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MULTI-WHEELED COMBAT VEHICLE MODELING ON RIGID AND SOFT TERRAIN

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ABSTRACT

Multi-wheeled off-road vehicles performance depends not only on the total engine power but also on its distribution among the drive axles/wheels. In this paper, a combat vehicle model was developed to examine dynamic performance on rigid and soft terrain. The vehicle dynamics is validated on rigid road against published measured data. Also non-linear tire look-up tables for rigid and soft terrain were constructed based on developed three-dimensional non-linear Finite Element Analysis off-road tire using PAM-CRASH. The measured and predicted results are compared on the basis of vehicle steering, yaw rates and accelerations using published US Army validation criteria.

The validated combat vehicle model then used to study vehicle lane-change maneuverability on rigid and soft terrain at different speeds and powertrain configurations. This comparison showed the importance of having active torque distribution system on soft terrain especially at high speeds.

INTRODUCTION

Multi-Wheeled vehicles that are used essentially for military or for special purposes have to fulfill several key requirements. One of these requirements concerns its off-road mobility. Off-road terrains are characterized by deformable irregular surfaces with abrupt slopes and obstacles of the distinctive nature. The interaction between wheeled vehicles and soft terrain is complex and strongly dominated by the terrain's mechanical properties. Moreover, some soils can behave exceptionally in terms of sinkage and slippage according to the applied wheel normal load and driving torque.

Mechanics of tire-soil interaction is one of the essential characteristics in off-road vehicle studies. The interaction between pneumatic tire and deformable soil is very complex and includes many effects such as sinkage, multi-pass and slip sinkage. Driven tire performance is usually characterized by its thrust, resistance to motion, sinkage, slip, driving torque and angular speed. One of the prime interest to all researches and designers of off-road vehicles is how to accurately predict these parameters.

In recent years, a variety of methods has been proposed to study the interactions of pneumatic tires with deformable soils [1]. They range from entirely empirical approaches to highly theoretical ones, Figure 1.

Accordingly, tire companies conduct many physical laboratory tests such as vertical stiffness and damping constant tests, cornering tests, and durability tests in order to examine tire performance. Generally, the measurement tests in laboratory significantly consume time and cost. Testing equipment, their arrangement, and data acquisition and analyses need high skills and long testing time. So, many investigators have tried to construct alternative tire testing environments in the last few years. Fortunately, current computer technology facilitates the development of new tire models and most of the laboratory tire tests can be virtually duplicated. Even tire tests that cannot be performed in laboratory, such as high speed and/or loading operations.

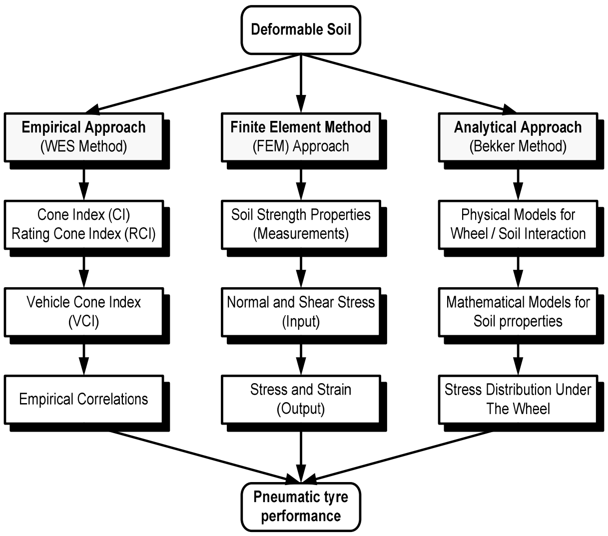

Figure 1: Common approaches used to study the mechanics of wheel-soil interaction.

Extensive research has been conducted to develop efficient but accurate pneumatic tire, and soil models to improve upon predictions of off-road vehicle dynamics through mathematical modeling and simulation. Soil modeling is useful for designers of driveline and braking systems as well as the prediction of motion and stability of off-road vehicles. Because traction, braking performance, and handling properties vary greatly with the terrain on which the vehicle is driven, it is important to model the tire-soil system accurately. While force generation between the tire and pavement is well understood, tire-soil interaction modeling is far behind in development.

Because tire-soil interaction field tests are both inherently costly and difficult to control, the cost efficient finite element analysis method (FEA) has been used for decades for conducting such tests. Likewise, FEA has been used to study a variety of aspects of terramechanics with great success. In 1978, FEA has been applied to model performance of flexible pneumatic tires on soft-soil [2].In conjunction with the analytical predictions, laboratory tests were conducted to measure tire carcass stiffness and drawbar pull as a function of inflation pressure. This work concluded that the FEA could be used to predict tire-terrain interaction accurately if the load-deformation behavior for a wheel is known. In addition, an FEM code has been developed to predict stress distribution under a rolling wheel and tire tractive performance [3]. Predictions of the stress distribution under the wheel and the coefficient of traction were compared with measurements and found to be reasonable. The concluding remark stated that, for low slip conditions, the finite element method could be used to predict the coefficient of traction.

Detailed modeling of a radial tire using finite element analysis methods has been developed to predict cornering forces. The model consists of five types of structural components; tread sidewall, tire carcass, steel belts, and bead filler. The model was found to predict cornering forces to an acceptable degree of accuracy. Finite element models were determined to be a valuable resource during the design phase of tires [5].

Tire-drum model has been developed to predict tire standing waves and tire free vibration modes. The visualized simulations of the standing waves phenomenon were carried out for the first time. The determination of the tire in-plane free vibration modes was achieved by recording the reaction force of the tire axle at longitudinal and vertical directions when the tire rolling over a cleat on the road. The results were compared to more than 10 previous studies and showed good agreement [6].

A finite element model has been developed to obtain the cornering force characteristics for rotating pneumatic tires, simulating the experiments on a tire test rig where the tire rotates on a flywheel. Results from both models are compared with each other and with the experimental results. It is concluded that the developed model provides results at least as accurate as the previously published models with a clear superiority in stability of solution [7].

A 2-D FEA tire model has been developed using ABAQUS. The ABAQUS Drucker-Prager material definition with extended Cap-Plasticity was used for modeling two different soils: wet, loose loam with high cohesion and dry sand with low cohesion. The tire was loaded and given constant longitudinal speed with no slip at two extreme inflation pressures for the two types of soil [8]. Likewise, a full nonlinear FEA model of a radial-ply truck tire has been developed using explicit FEA simulation software, PAM-SHOCK. The tire model was constructed to its extreme complexity with solid, layered membrane, and beam elements. In addition, a rim model was included and rotated with the tire with proper mass and rotational inertial effects. The predicted tire characteristics and responses, such as vertical stiffness, cornering force, and aligning moment, correlated very well to physical measurements [9].

A simplified Finite Element Analysis truck tire model has been developed and used to examine the interaction between the tire and various types of terrain. Soft terrain such as hard soil and dry sand is modeled using solid, elastic-plastic elements [10]. The general trends of vertical and longitudinal forces and normal and shear stress distributions in the soft soil are compared with published data for preliminary validation. The cornering characteristics on both rigid and soft soil terrains are also predicted and compared.

New off-road rigid ring model has been developed from the FEA Regional Haul Drive (RHD) tire and soil (dense sand in this study) which could be used to replace the FEA model for all full vehicle simulations and to further save CPU time and reduce costs. This initial version of the off-road rigid ring model will be subjected to extensive tune up using various types of soils and various operating conditions [11].

A 3D tire-soil FEA model has been developed in ABAQUS® specifying 175R14 tire and soil interaction. The static-steady tire-soil model is analyzed for studies on the stress, strain and deformation of tire and soil under a certain sinkage taking into the consideration of tire structure and soil constitution. It also obtains the relationship between load and contact pressure, which will be helpful for the further tire-soil study under serious condition [12].

A finite element model for a tire rolling on a drum has been developed demonstrating the flexibility of CAD based meshing approach introduced by the authors. The results of the analyses conducted on the model have successfully been compared to experimental ones, confirming FE model validity. The differences between experimental and numerical results were decreased after the calibration of friction coefficient had been performed. The presented FE tire model and associated analyses are used for performing parametric studies within the tire design process, helping the tire designer to quickly find the optimal values of tire design parameters. The tire design process is thus shortened and at the same time, greater predictability and improvement of tire performance are achieved [13].

Study concentrating on vehicles weighing more than 36ton (80,000 pounds) has been performed using the same evaluation methods used in the Canadian Weights and Dimensions Study. They developed handling performance targets based on accumulated research experience, including knowledge gained from the examination of trucks involved in fatal accidents. This study showed that future transportation technology would involve developing heavy commercial vehicles with measurable and predictable levels of performance in safety-related maneuvers [20].

The results of comparative study of the predictions, made using computer simulation models of different levels of complexity, of the directional responses of commercial articulated vehicles in steady state and lane-change maneuvers has been presented. The differences in the predictions obtained using various models are examined and were compared with available experimental data [21].

