15th International Conference on
AEROSPACE SCIENCES & AVIATION TECHNOLOGY,
ASAT - 15 – May 28 - 30, 2013, Email: asat@mtc.edu.eg ,
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Multi-Wheeled Combat Vehicle Maneuverability on Rigid and Soft Terrain

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Abstract: The dynamic performance of multi-wheeled off-road vehicles on rigid and soft terrain was developed using multi-body dynamics software and validated against measured data. Non-linear tire look-up tables for rigid and soft terrain obtained from three-dimensional non-linear Finite Element Analysis (FEA) off-road tire models developed using PAM-CRASH, were used in the simulation. 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. The combat vehicle model was 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.

Keywords: Off-road, multi-wheeled, dynamic model validation, FEA, PAM-CRASH, TruckSim, validation methodology, handling characteristics.

1. Introduction

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 consisting of three main steps, experimental data collection, measurement of the performance parameters and comparison of the simulation results with the experimental test data [1]. 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 also contribute towards the inconsistency in results.

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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 [2].

Fancher et al. (1989) showed that future transportation technology would involve developing heavy commercial vehicles with measurable and predictable levels of performance in safety-related maneuvers [3].The study concentrated on vehicles weighing more than 36ton (80,000 pounds) and used 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.

El-Gindy and Wong (1987) presented 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. The differences in the predictions obtained using various models are examined and were compared with available experimental data [4].

LeBlanc and El-Gindy (1992) presented the findings of an experimental and theoretical study on the influence that self-steering axle has on the directional stability of straight truck. 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 [5].

El-Gindy and Mikulcik (1993) published a paper deals with the evaluating the sensitivity of the yaw rate response of a three-axle single unit heavy vehicle to sinusoidal steering input [6]. 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.

Hillegass et al. (2005) published a paper dealing with evaluating and validating a computer generated multi-wheeled combat vehicle. 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) [7].

Matthew J. Hillegass et al. (2004) discussed a methodology for validating the vertical dynamic performance of a virtual vehicle [8]. 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.

2. Combat Vehicle Model and Validation

Figure 1 shows the multi-wheeled combat vehicle model. 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. The vehicle model consists of 24 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.

(a) **(b)**

Fig. 1 (a) Typical vehicle configuration, (b) The simulation model [9]

2.1 Vehicle Model

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.

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).

2.2 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 87 psi. Different constant speeds were used for each test course. Table 1 shows the test course, the tire pressures and vehicle speeds.

Table 1: Test Matrix

Test Course	Tire Pressures	Vehicle Speed
J-Turn Maneuver	87 psi	6, 8, and 10 mph
TOP Lane-change Maneuver	87 psi	5, 10, and 20 mph

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.

To examine the vehicle transient response, the vehicle was tested during TOP Lane-change maneuver at different speeds, Figure 2 Shows how a lane- change maneuver is performed.

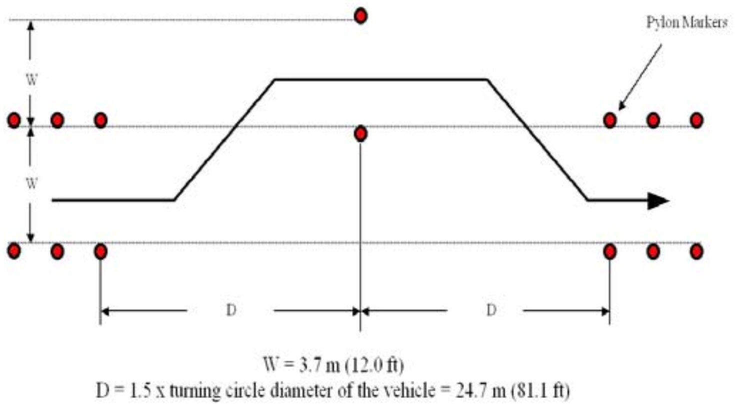

Fig. 2 TOP lane change course [8]

2.2.1 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 3. The steering wheel input used in the simulation was obtained from the published measurement data, [8], and the steering system model predicted the steering input at the first and second axles, Figures 4 and 5.

The vehicle yaw rate and lateral acceleration are given in Figures 6 and 7 respectively. As it can be seen there is excellent agreement between the measurement and simulation.

