Rollover Simulations for Vehicles using Deformable Road Surfaces

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Abstract

Vehicle Rollover simulations have been performed using LS-DYNA to predict both the vehicle dynamics and structural performance. However, these simulations do not consider a deformable road surface, affecting both the propensity of the vehicle to achieve a condition which will initiate a roll over or the effect of that surface to impart or mitigate damage to the structure. This study will highlight the capabilities of LS-DYNA for the simulation of deformable road surfaces as applied to rollover events.

Roll Over Events
A brief description of Rollover events which are typically seen in the field are described, as well as the corresponding physical test procedure. These tests are performed to assess the propensity for a vehicle to rollover and the subsequent damage to the vehicle resulting from the rollover event. Two testing events; ditch maneuvering and soil tripping are identified as events in which the road surface deformation would have an effect on the simulation results and are thereby candidates for using a deformable road surface to improve the simulation.

Vehicle System Modeling
A simplified system level model was assembled for use in the study of rollover simulations. This model is described and the validation of this model is discussed.

Soil Modeling
Soil is included in our simulation models via a MAT5_SOIL_AND_FOAM material model. The necessary test procedure to attain the material properties is discussed, as well as an example of the test data requirements.

Simulation Results
The results of a Ditch Maneuver and a Soil Tripping analysis are presented, discussing the challenges associated with modeling this type of vehicle/roadway interaction.

Challenges and Future Work
Since the simulation considers a single vehicle speed and vehicle type, future work would focus on the understanding the effect of variables such as types of soil, vehicle speed and additional correlation aspects.

Introduction

Rollover crashes are the most complicated and least understood type of vehicular crash. Based on Traffic Safety Facts 2005 (NHTSA 2005), although only 2.6 percent of passenger vehicle crashes resulted in rollovers, they accounted for 5.3 percent of injury crashes and 21.1 percent of fatal crashes in the US. According to the Fatality Analysis Reporting System (FARS), 10,816 people died in rollover crashes in 2005 alone, accounting for more than one-third of all deaths from passenger vehicle crashes in the US. The associated costs of rollover related injuries and fatalities are nearly $50 billion per year. Additionally, the fatal rollover rates were considerably higher for light trucks, especially SUVs, than for passenger cars. [1]

Vehicle roll over simulations have been studied using LS-DYNA for study of the vehicle’s propensity to roll over. The ability to simulate the interaction between a vehicle system model under dynamic conditions such as those found in roll over events has been developed and demonstrated in various studies.[2][3][4]

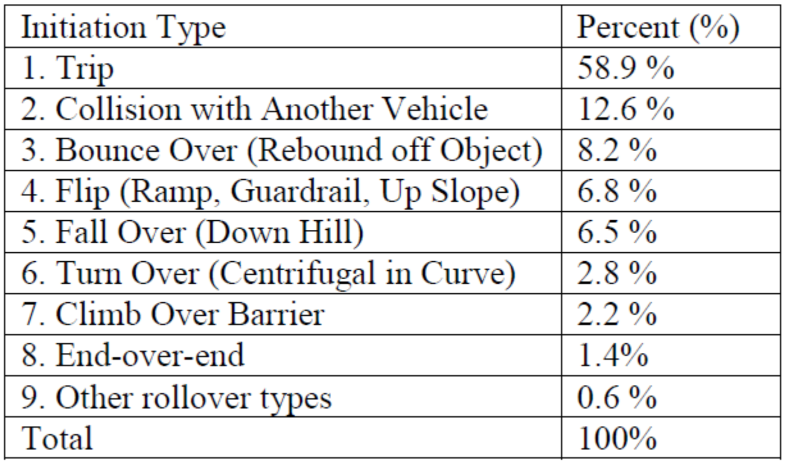
The various material models available within LS-DYNA allow the user to define materials modeling soil behaviors. While many of the rollover events described above occur on relatively rigid road surfaces, some events occur as a result of a change in surface friction or the stiffness of the surface.

Combining the system level simulation capabilities and the deformable soil road surface model capabilities into a rollover event simulation will be demonstrated through the execution of 2 specific events; ditch maneuvers and soil tripping.

Rollover Conditions

Vehicle rollover conditions are typically the result of evasive maneuvers, in avoidance of another impact. These maneuvers result in lateral roll of sufficient magnitude that the vehicle will sustain a rotation about the vehicle longitudinal axis.

Based on accident statistics, the majority of these rollover events may be classified as a ‘soil tripping’ event, where the vehicle has an initial avoidance maneuver and then interacts with a more deformable and higher friction surface, which causes the vehicle to decelerate in a manner that results in a rollover. In these cases, the interaction of the tire and the road surface is critical in attaining the proper boundary conditions which initiate the rollover event.