An experimental and theoretical study on the influence that self-steering axle has on the directional stability of straight truck has been presented by the authors. The truck was instrumented for stability and control tests. The field tests were aimed at generating steady-state handling diagrams to evaluate the directional behavior under different operating conditions. The study resulted in recommendations that minimize the deteriorating effect of self-steering axles [22].

The sensitivity of the yaw rate response of a three-axle single unit heavy vehicle to sinusoidal steering input has been presented. The frequency response method and first order standard and logarithmic sensitivity functions were applied. In this study the frequency response of ten of the Canadian logging trucks operating in the interior of British Columbia in Canada. The logging trucks simulation results were compared with corresponding field tests results [23].

Evaluating and validating a computer generated multi-wheeled combat vehicle has been developed. In this study, computer simulation results were compared with the actual field test measurements. The study concentrated on the handling performance of the modeled vehicle compared to the actual response of the vehicle. The validation methodology for the model versus test data involved J-Turn and double lane change simulations at three speeds and one tire pressure. Criteria were defined on statistical measures (kurtosis, skewness, root mean square) [24].

A methodology for validating the vertical dynamic performance of a virtual vehicle has been presented. The vehicle weights, dimensions, tires and suspension characteristics were measured and referenced in the specially developed computer simulation model. The data for the tire and suspension characteristics were acquired from the respective leading manufacturers in the form of look-up tables. The predictions of the vehicle vertical dynamics on different road profiles at various vehicle speeds were compared with the field test results. The time domain data for the vertical acceleration at the vehicle center of gravity, pitching, vehicle speed and the suspension/damper displacement were compared to analyze the feasibility of using the computer simulation models to predict the vertical dynamic performance of the vehicle [25].

In this paper, the stability and controllability of multi-wheeled combat vehicle have been studied. The vehicle performance was evaluated using computer simulations during step steering input (J-Turn) and lane change maneuvers. The vehicle model is validated against published measurements for directional responses on rigid road. With increases in computational power and the accuracy of the simulation models, validated computer simulation models can be extensively used as an alternative to the full-scale real tests, in particular severe maneuvers. Validation of the simulation results is very important for the acceptance of the simulation models. Which is generally consist of three main steps, experimental data collection, measurement of the performance parameters and comparison of the simulation results with the experimental test data [18]. The inconsistency in the virtual test and the real test can be attributed to many factors such as virtual modeling, programming, and experimental data quality during full-scale tests.

The full-scale test has many sources of variation due to randomness and human error. These sources are absent in the simulation models and can contribute towards the inconsistency in results.

In this study, once the test data are compared the virtual model could be tuned depending upon the inconsistent performance parameter. Virtual vehicle should be tuned at the component level and care should be taken that the comparison is made at the linear as well as the non-linear range. The comparison should be made in the time and the frequency domain. Time domain is ideal for comparing the steady state and input output correlation whereas the frequency domain provides a better means to study the correctness of simulation transient predictions. Correlation of the two types of results essentially requires a software tool, which can interpret and display the results from two different domains, the physical Test data and the analytical prediction from the simulation software [19].

FEA Off-Road Tire Model

In this research work, tread patterns of the 4-groove off-road tire has been developed to represent the Off-road12.00R20 XML TL 149J tire tread [14, 15]. The developed tire model has an asymmetric tread pattern to prevent tire from trapping and holding stones in the tread. The complicated design was simplified to contain the fundamental elements while minimizing modeling and processing time. Straight edges were used wherever possible to replace curves for the shape of the lugs and the grooves between the lugs. The max tread depth is modeled as 30 mm. Each lug was simplified as rectangular with angled sides, and the grooves between lugs are simple V's. Solid tetrahedron elements with Mooney-Rivlin material properties were chosen for the tread. Figure 2 shows the final FEA model tread design. The material property for the two different layers (one for rubber and the other for steel cords) and the orientation of each layer is assigned appropriately to model the rubber tire carcass and belts. In this case, the cords in the carcass run radially in the carcass from bead to bead.

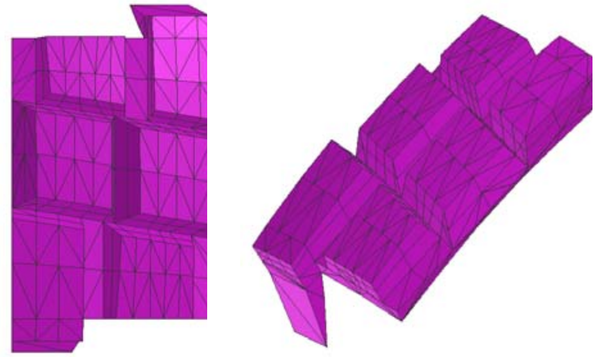

Figure 2: Tread design as viewed from different views.

The tire model is constructed using the following finite element components:

- 25 Parts,
- 9,920 nodes,
- 1,800 layered membrane elements,
- 13,280 solid elements,
- 120 beam elements,
- 25 material definitions, and
- One rigid body definition.

The advantages of this tire model are its computational efficiency and stability. Figure 3 shows the basic dimensions of the finite element tire model. Figure 4 shows a comparison between the actual tire and the FEA tire model. Technical data for the off-road tire model is shown in Table 1. The Mooney-Rivlin material properties for the solid tread and under-tread elements are shown in Table 2.

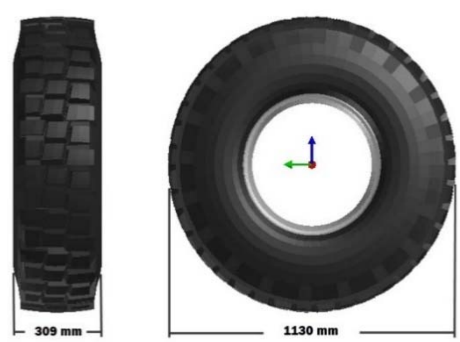

Figure 3: Tire Basic Dimensions.

a) **b)**

Figure 4: Comparison of actual (a) and detailed FEA model (b) combat vehicle tire.

Max. Tread depth	30 mm	1.181 in
Rim Width	283.4 mm	11.16 in
Rim Weight	31.2 kg	68.78lbs.
Tire Weight	55.3 kg	121.92lbs.
Total Tire Weight	86.5 kg	190.7lbs.
Overall Width	309 mm	12.16 in
Overall Diameter	1130 mm	44.48 in

Table 1: FEA Tire Model Technical Data

Tire Component	**Under-tread**	**Tread**
Density (kg/m^3)	596.2	693.3
1st Mooney-Rivlin coeff. (C_{10})	0.51	0.67
2nd Mooney-Rivlin coeff. (C_{01})	1.86	2.46
Poisson's ratio	0.49	0.49

Table 2: Material properties for tread and under-tread solid rubber elements

Tire Model Validation

The tire model will be used to determine the tire-soil characteristics that are required to build a new off-road tire model based on FEA results. Therefore, the tire model needs to be validated by checking whether it shows real tire characteristics. For the validation, different tire simulations were conducted at various operating conditions (load, inflation pressure and slip angles). The results of the validation tests are compared with physical measurements.

- Static vertical deflection on flat surface:

The tire model was subjected to extensive sensitivity analysis to tune up the mechanical properties of various material components in order to achieve reasonable load-deflection characteristics in comparison with measured data. In order to obtain the correct model characteristics, it is necessary to adjust the thickness (h), the Mooney-Rivlin coefficients of rubber compounds of the tread and under-tread (C_{10} and C_{01}), and the modulus of elasticity (E) of both the sidewall and the under-tread of the tire model. The final tire model with adjusted material parameters is shown under a 55 kN static load with an inflation pressure of 0.6 MPa in Figure 5.

Figure 5: FEA Off-road tire model under 55 kN load and 0.6 MPa inflation pressure.

Figure 6 shows the static deflection curve from actual tire data and the predicted results using the FEA tire model over a wide range of loads and inflation pressures. The actual tire data was obtained from published measurement data for a tire similar to the Off-road 12.00R20 XML TL 149J. Reasonable agreement can be observed, and this data is presented as model validation.

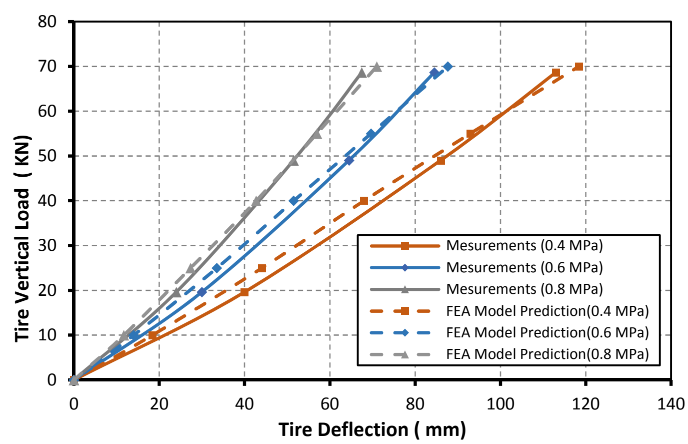

Figure 6: Load - Deflection curve at different inflation pressure.