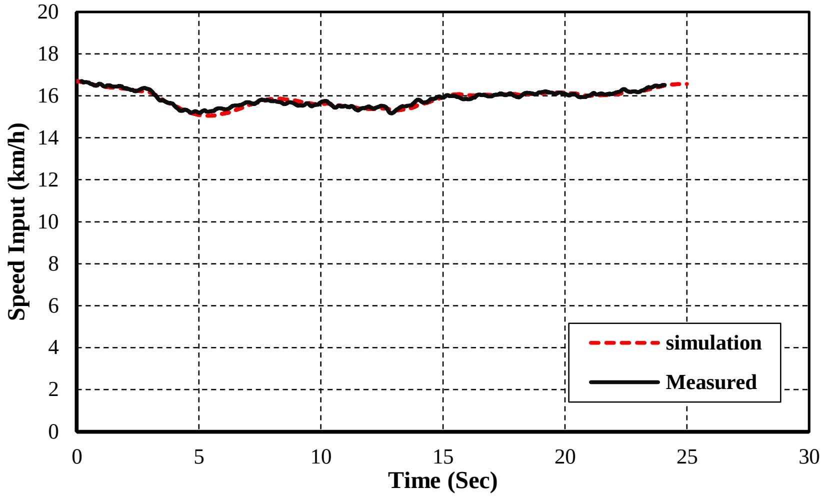

Fig. 3 Vehicle input speed versus time

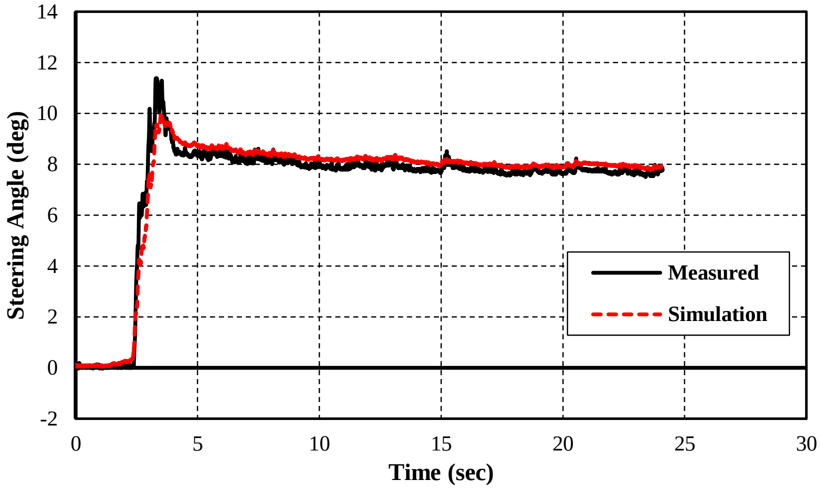

Fig. 4 First axle steering time history

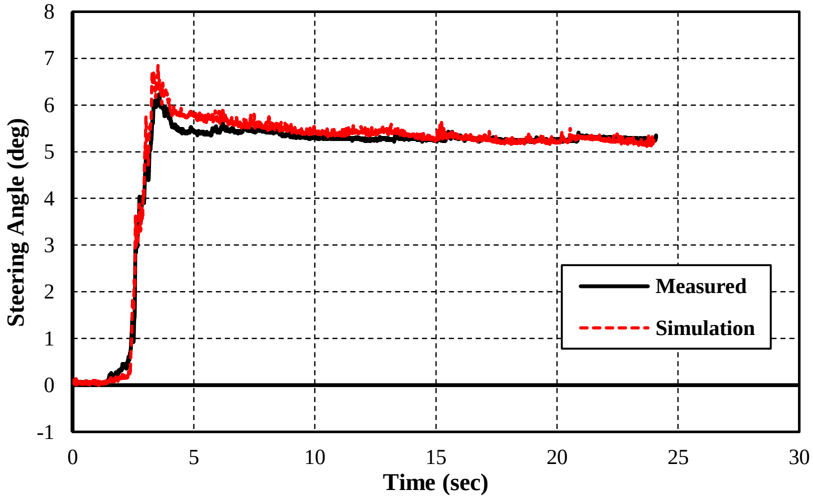

Fig. 5 Second axle steering time history

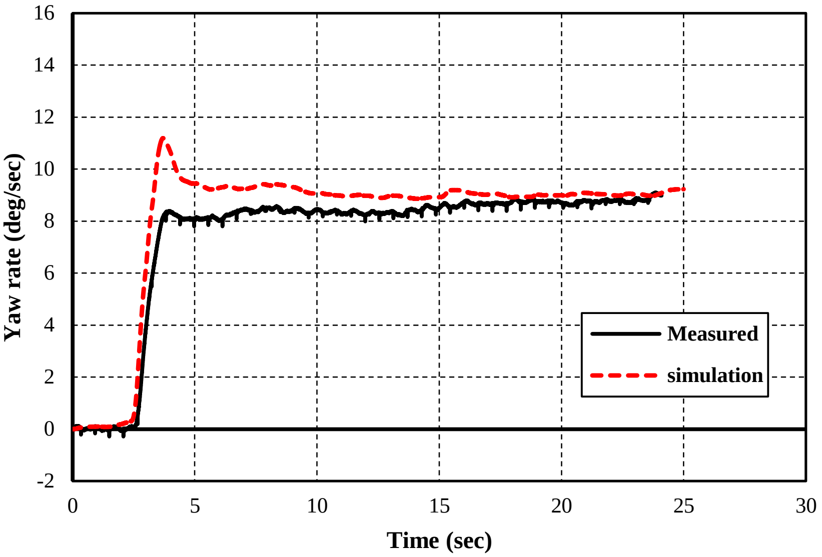

Fig. 6 Yaw rate time history

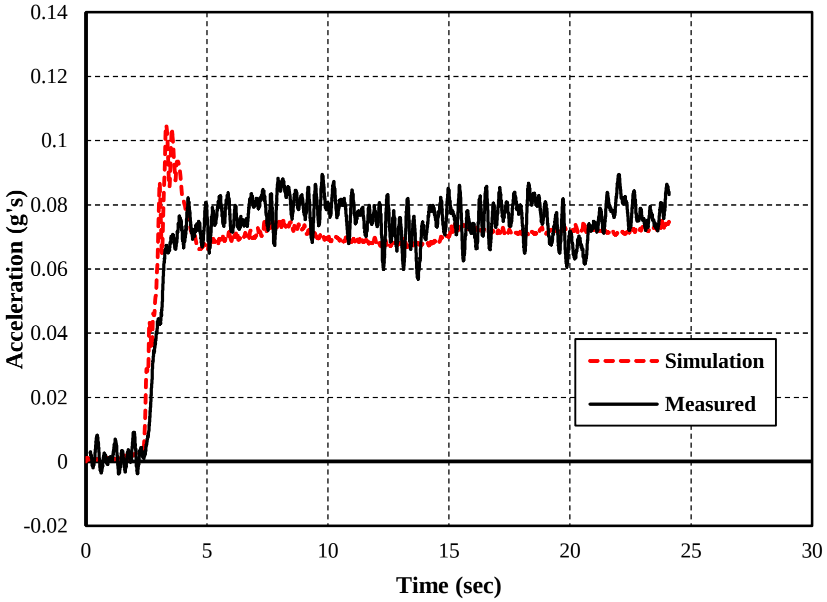

Fig. 7 Lateral acceleration time history

US army validation criteria have been used to validate the J-Turn simulation at three speeds. As it can be seen from Table 2 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.

Table 2 Validation of predicted and measured responses at 16.1 km/h

	Yaw Rate			
			US Army Validation Criteria	
	Measurements	**Simulation**	**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	
	Measurements	**Simulation**	**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

2.2.2 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 8. 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 9 and 10.

The vehicle yaw rate and lateral acceleration are given in Figures 11 and 12 respectively. As it can be seen, there is excellent agreement between the measurement and simulation.

