbouring link. Three-dimensional contact force elements are used to describe road-wheel track-link interaction. Further, the pressure-sinkage force relationship is used to model track-link terrain interaction.

The most commonly used MBS software are Dynamic Analysis and Design System (DADS) and ADAMS. These software packages are used to build mathematical models of mechanical systems and to determine the position, speed, and forces acting on rigid or flexible bodies. By modelling vehicle interaction with terrain, MBS software gives a more realistic simulation of the dynamic behaviour of the system[59].

D. Rubinstein & Hitron[59] developed a tracked vehicle model using DADS software that included the implementation of soil mechanics laws[59-62]. This was able to accurately simulate the dynamic behavior of the tracked vehicle as it interacted with the terrain and showed close results with Wong[41]*, et. al.* Similarly, Andrea[10], *et al.* a tracked vehicle model using MSC ADAMS software is developed and performed simulations on deformable terrain. The results of their simulations showed close agreement with other studies, demonstrating the effectiveness of MBS in modelling and simulating the dynamic behavior of mechanical systems.

Ryu[63]*, et. al.* discussed a three-dimensional multibody approach where revolute joints are modelled with compliant force elements. The authors have described the compliant force elements by stiffness and damping values. Ryu[64]*, et. al.* further worked on the methodology proposed by Ruy[63]*, et. al.* and developed the contact force model to study the benefits of the vehicle design with an active track tensioner.

5.3 Mathematical Ride and Cornering Vibration Modelling

Before proceeding to vehicle terrain interaction modelling, it is important to understand the nature of road profiles employed in mathematical modelling. The development of mathematical models for random road profiles is a common thing however they are lacking in the detailed analysis of the results obtained. In their technical report, Tyan and FenHong[65] revisited two of the most common methods, namely sinusoidal approximation and shaping filter for generating one-dimensional random road profiles which helped in better understanding and modelling of terrain vehicle interaction in dynamic conditions.

The dynamic nature of terrain-vehicle interaction produces extreme vibration levels which causes discomfort to the crew members of tracked vehicles. It is important to learn and analyze the levels of vibration transmitted to the tracked vehicle negotiating different terrains at different speeds. Torsion bar suspensions used in tracked vehicles have poorer mobility due to the absence of non-linear characteristics resulting in bad ride performance. Hydro-gas suspensions can provide higher mobility and better ride comfort due to their non-linear behavior. A hydro-gas suspension system model is presented by Solomon and Padmanabhan[66] which uses a hydraulic conductance model for damper orifices and a polytropic gas compression model for springs. Based on the experimental validation of the analytical model, the effect of suspension parameters on ride comfort is evaluated.

To simulate the ride dynamics, Banerjee[67]*, et. al.* in their study emphasize the development of trailing arm hydro-gas suspension systems fitted with single-station models of tracked vehicles. MATLAB is used to solve non-linear governing equations of unsprung and sprung mass systems by incorporating actual suspension kinematics of hydro gas suspension at different charging pressures—further, MSC. ADAMS has been employed to validate the results obtained by MATLAB.

It is important to assess the level of vibration transferred to the chassis under the harsh dynamic operating conditions of military-tracked vehicles. For this, a ride dynamics model for tracked vehicles is developed to evaluate the level of vibration transferred. A detailed ride mathematical model having 17 degrees of freedom of a fully tracked vehicle with trailing arm hydro-gas suspensions is developed[68]. The non-linear coupled governing equations for the sprung mass and fourteen unsprung masses incorporating actual trailing arm kinematics and inertia coupling effects are solved on MATLAB and validated using a multi-body dynamic model developed in MSC.ADAMS. Authors have carried out parametric analysis and ride studies over random terrain with different suspension characteristics.

6. SETUP OF TERRAMECHANICS LAB AT THE DIAT CAMPUS

Defence Institute of Advanced Technology, DIAT (formerly known as IAT) under the umbrella Defence R&D (DRDO) – Ministry of Defence (Govt of India), has been serving the nation since 1952 in cutting-edge Defence technology by imparting higher education to tri-services, Defence PSU's, Ordnance factories, DRDO and few foreign-friendly countries. DIAT, a Deemed-to-be University is a specialized academic institution, established to cater to the human resource needs of India's growing defence and allied sectors. DIAT is engaged in imparting technical education, in niche areas at post-graduate (MTech.) & PhD levels, in its various forms & capacities.