- First mode of vibration test

A tire and cleat-drum test was conducted to determine the first mode of vertical free vibration. Figure 7 shows the tire running on the virtual cleat drum test rig. A test was run for a tire load of 26.7 kN and an inflation pressure of 0.76 MPa.

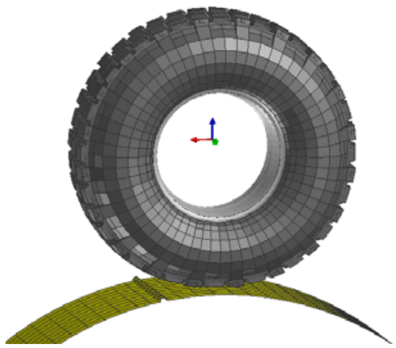

Figure 7: FEA model on cleat drum.

A Fast Fourier Transform (FFT) algorithm was applied to the vertical reaction force at the tire spindle to obtain the frequency analysis shown in Figure 8. Peaks in the figure represent free vibration modes. The drum rotates at an angular velocity of 15 rad/sec, which results in about a 2.5 Hz excitation due to the cleat impact. This impact is shown by the first peak from around 1 to 4 Hz in the FFT. The second peak at approximately 46 Hz corresponds to the first vertical free vibration mode. The available experimental data for the first vertical free vibration mode for passenger cars tires lies in the range of 60-80 Hz [16].For the developed FEA off-road tire that has larger diameter and softer materials comparing to passenger car tires, its sidewalls will absorb more vibrations instead of transferring it to the tire center. So, it can be expected to have values lower than 60 Hz.

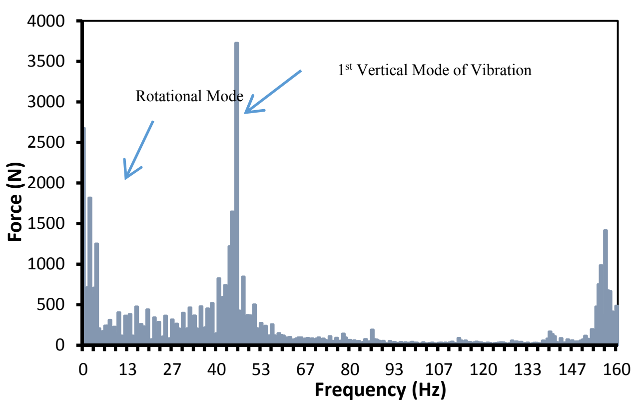

Figure 8: FFT Result of Vertical Reaction Force at Tire Spindle at 26.7 kN vertical load and 0.76 MPa inflation pressure.

- Cornering characteristics on flat surface

The cornering test is virtually conducted to examine the characteristic cornering performances of the FEA off-road tire model. The tire model is inflated at a pressure of 0.72 MPa and loaded vertically up to 63.75 kN at the spindle of the tire model. Then, the tire model is steered at slip angles (α)up to 6°. A flat road is moving at constant speed of 10 km/h under the tire to rotate the tire model. Figure 9 shows the cornering simulation at slip angles of 2°, 4° and 6° and the lateral deformation of the tire at the contact area with the road surface.

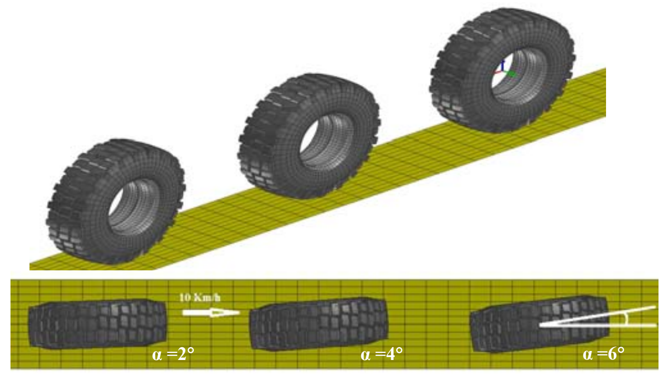

Figure 9: Cornering Simulation for the FEA off-road tire at Slip Angles of 2°, 4° and 6°.

The predicted cornering forces with respect to different slip angles up to 6° at vertical loads of 15.94 kN, 31.88 kN, and 63.75 kN are plotted in Figure 10 and compared with the published measurement data from the tire manufacturer. Another important cornering characteristic parameter, such as the aligning moment, is also predicted with respect to various slip angles (α), and compared with published measurement data as seen in Figure 11.

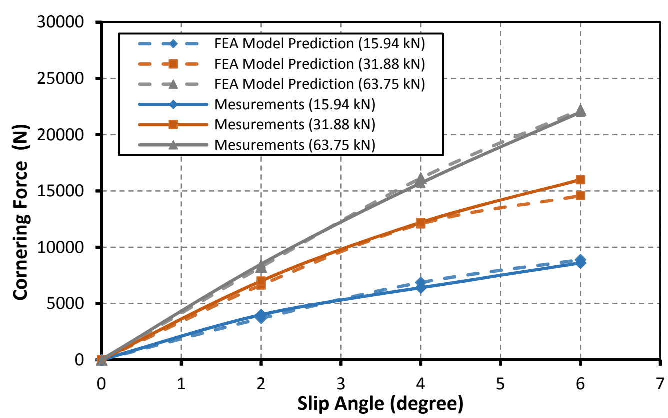

Figure 10: Cornering force - Slip angle curve at different Vertical loads.

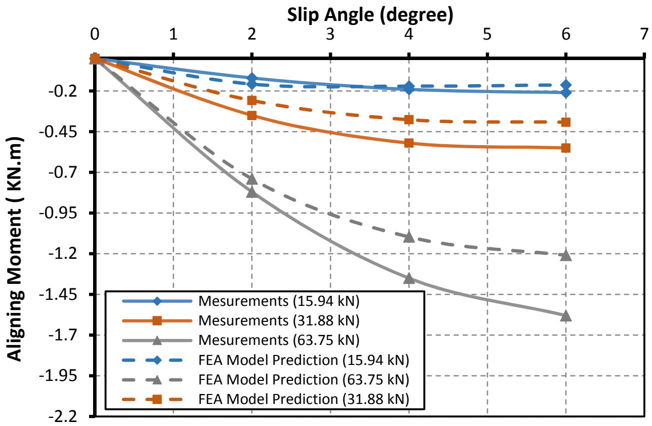

Figure 11: Aligning moment - Slip angle at different Vertical loads.

In the regions of slip angles from 0° to 6°, the predicted aligning moments show good agreement with the measurements at the lower two tire load cases. For slip angles (α)> 3°, considerable discrepancies are observed. The discrepancies are considered to be due to the differences in cross-sectional shapes, contact areas, and tread patterns between the FEA and real off-road tire.

-Tire-slip characteristics

A tire and drum model was conducted to determine the normalized longitudinal force at different road friction coefficient (μ). A test was run for a tire load of 18 kN and an inflation pressure of 0.76 MPa and road friction coefficient (μ) 0.2, 0.4, 0.6, and 0.8 as seen in Figure 12.These results shows good agreement with the published experimental data, [27], as the peaks reach the road friction coefficient value and then decreases with different rates depending on road friction coefficient, i.e. higher rates for higher friction coefficient.

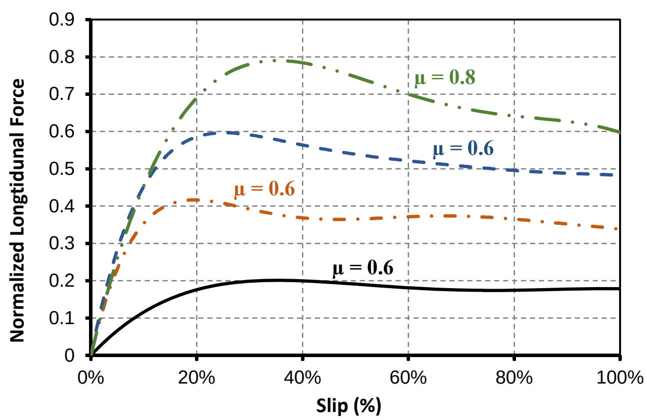

Figure 12: Normalized Longitudinal Force vs. Slip

Soil Model Representation

A new type of soil was created using an elastic-plastic solid material (PAM-CRASH Material 1). The meshing is performed in PAM-CRASH by splitting a large solid block into 25mm by 25mm by 25mm elements. The tire-to-soil contact is defined as a node to segment contact with a friction coefficient of 0.8. The new soil modeled is a clayey soil. The material properties for this new soil are listed in Table 3. It should be noted that the material properties are chosen by using the mean value of the ranges given by the U.S. Department of Transportation, Federal Highway Administration.

Soil Type	**Elastic Modulus, E (MPa)**	**Bulk Modulus, K (MPa)**	**Shear Modulus, G (MPa)**	**Yield Stress, Y (MPa)**	**Density, ρ (ton/mm³)**
Clayey Soil	24	15	9	0.016	1.60E-09

Table 3: Material properties for the new soil.