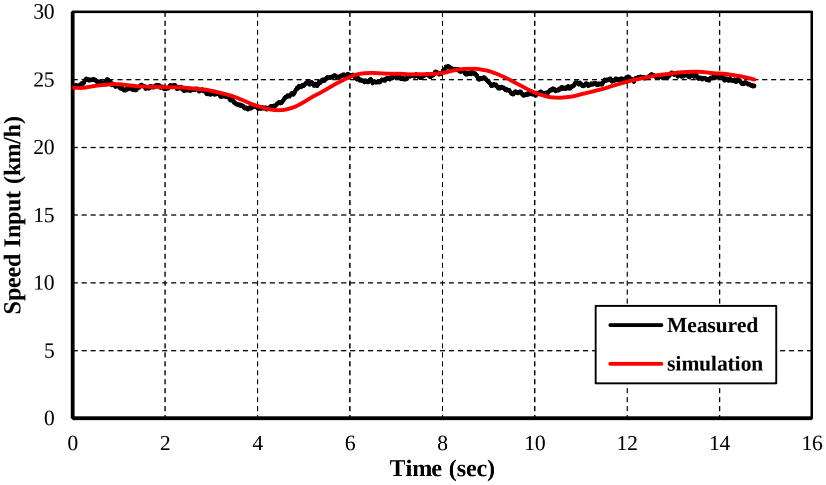

Fig. 8 Vehicle input speed versus time

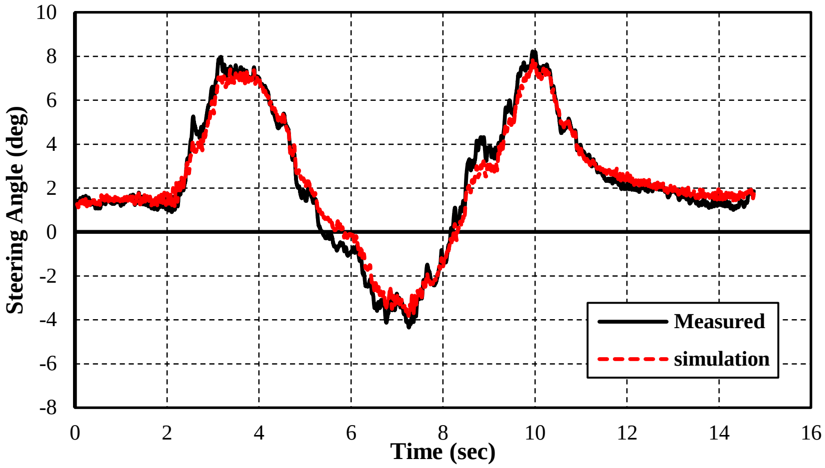

Fig. 9 First axle steering time history

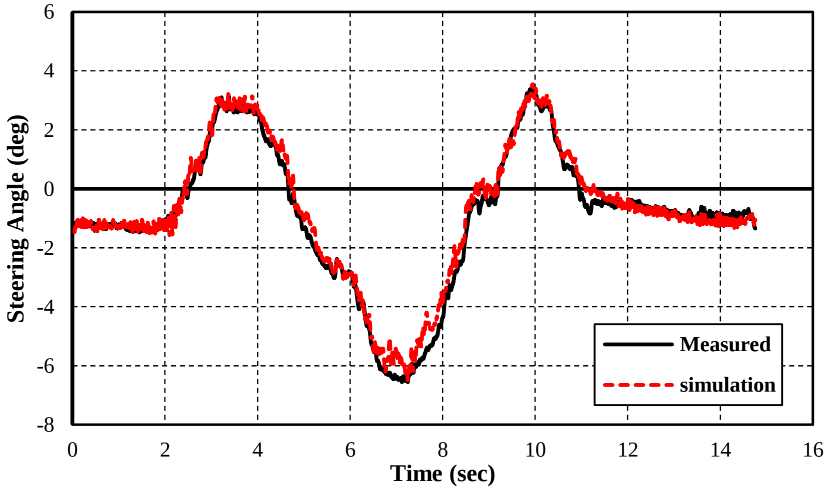

Fig. 10 Second axle steering time history

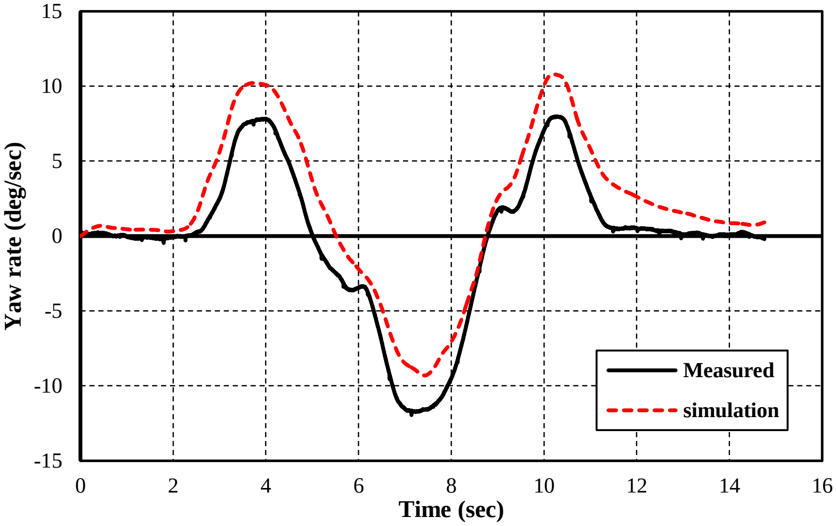

Fig. 11 Yaw rate time history

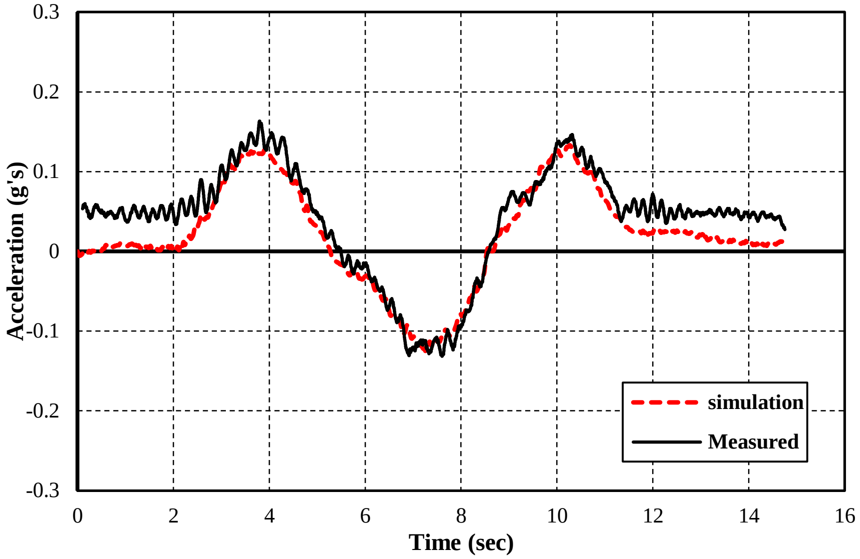

Fig. 12 Lateral acceleration time history

Similar to the lane change maneuver validations, the results obtained from set of tests at 10, 15 and 20 mph were used to validate the model using US army criteria. Table 3 shows 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.

Table 3 Validation of predicted and measured responses at 24.5 km/h

	Yaw Rate			
			US Army Validation Criteria	
	Measurements	**Simulation**	**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	
	Measurements	**Simulation**	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

3. 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 4 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 2

Table 4 Test Matrix

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

3.1 Test Results on Rigid Road

In this test, the speed was increased gradually to 50 km/h in 15 sec and then maintained at this speed. Figure 13 shows the target path and vehicle trajectory response in two different powertrain configurations, 8x8 and 8x4, for comparison. Figures 14 and 15 shows vehicle lateral acceleration and yaw rate respectively.