MTech in Mechanical Engineering with specialization in Armament and Combat Vehicles is one of the unique and important master's programs offered at DIAT for officers of the Army, DRDO scientists, DPSU executives, and GATE-qualified civil students. In India, DIAT is the only institute offering this M. Tech—program for more than 30 years. Terramechanics is part of the syllabus taught under this M. Tech. program for which the requirement of a lab is felt to impart better learning to the students.

Figure 10 shows the proposed Terramechanics lab layout for which the work is in progress. Bin 1 and Bin 2 shown in the below figure are sets of three units filled with the mixture of sand, clay, stone, and water in different proportions simulation 6 different terrain conditions. Rooms 1-3 are proposed for the instrumentation room, faculty room, and classroom.

Figure 11 shows the conceptual design of a single-wheel setup (quarter car model) to evaluate different terramechanical parameters of an off-road vehicle. The preliminary calculations of different components of the setup are done to understand the size and shape of the setup.

The heaviest component is the soil bin which is designed to have three compartments to fulfil the multiple terrain requirements. The soil bin should be designed such that the bin should be able to hold that heavy load of soil in it whilst the heavy load acting over it by the quarter car system.

According to the room dimensions, i.e., 35m×20m×5 m approx, the speed required to study the velocity effects can range between 10 kmph to 20 kmph. The length of the soil bin considered is approximately 30 m to study velocity effects. The

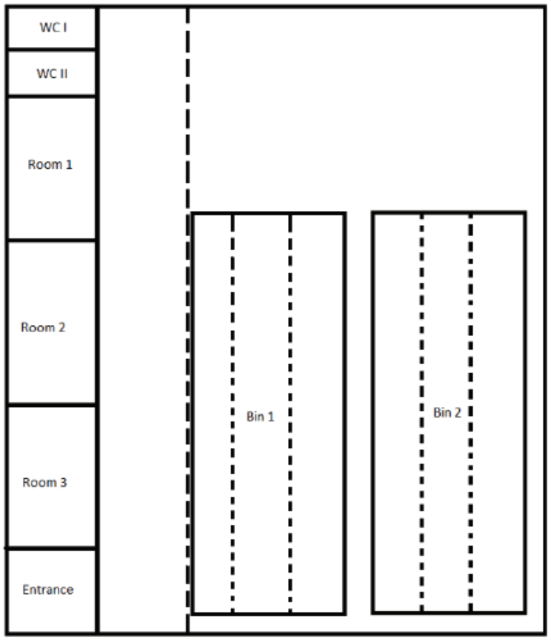

Figure 10. Terramechanics lab layout, DIAT.

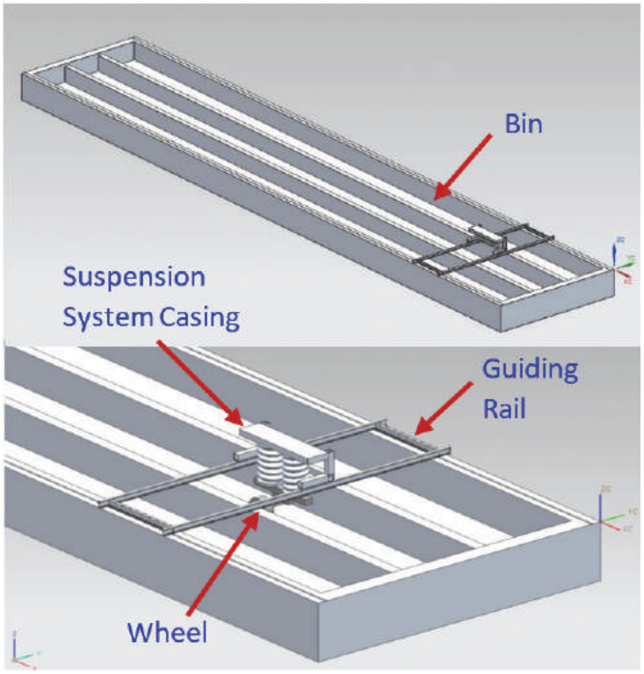

Figure 11. CAD model of the proposed terramechanics test setup.