- Validation using pressure-sinkage test

Soil characteristics can be compared and validated by looking at the relationship between applied pressure and soil sinkage. This type of testing is discussed in detail by reference [17].

$$p = \left(\frac{k_c}{b} + k_\varphi\right) z^n = kz^n \qquad (1)$$

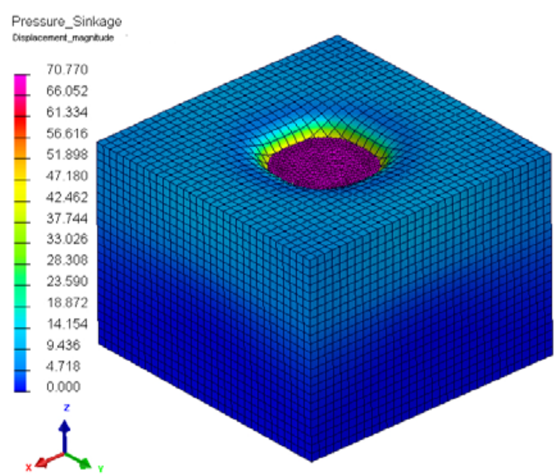

Figure 13: Virtual measurements of pressure-sinkage using a 15 cm circular plate on the new soil with a pressure of 0.2 MPa

The pressure-sinkage test is done by applying a known pressure over a circular plate placed on the soil and observing how far the plate sinks into the soil. The new soil is compared to the terrain values, given in Table 2.3 from reference [17] using the Bekker formula, Equation (1).

Figure 13 shows the pressure-sinkage simulation of the soil with a rigid 15 cm circular plate. Figure 14 depicts the effect of normal pressure on tire sinkage. As can be seen in the figure a comparison between the predicted and previously published measurements confirm the validity of the proposed model.

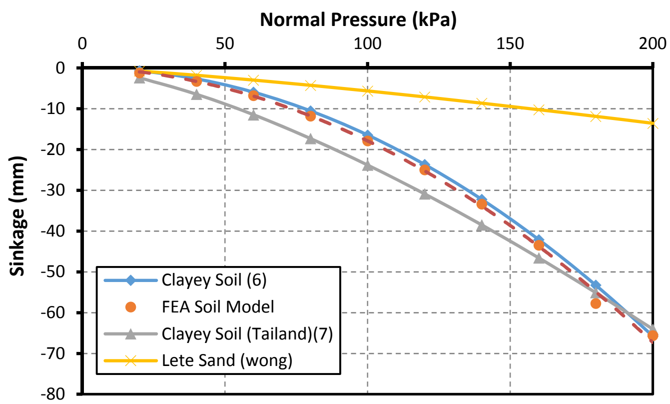

Figure 14: Effect of Normal pressure on Sinkage

FEA Off-Road Tire Model on Soft Soil

After validation of the new FEA off-road tire model, as well as the soil model, it was used to evaluate tire performance on soft soil to facilitate the development of a set of empirical equations that can be used to represent the tire-soil interaction characteristics.

In addition, the FEA off-road tire models used to investigate the multi-pass behavior of the wheels running on soft terrain and its effect on vehicle mobility performance. The steering characteristics of the multi-wheels are also predicted.

The objectives in this part are:

- Calculate tire vertical stiffness on soft soil.
- Calculate rolling resistance on soft soil for multi-wheels.
- Calculate steering characteristics on soft soil for multi-axle steering.

- Equivalent Tire Vertical stiffness on soft soil

The off-road tire model was inflated at three different inflation pressures of 0.4, 0.6 and 0.8 MPa and loaded at the spindle of the tire model on soil surface instead of the flat road surface as seen in Figures 15 and 16. After the tire model reaches stability, the steady-state vertical deflection of the tire model and soil is recorded to calculate equivalent tire stiffness as seen in Figure 17, using Equation (2).

$$\frac{1}{K_{equ}} = \frac{1}{K_{soil}} + \frac{1}{K_{tire}} \qquad (2)$$

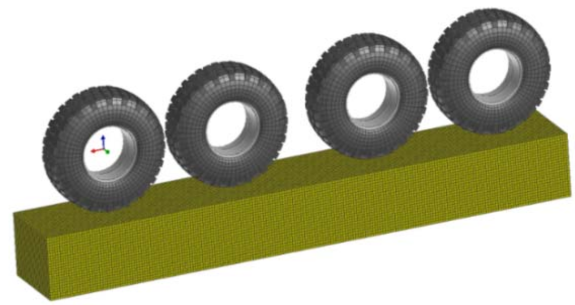

Figure 15: FEA off-road tires on soil surface

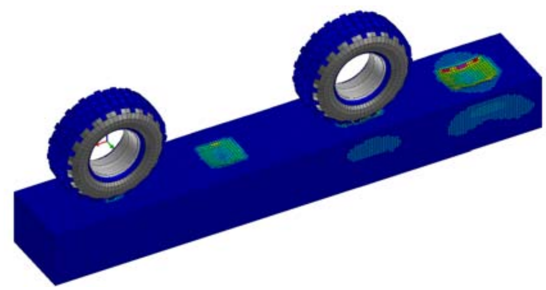

Figure 16: FEA off-road tires on soil surface simulation

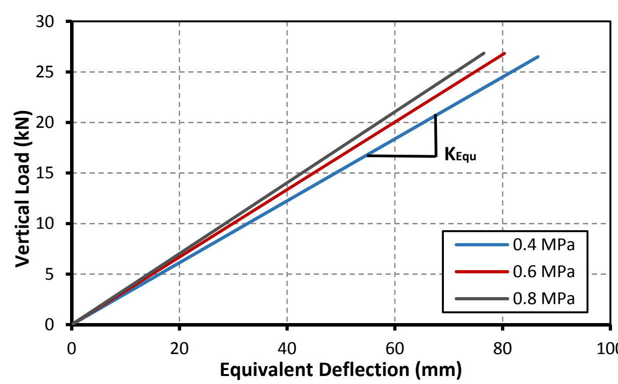

Figure 17: Equivalent tire vertical stiffness on soft soil

- Rolling resistance on soft soil for multiple wheels

For the rolling resistance of multi-wheels (4 tires) running on soil surface, the off-road tire model is inflated at three different inflation pressures of 0.4, 0.6 and 0.8 MPa and loaded with three vertical loads of 6, 18 and 48kN at the spindle of the tire model on soil surface as seen in Figure 18.

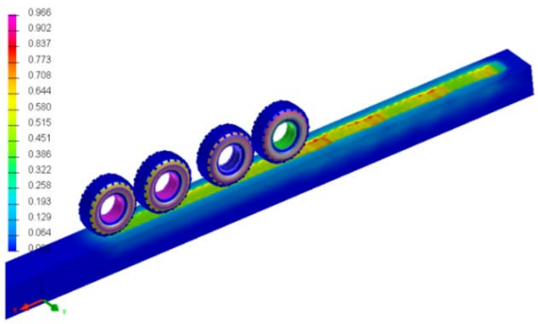

Figure 18: FEA off-road tires (4 tires) running on soil

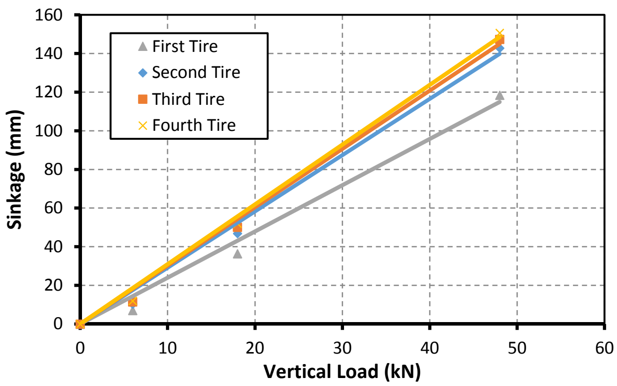

Figure 19: FEA off-road tires (4 tires) sinkage on soil (inflation pressure 0.6 MPa)

As soon as the tire model stabilizes, the steady-state tire model sinkage and rolling resistance coefficient are recorded to clarify the multi-pass effect on vehicle mobility performance as shown in Figures 19 and 20 for tire inflation pressure 0.6 MPa.

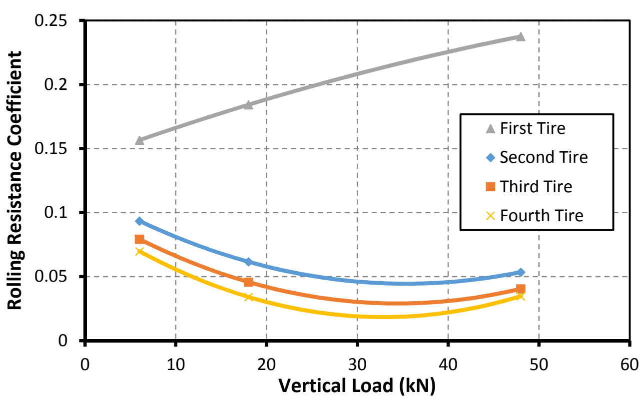

Figure 20: FEA off-road tires (4 tires) Rolling Resistance Coefficient on soil (Inflation pressure 0.6 MPa)

- Steering characteristics on soft soil for multi-axle steering

For the steering characteristics on soil surface, the off-road tire model was developed for two steered tires with different steering angles (δ) and it will be tested for different inflation pressures (0.4, 0.6 and 0.8 MPa) and vertical loads (6, 18 and 48kN), as seen in Figures 21 and 22.