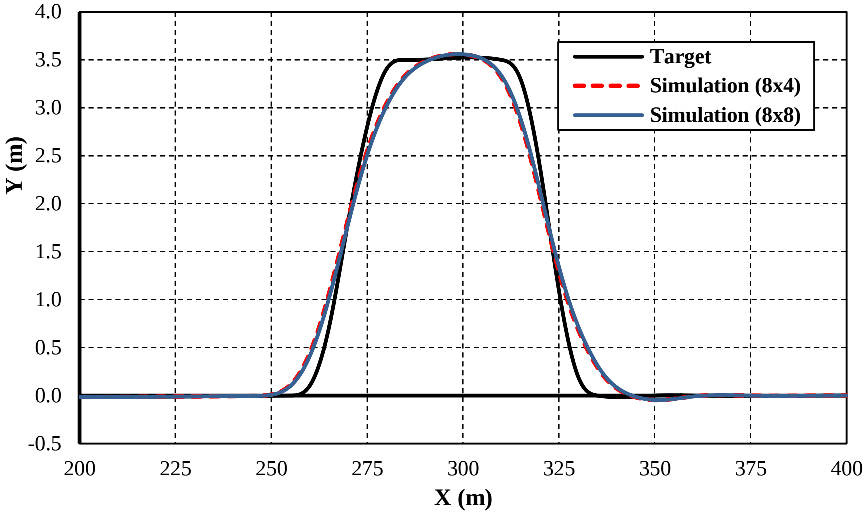

Fig. 13 Vehicle trajectory on rigid road

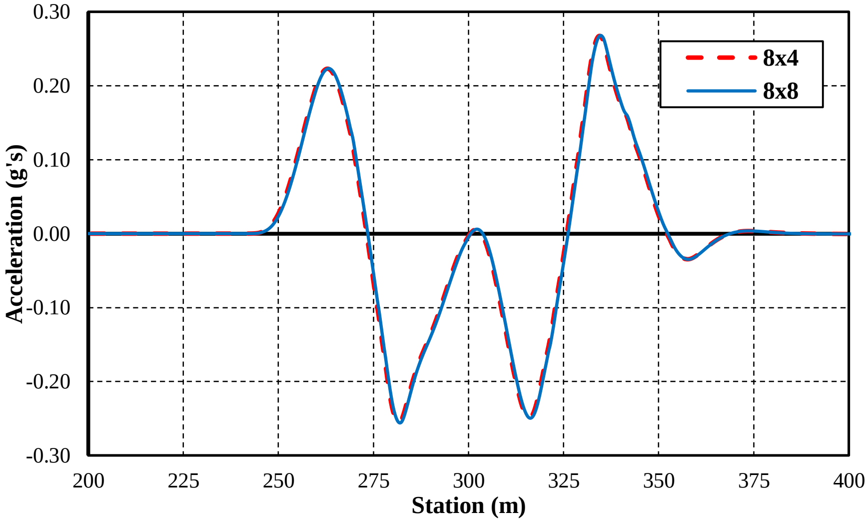

Fig. 14 Vehicle lateral acceleration on rigid road

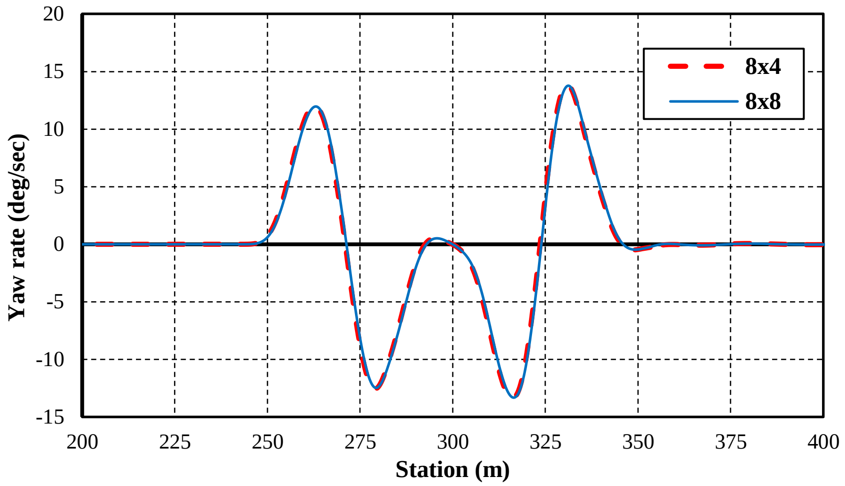

Fig. 15 Vehicle yaw rate on rigid road

From the predicted responses of vehicle testing simulation on rigid road, it can be mentioned that different powertrain configurations have no effect on vehicle maneuverability on dry and rigid road conditions.