Table 4. Summary of all approaches

Approach	Definition	Advantages	Disadvantages	Level of complexity handled	Time consumed	Cost
Empirical	Based on experimental data and field observations.	Easy to apply, fast, and inexpensive.	Low accuracy.	Low to medium	Low	Low
FEM	Numerical method for complex engineering problems.	Handles complex geometries and materials.	Computationally expensive.	High	High	High
DEM	Simulates behavior of granular materials.	Accurately captures granular physics.	Computationally expensive.	High	High	High
Semi-empirical	Combination of empirical and theoretical models.	More accurate than empirical models.	It can be complex.	Medium to high	Medium to high	Medium
Simulation models	Simulates motion of mechanical systems.	Accurately captures system dynamics.	Computationally expensive.	High	High	High

width of the bin is considered 1.8 m allowing a tyre of 0.8 m width to be simulated during experiments. A total of six such terrains are considered to be set up. The depth of the terrain is taken as 1.0 m. A remolding setup is also provided to remold the terrain one compaction is done after several passes.

An I-beam is selected for guiding rail assembly (Fig. 11) to ensure the sliding motion of the suspension system along the length of the bin. The suspension casing is installed on it which will house the spring system giving forces and torque to the shaft of the quarter car model. Suspension system casing can be shifted from one bin to another simulating effects on different terrain. The shaft is affixed with the hub of the wheel which can give enough payload and suspension through springs. Themotorized wheel which is subjected to one-fourth of the vehicle's weight moves forward and backward. The sliding system should be able to slide on the bin efficiently. Figure 11 shows the CAD model of the proposed test setup.

The test rig as shown in Fig. 11 should be able to observe the steering effects over the terrain and the wheel. There is a requirement for a screw jack system to lift the entire suspension system according to the change in tire diameter and allowance to sink. The screw jack system is inserted in between the rail assembly and the suspension casing so that the rails allow the suspension casing and the components housed in it to lift to the required height to compensate according to the tire variations and payload variations.

The design calculations for the proposed setup are under progress and expected to deliver a full-fledged experimental setup which will enable us to carry out research work related to terramechanics.

7. CONCLUSION

In conclusion, the study of vehicle-terrain interaction is crucial for accurately determining the mobility of the tracked vehicles and improving their design. In this paper, various methods such as empirical, numerical, semi-empirical, and simulation models with their advantages and limitations for studying tracked vehicle performance have been examined.

Table 4 presents the summary of the different methods examined in this paper. Our review highlights that while each approach has its strengths, the semi-empirical approach stands out as the best method for considering a wide range of vehicle parameters and terrain characteristics while also being a less time-consuming process. Additionally, computer models such as NTVPM, NRMM, and RTVPM have been developed from different approaches, allowing for more accurate analysis of tracked vehicle dynamics.

Overall, the insights gained from this review provide valuable information for researchers and engineers to know research done previously in the various approaches and selected best-fit approach for them to improve the performance of tracked vehicles/rovers and plan the deployment of the armed forces vehicles effectively.

This paper also helps the students and researchers at DIAT to set up one state-of-the-art laboratory for experimental study and analysis of terramechanical aspects of off-road vehicles.

Based on the study presented in the present manuscript various vehicle-terrain interaction models can be employed in the proposed experimental setup. The numerical, semi-empirical, and simulation models can be validated through experiments at the present setup. It is also thought to equip the proposed lab with computer models such as NTVPM, NRMM, and RTVPM.

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CONTRIBUTORS

Mr Pogula Nikhil Chakravarthy is a Distinguished Mechanical Engineer, currently serving as a Jr. Mechatronics Engineer at the esteemed Phoenix Group. He holds a Master's degree in Mechanical Engineering specialising in Armament and Combat Vehicles from the prestigious Defence Institute of Advanced Technology.

For the current study, he played a pivotal role in conducting a thorough literature survey, identifying research gaps, and synthesizing findings into a coherent framework, showcasing adeptness in technical writing and meticulous attention to detail.

Dr Pankaj Kumar Sharma is working as Scientist-F and a faculty in the Department of Mechanical Engineering at DIAT(DU). His areas of interest include: Terramechanics, blast, explosion, shock tube studies, heat transfer, CFD, FSI, etc.

In the current study, he have provided domain knowledge, conceptualization, technical guidance, and support throughout the research process, ensuring the successful completion of the manuscript.