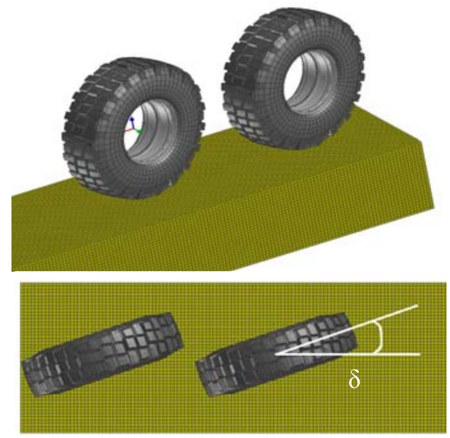

Figure 21: FEA off-road tires (2 steered tires) on soil

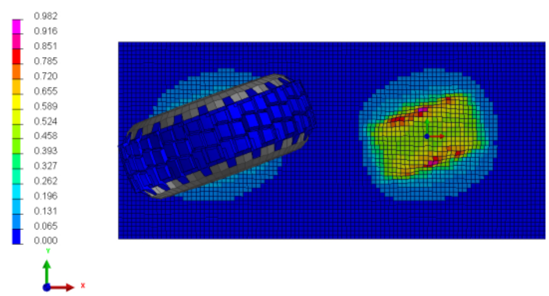

Figure 22: FEA off-road tires (2 steered tires) on soil

As soon as the tire motion is stabilized, the steady-state longitudinal and lateral forces acting on the tire are recorded to calculate tire cornering characteristics.

Lateral forces and aligning moments acting on steered tires are presented in separate 3D surfaces for the first and second steering axles for each inflation pressure as seen in Figures 23, 24, 25 and 26.

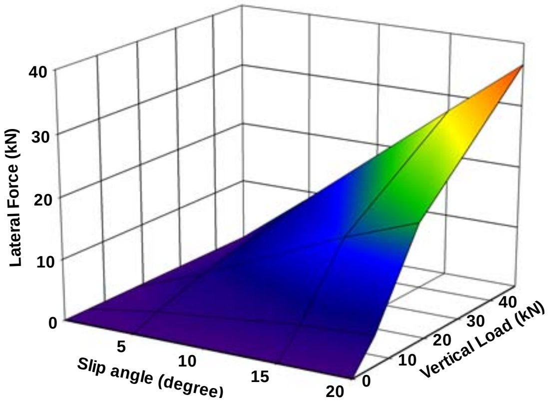

Figure 23: Lateral forces acting on the first FEA off-road tire on soil (inflation pressure 0.4 MPa)

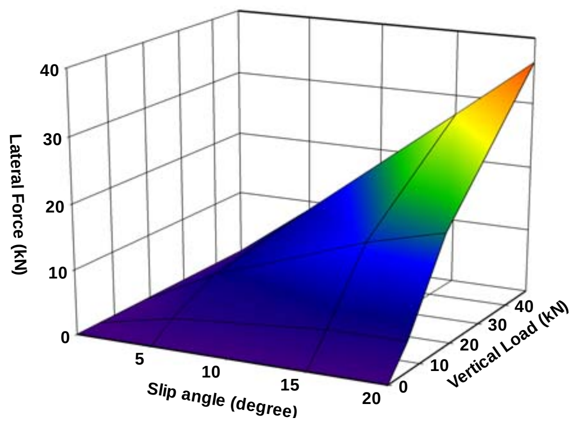

Figure 24: Lateral forces acting on the second FEA off-road tire on soil (inflation pressure 0.4 MPa)

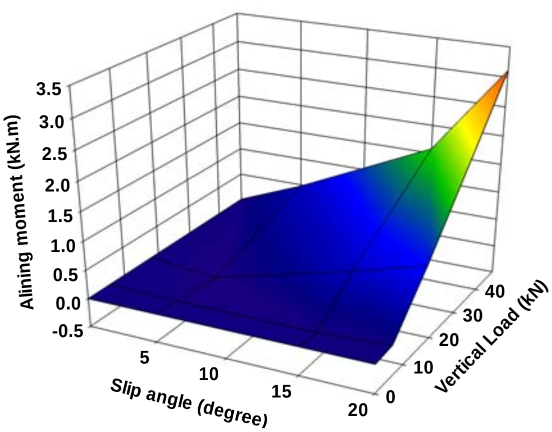

Figure 25: Aligning moment acting on the first FEA off-road tire on soil (inflation pressure 0.4 MPa)

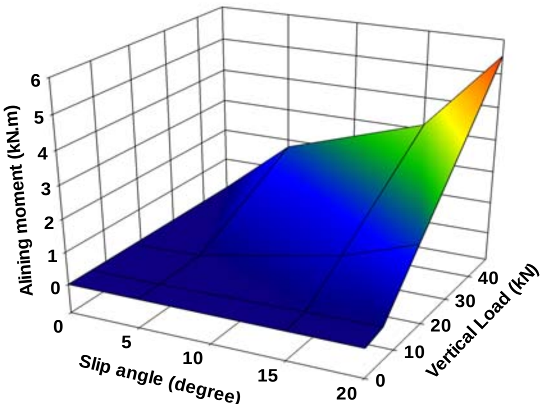

Figure 26: Aligning moment acting on the second FEA off-road tire on soil (inflation pressure 0.4 MPa)

- Tire-slip characteristics on soft soil

Figures 27 shows the traction test of the off-road tire on soft soil to determine the longitudinal slip characteristics. In this test, two longitudinal tires under different inflation pressures (0.4, 0.6 and 0.8 MPa) and vertical tire loads (6, 18 and 48 kN), are rapidly accelerated to a rotational velocity of 30 km/hr and is allowed to roll forward. Initially there is nearly 100% slip before the tire begins to move forward, and the slip approaches 0% as the tire asymptotically nears a linear velocity of 30 km/hr.

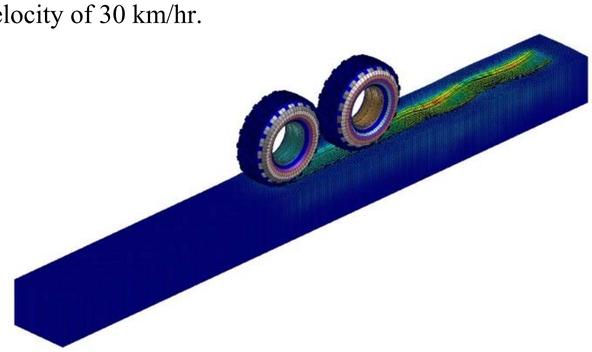

Figure 27: FEA off-road tires (2 tires) on soil

Figures 28 and Figures 29 show sample result of the predicted normalized force at different slip percentages for both first and second tire at inflation pressure 0.6 MPa and different vertical loads (6, 18, 48 kN).

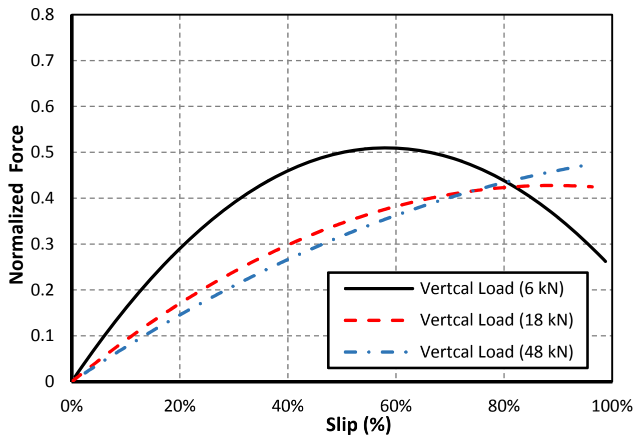

Figure 28: First tire slip characteristics on soil (Inflation pressure 0.6 MPa)

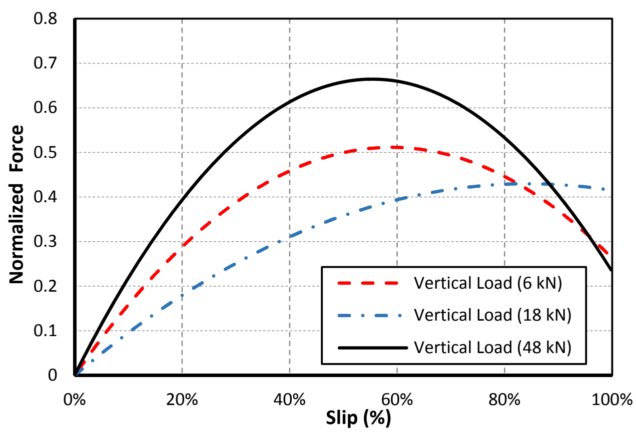

Figure 29: Second tire slip characteristics on soil (Inflation pressure 0.6 MPa)

Combat vehicle model and validation

The vehicle is equipped with four axles, which can be operated in either 4WD or 2WD. The front two axles are steering axles ($\delta_1$and δ_2). The vehicle is equipped with independent suspensions. Figure 30 shows the multi-wheeled combat vehicle model.