3.2 Test Results on Soft Soil

The same test course has been used for vehicle testing on soil. Figure 16 shows the target path and vehicle trajectory response in two different powertrain configuration, 8x8 and 8x4. Figures 17 and 18 show vehicle lateral acceleration and yaw rate respectively.

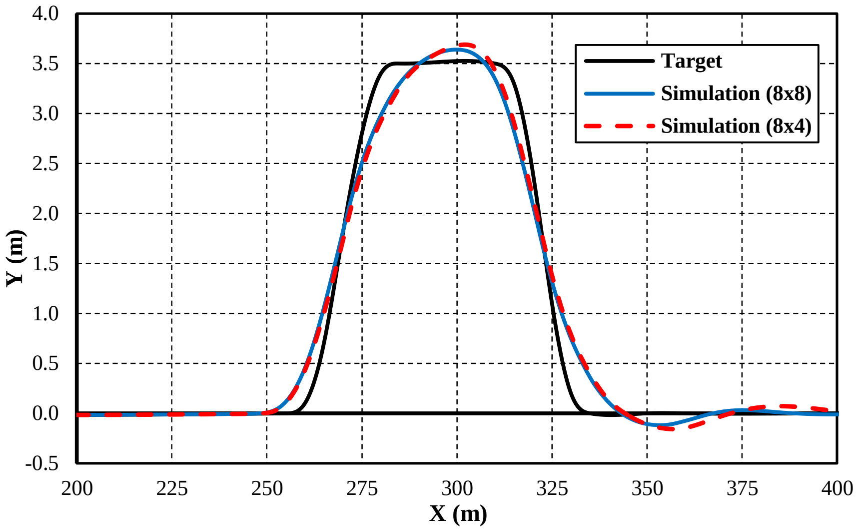

Fig. 16 Vehicle trajectory on soft soil

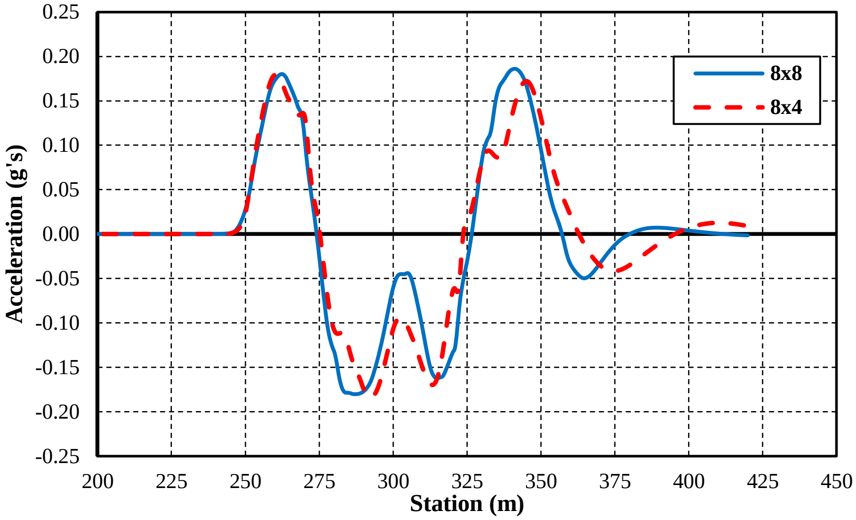

Fig. 17 Vehicle lateral acceleration on soft soil

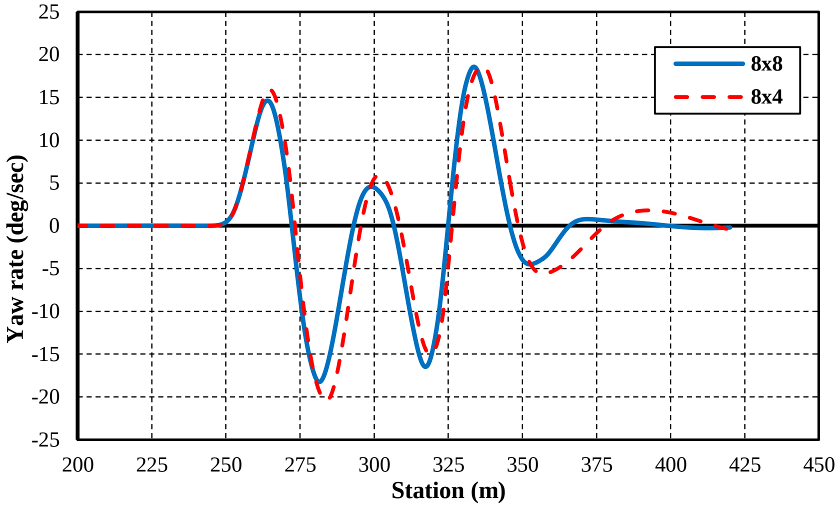

Fig. 18 Vehicle yaw rate on soft soil

From the predicted responses on soft soil, it can be mentioned that vehicle maneuverability on soil is more sensitive to power distribution among axles.

3.3 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 (8×8 and 8×4) on both rigid and soft terrain.