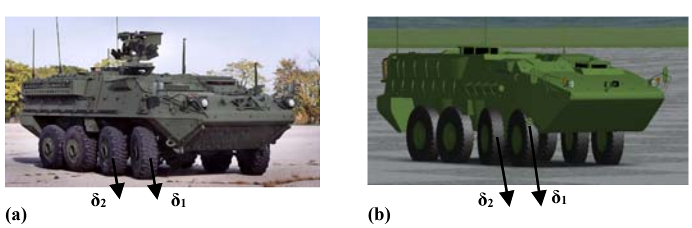

Figure 30: Typical vehicle configuration (a) and the simulation model (b) [26]

Vehicle Model

The vehicle model consists of 22 Degrees of freedom, namely pitch, yaw and roll of the vehicle sprung mass and spin and vertical motions of each wheel of the eight wheels. The TruckSim vehicle model has been developed based on the real vehicle configurations for M1126 Stryker ICV and using the non-linear tire look-up tables for rigid and soft terrain obtained from FEA off-road tire models developed using PAM-CRASH.

The individual steering angles, for a specific turning radius, can be determined by halving the distance between third and fourth axles, and connecting it perpendicular with the individual steering wheels as shown in Figure 31. The steering angles for both first and second axles has been calculated using Equation (3), as shown in Figure 32.

$$\cot \delta_o - \cot \delta_i = B / L \qquad (3)$$

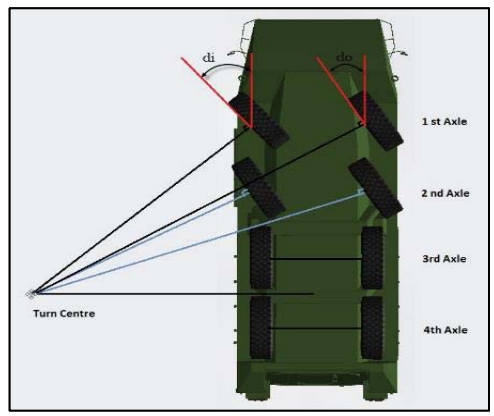

Figure 31: Ackerman steering, eight-wheel vehicle steering with first and second axles

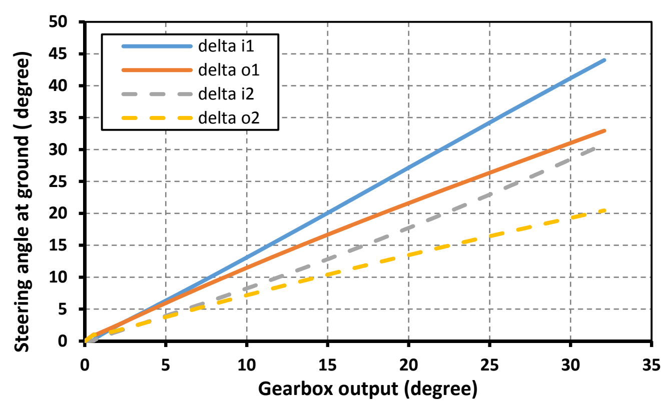

Figure 32: First and second axles steering angle vs. gearbox output

In order to use the developed combat vehicle model to study vehicle lane-change maneuverability on rigid and soft terrain at different speeds and powertrain configurations, The predictions of the vehicle handling characteristics and transient response during lane change on rigid road at different vehicle speeds were compared with field tests results. Measured and predicted results are compared on the basis of vehicle steering, yaw rates and accelerations. Published US Army validation criteria have been used to validate simulations [8]. At each measurement location, the model predicted RMS value should agree with the measured RMS acceleration within +10%. The model time domain data and measured time domain data skewness and kurtosis values should agree within + 50% of the measured data values (to provide a comparison on wave shape in the time domain).

Vehicle Model Validation

The vehicle was operated in four-wheel drive for all test courses on rigid road. The tires inflation pressures were maintained at 0.6 MPa. Different constant speeds were used for each test course. Table 4 shows the test course, the tire pressures and vehicle speeds.

Test Course	Tire Pressures	Vehicle Speed
J-Turn Maneuver	0.6 MPa	10, 13, and 16 Km/h
TOP Lane-change Maneuver	0.6 MPa	8, 16, and 32 Km/h

Table 4: Test Matrix

The J-Turn maneuver was performed to examine the steady state vehicle handling characteristics. A step steering input of approximately 6 degrees at two front axles was applied at given constant speeds. The steering wheel and road wheel steering angles were calibrated before the tests. The J-Turn was performed for right and left turning. Each J-Turn was performed twice for each speed and direction.

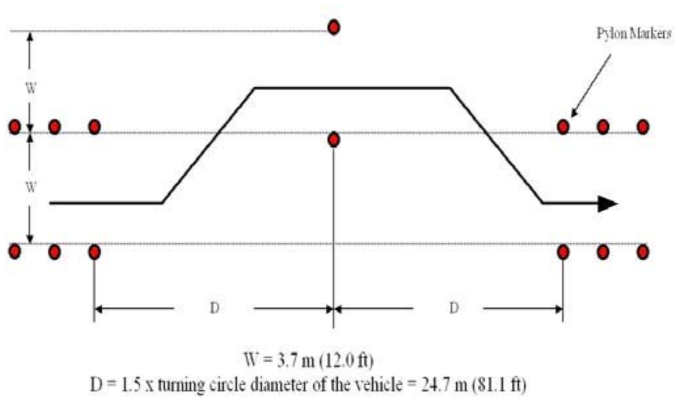

Figure 33: TOP lane change course [25]

To examine the vehicle transient response, the vehicle was tested during TOP Lane-change maneuver at different speeds, Figure 33 Shows how a lane- change maneuver is performed.

- J-Turn maneuver

Samples of the results of the published measured data and predicted responses during the J-Turn maneuvers are given in the figures below. In these figures, the vehicle speed was maintained at approximately 16.1 km/h as shown in Figure 34. The steering wheel input used in the simulation was obtained from the published measurement data, [25], and the steering system model predicted the steering input at the first and second axles, Figures 35 and 36.

The vehicle yaw rate and lateral acceleration are given in Figures 37 and 38. As it can be seen, there is a good agreement between the measurement and simulation.