3.3.1 Test results for 8×4 combat vehicle

Figure 19 shows the target path and vehicle trajectory response on rigid and soft soil. Figures 20 and 21 show vehicle lateral acceleration and yaw rate respectively.

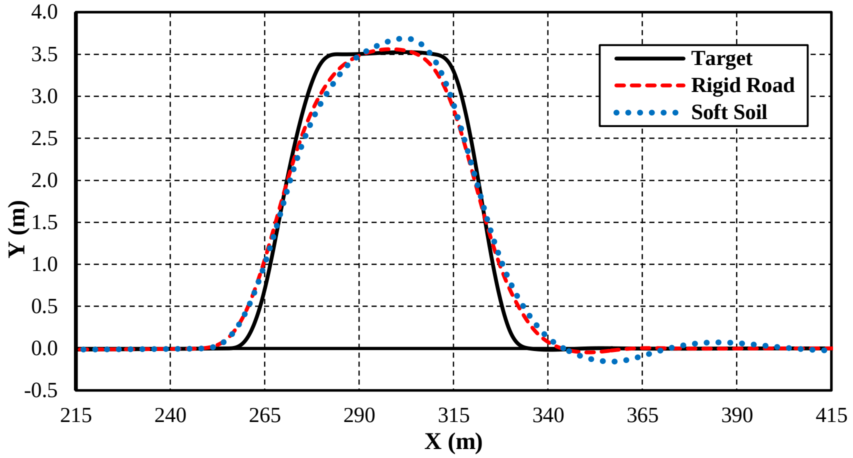

Fig. 19 Vehicle trajectory for 8×4 combat vehicle

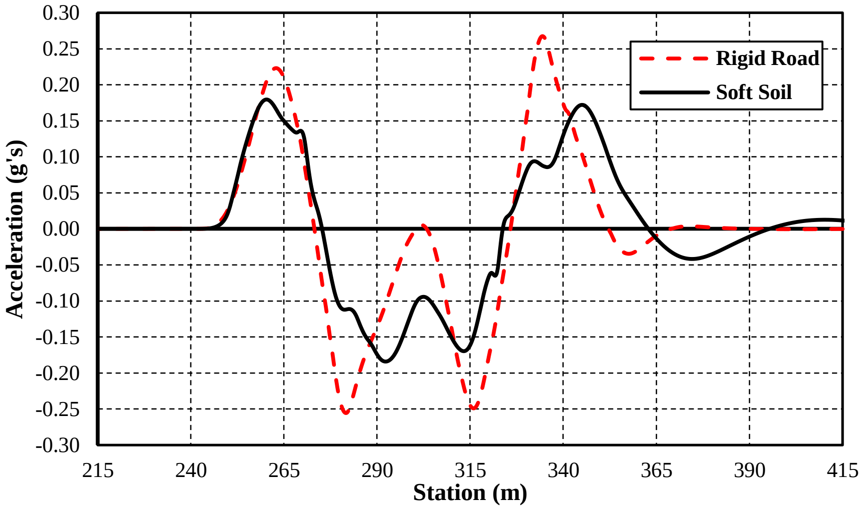

Fig. 20 Vehicle lateral acceleration for 8×4 combat vehicle

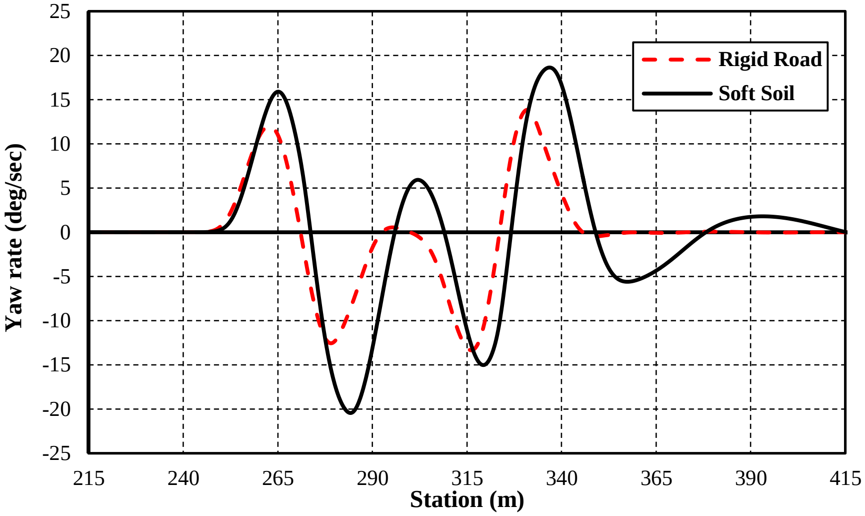

Fig. 21 Vehicle yaw rate for 8×4 combat vehicle

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.

3.3.2 Test results for 8×8 combat vehicle

Figure 22 shows the target path and vehicle trajectory response on rigid and soft soil. Figures 23 and 24 show vehicle lateral acceleration and yaw rate respectively.