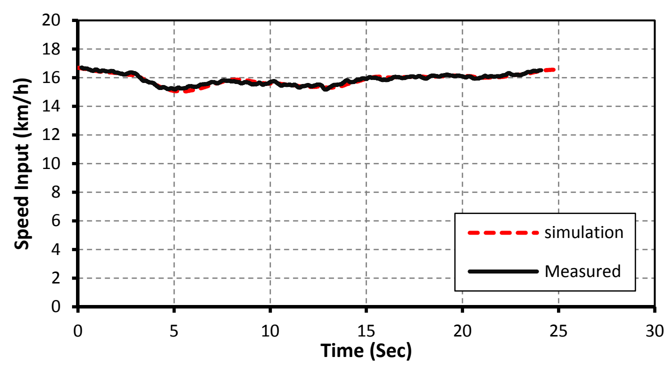

Figure 34: Vehicle input speed versus time

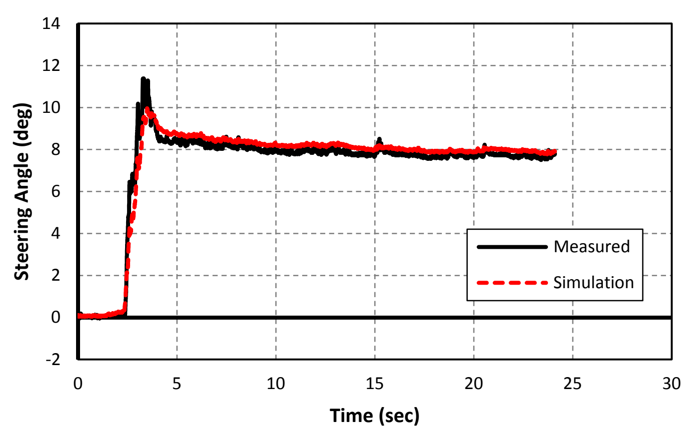

Figure 35: First axle steering time history

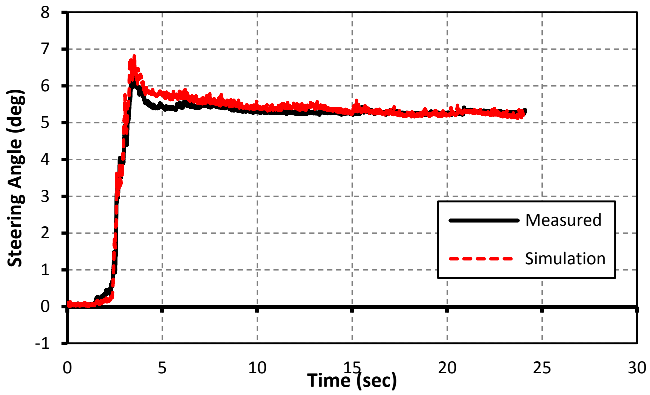

Figure 36: Second axle steering time history

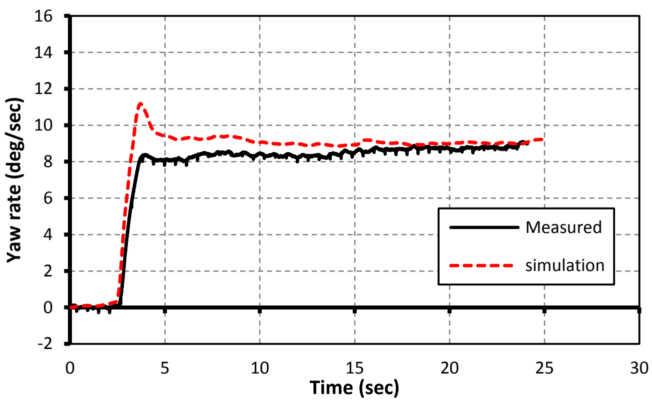

Figure 37: Yaw rate time history

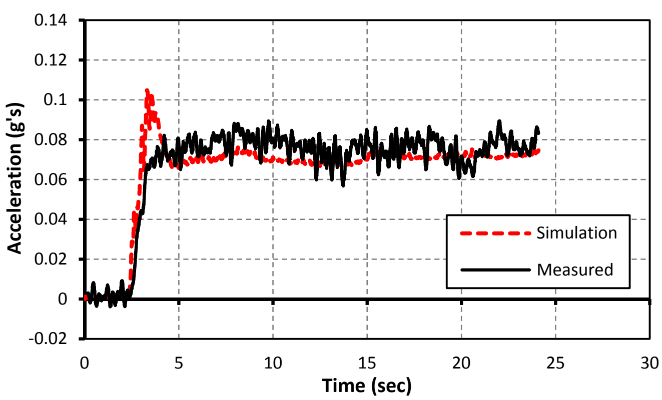

Figure 38: Lateral acceleration time history

US army validation criteria have been used to validate the J-Turn simulation at three speeds. As it can be seen from Table 5 for 16.1 km/h vehicle speed, the model predicted RMS value agrees with the measured RMS acceleration within +10%. The model time domain data and measured time domain data skewness and kurtosis values are found to be within + 50% of the measured data values. J-turn simulation reflects the accuracy of the model used to simulate this vehicle during steady state maneuvers, which is usually difficult to achieve.

	Yaw Rate			
			US Army Validation Criteria	
	Meas.	Sim.	Min.	Max.
Kurtosis	5.361	5.723	2.680	8.585
Skewness	-2.018	-1.955	-1.009	-2.932

	Lateral Acceleration			
			US Army Validation Criteria	
	Meas.	Sim.	Min.	Max.
Kurtosis	2.853	6.004	1.427	9.005
Skewness	-0.007	-1.260	-0.004	-1.890
RMS	0.005	0.005	0.005	0.005

Table 5: Validation of predicted and measured responses at 16.1 km/h

-TOP Lane Change maneuver

Samples of the results of the published measured data and predicted responses during the TOP lane change maneuvers are given in the figures below. In these figures, the vehicle speed was maintained at approximately 24.5 km/h as shown in Figure 39. The steering wheel input used in the simulation was obtained from the measurements and the steering system model predicted the steering input at the first and second axles, Figures 40 and 41.

The vehicle yaw rate and lateral acceleration are given in Figures 42 and 43. As it can be seen, there is excellent agreement between the measurement and simulation.

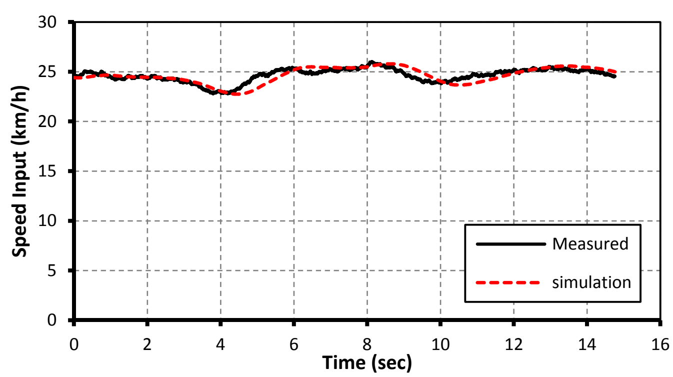

Figure 39: Vehicle input speed versus time

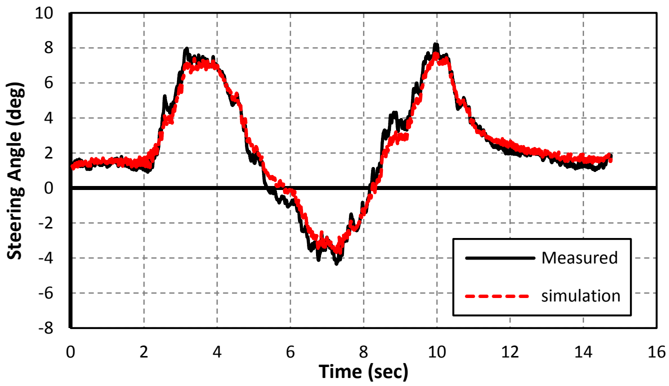

Figure 40: First axle steering time history

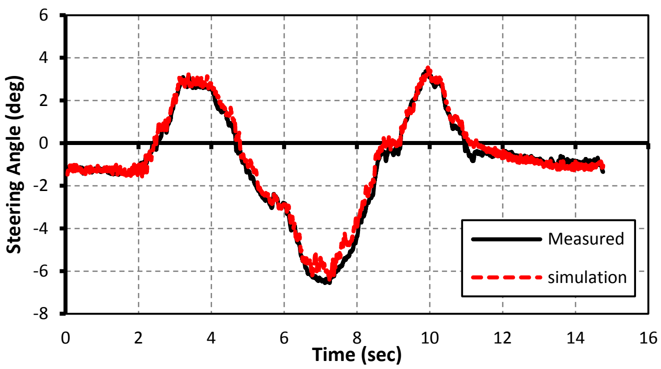

Figure 41: Second axle steering time history

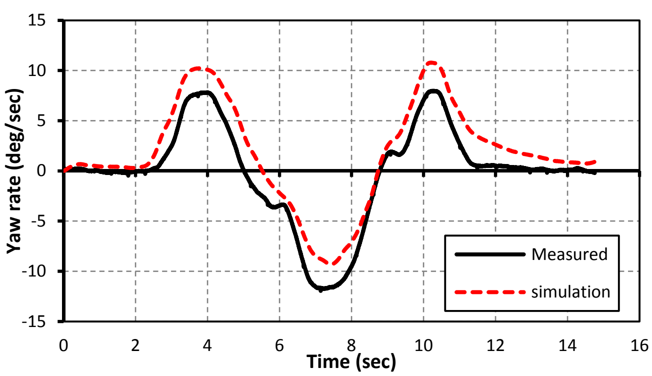

Figure 42: Yaw rate time history

Similar to the lane change maneuver validations, the results obtained from set of tests at 16.1, 24.5 and 32.2 Km/h were used to validate the model using US army criteria. Table 6 show the calculated and measured Kurtosis, Skewness and RMS for 24.5 km/h vehicle speed. The predicted values are within the US army criteria range. That means the simulated responses are in excellent agreement with measurements from the point of the magnitude and the shape. It should be noted that the RMS is calculated only for the lateral acceleration as specified by US army.

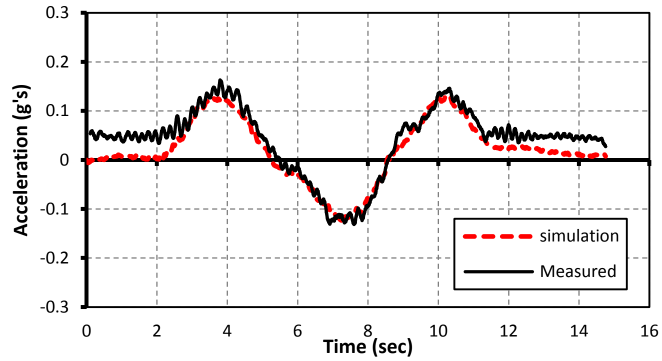

Figure 43: Lateral acceleration time history

	Yaw Rate			
			US Army Validation Criteria	
	Meas.	Sim.	Min.	Max.
Kurtosis	5.135	2.713	2.568	4.070
Skewness	1.767	1.072	0.883	1.609

	Lateral Acceleration			
			US Army Validation Criteria	
	Meas.	Sim.	Min.	Max.
Kurtosis	4.830	2.470	2.415	3.704
Skewness	1.482	0.991	0.741	1.486
RMS	0.001	0.004	0.001	0.005

Table 6: Validation of predicted and measured responses at 24.5 km/h

Combat Vehicle Testing on Rigid and Soft Terrain

The vehicle was operated in two different drive configurations on rigid and soft terrain. The tires inflation pressures were maintained at 87 psi. Table 7 shows the test course, the terrain type, vehicle drive configuration and vehicle speeds.