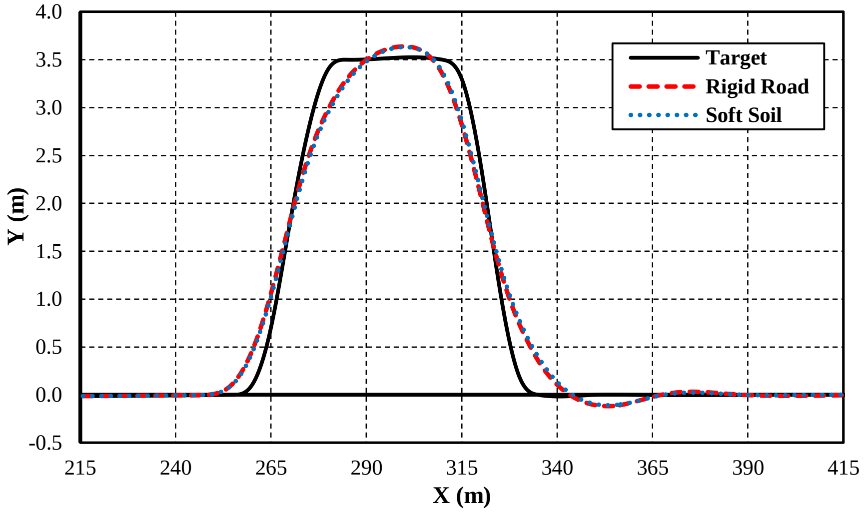

Fig. 22 Vehicle trajectory for 8×8 combat vehicle

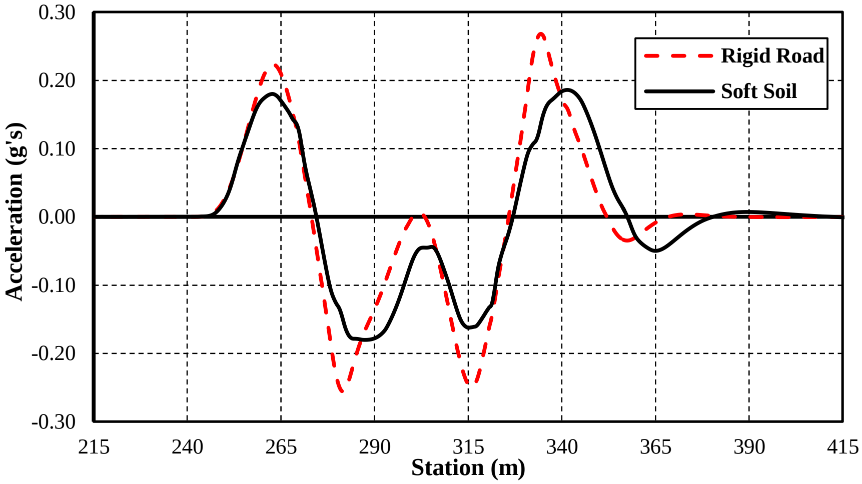

Fig. 23 Vehicle lateral acceleration for 8×8 combat vehicle

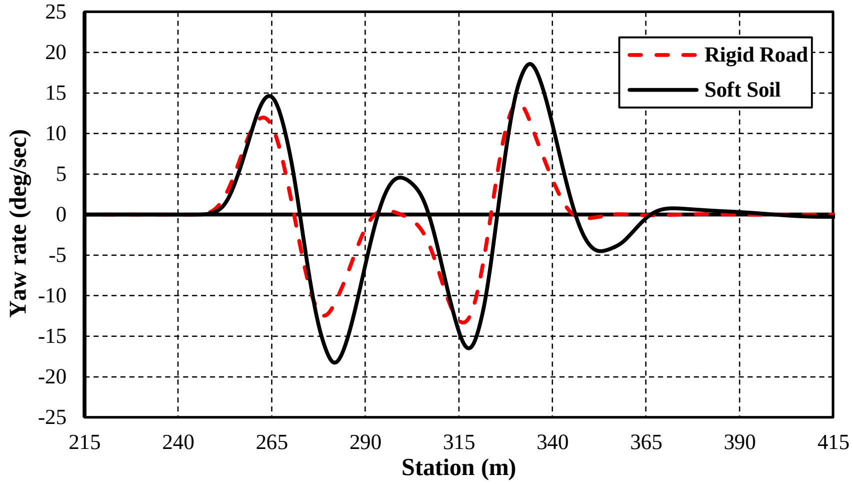

Fig. 24 Vehicle yaw rate for 8×8 combat vehicle

From the predicted responses for 8×4 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.

4. Conclusions

The steady state handling and transient responses during TOP lane change and J-Turn maneuvers of a multi-wheeled combat vehicle were predicted and validated against published experimental tests measurements. A developed multi-body dynamics model was used in this study. 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 developed model predictions of the steady state response during J-turn maneuvers and the transient responses during TOP lane change maneuvers 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:

- Different powertrain configurations have no effect on vehicle maneuverability on dry rigid road conditions.
- Vehicle maneuverability on soft soil is more sensitive to power distribution among axles.

- 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.
- 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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