The test course used in this section the same as shown previously in Figure 33

Test Course	Terrain	Drive	Speed
TOP Lane-change Maneuver	Rigid Road	8x8 and 8x4	50 km/h
	Clayey soil		

Table 7: Test Matrix

Test results for combat vehicle on rigid and soft terrain

In this section, a comparison between the combat vehicle maneuverability performance with different power train configurations (8x8 and 8x4) on both rigid and soft terrain.

-Test results for 8x4 combat vehicle

Figure 44 shows the target path and vehicle trajectory response on rigid and soft soil. Figures 45 and 46 shows vehicle lateral acceleration and yaw rate respectively.

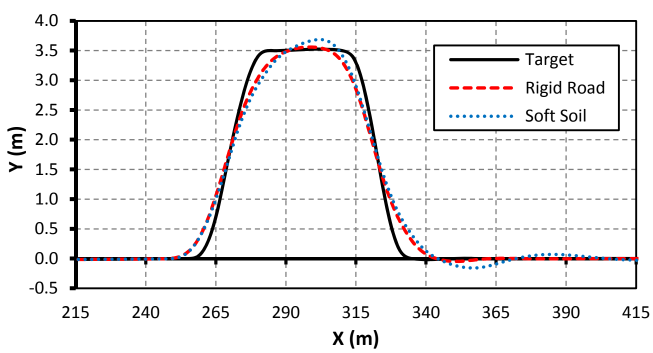

Figure 44: Vehicle trajectory for 8x4 combat vehicle

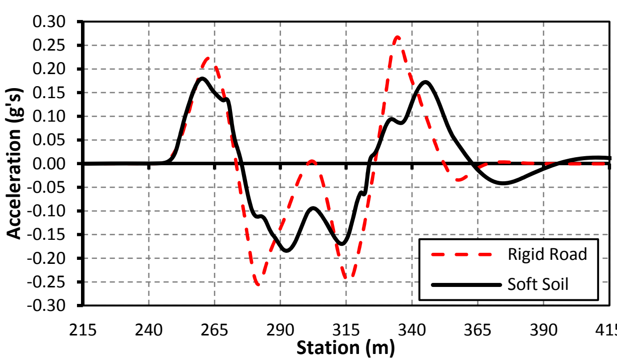

Figure 45: Vehicle lateral acceleration for 8x4 combat vehicle

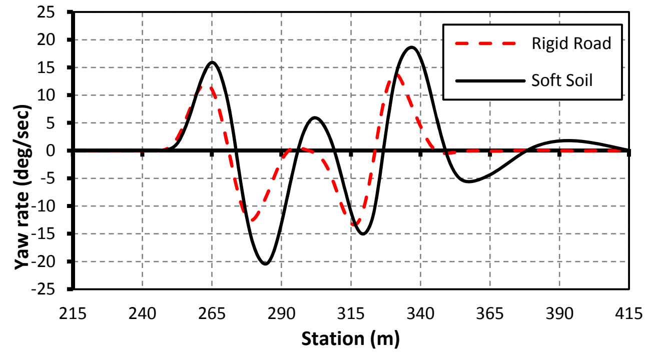

Figure 46: Vehicle yaw rate for 8x4 combat vehicle

From the predicted responses for 8x4 combat vehicle on rigid and soft terrain, it can be mentioned that vehicle yaw rate is more sensitive on soft soil when compared with rigid road.

However, at the same time soft soil reduces vehicle lateral acceleration when compared with rigid road at the same vehicle speed. Moreover, there is a slight drift in vehicle trajectory on soft soil when compared to vehicle response on rigid road at the same vehicle speed.

-Test results for 8x8 combat vehicle

Figure 47 shows the target path and vehicle trajectory response on rigid and soft soil. Figures 48 and 49 shows vehicle lateral acceleration and yaw rate respectively.

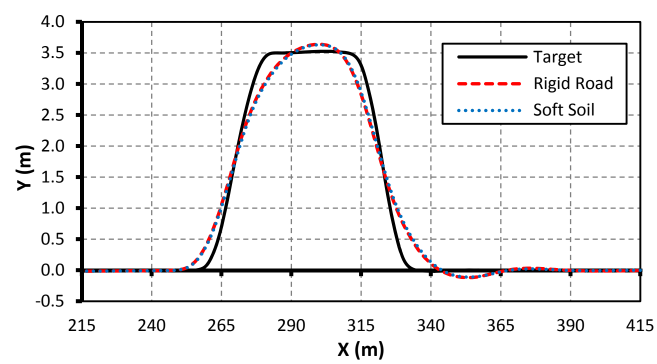

Figure 47: Vehicle trajectory for 8x8 combat vehicle

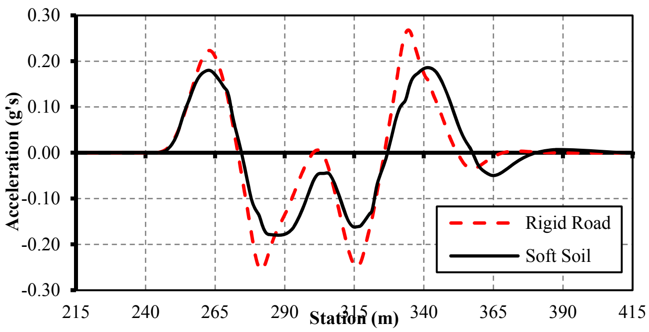

Figure 48: Vehicle lateral acceleration for 8x8 combat vehicle

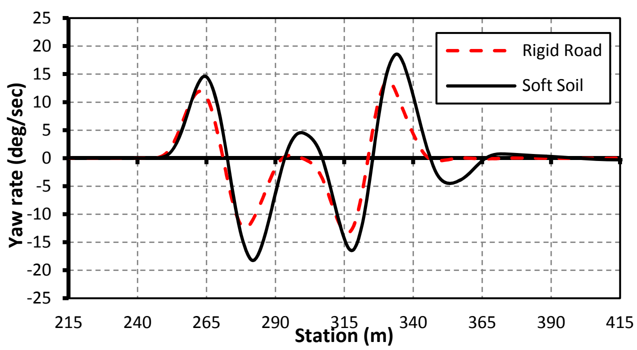

Figure 49: Vehicle yaw rate for 8x8 combat vehicle

From the predicted responses for 8x4 combat vehicles on rigid and soft terrain, it can be mentioned that vehicle yaw rate is more sensitive on soft soil when compared with rigid road.

However, at the same time soft soil reduces vehicle lateral acceleration when compared with rigid road at the same vehicle speed. Moreover, there is no difference in vehicle trajectory on soft soil when compared to vehicle response on rigid road at the same vehicle speed in case of 8x8 vehicle drive.

Finally, torque distribution among axles/wheels has a great effect especially on soft soil driving conditions.

CONCLUSIONS

In this paper, a Finite Element Analysis (FEA) off-road tire models were developed. The FEA of off-road tire models were used to examine the interaction between the tire and both rigid and soft terrain. The following conclusions can be made:

- Vertical tire stiffness and cornering characteristics of the developed FEA off-road tire has been compared with published experimental data and they showed a good agreement.

- The FEA of off-road tire-soil model simulation results exhibited a large difference between the first and second tire in sinkage, rolling resistance and aligning moments, while differences from second to fourth are negligible, and therefore the effects of these tires may be omitted during development of a simplified tire-soil model.

- The steady state and transient responses during J-Turn and TOP lane change maneuvers of a multi-wheeled combat vehicle were predicted and validated against published experimental tests measurements. The US Army validation criteria have been used to validate both the J-Turn and the TOP lane change simulations at three vehicle speeds. The predictions were in good agreements with the measurements.

- The developed model has been used to examine the vehicle directional behavior at high speeds and different powertrain configurations (8x8 and 8x4) on both rigid and soft terrain. The developed model predictions on both rigid and soft terrain showed that:

  1. Different powertrain configurations have no effect on vehicle maneuverability on dry rigid road conditions.
  2. Vehicle maneuverability on soft soil is more sensitive to power distribution among axles.
  3. Vehicle yaw rate is more sensitive on soft soil when compared with rigid road in case of 8x4 driving condition. However, at the same time soft soil reduces vehicle lateral acceleration when compared with rigid road at the same vehicle speed.
  4. There is no difference in vehicle trajectory on soft soil when compared to vehicle response on rigid road at the same vehicle speed in case of 8x8 driving condition.

- Finally, torque distribution among axles/wheels has a great effect on multi-wheeled combat vehicles maneuverability and directional stability especially on soft soil.

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