Initiation Type	Percent (%)
1. Trip	58.9 %
2. Collision with Another Vehicle	12.6 %
3. Bounce Over (Rebound off Object)	8.2 %
4. Flip (Ramp, Guardrail, Up Slope)	6.8 %
5. Fall Over (Down Hill)	6.5 %
6. Turn Over (Centrifugal in Curve)	2.8 %
7. Climb Over Barrier	2.2 %
8. End-over-end	1.4%
9. Other rollover types	0.6 %
Total	100%

Figure :1 NTSHA 1995-2005 NASS-CDS Rollover Initiation By Type

Standardized testing has been developed by automakers and governmental agencies for the purpose of evaluating both the vehicle structure and occupant safety aspects of the roll over event.

Tests are designed to achieve the basic conditions encountered in the classes of roll over events. These tests include side sled ejection (SAEJ2114), Corkscrews, High Ditch, and Soil Tripping. These last two conditions are difficult to simulate since the deformation of the road surface or soil may greatly affect the roll over event.

The SAEJ2114 test ejects a vehicle laterally from a 23 degree incline sled which is decelerated from 30 miles per hour over a distance of 3 feet. This test uses a rigid impact surface.

Corkscrew tests make use of a ramp which the vehicle approaches, resulting in a rotation about the vehicle's longitudinal axis. The vehicle rolls onto a rigid surface to complete the test event.

Ditch maneuvers are conducted by driving a vehicle along a 35 degree inclined surface such that one side of the vehicle is initially riding on the horizontal surface and the other side is on an incline. This type of event can be greatly influenced by the presence of a deformable surface. In certain instances, the road deformation can inhibit the vehicle's ability to roll over.

These tests are conducted in an effort to study vehicle behavior under given off-road circumstances, such as when a vehicle leaves the road and travels into an embankment or ditch. The test procedure is carried out as follows:
The vehicle is towed at a specified speed and released from the tow system.

The vehicle then enters the ditch at a prescribed incident angle.

After all the wheels enter the ditch, the steering input is added

The vehicle may or may not rollover, based on a combination of parameters such as CG height, lateral acceleration and yaw and roll rates.

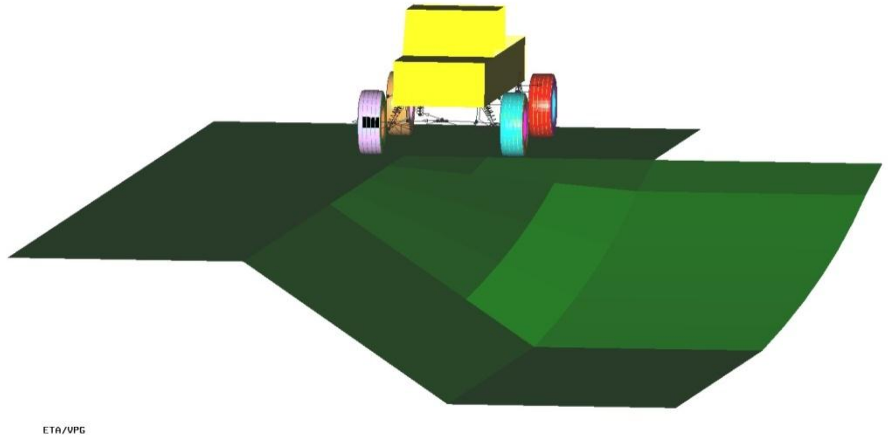


Figure 2: Ditch Maneuver Event

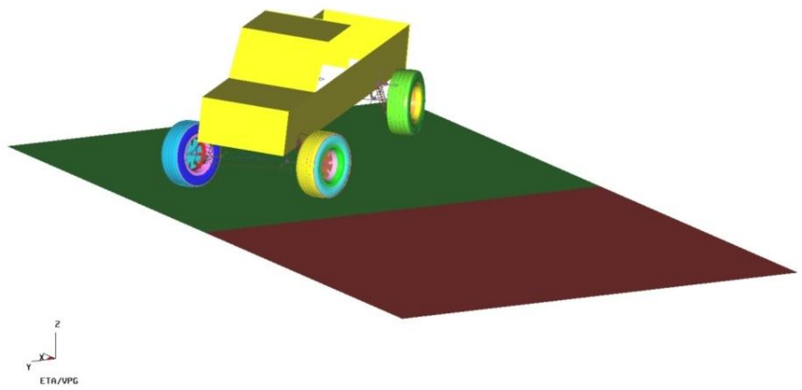
Soil Tripping tests are based on a study by Berg et al. (2007) [3] where they developed a test procedure for soil trip rollover that allowed simulation of the pre-roll phase prior to the vehicle rollover. The test setup, consists of three different phases:

1) A guided acceleration phase in which the test vehicle is guided by an optically controlled steering system while accelerating by its own engine to a predefined velocity, and moves straight

forward into a skidding phase. In the simulation model, the vehicle model is set at a prescribed initial velocity and the steering system is locked.
2) The skidding phase, where the ground is divided into low- and high-friction areas. As the vehicle enters the low-friction area, the vehicles front wheels are steered as fast as to the right possible to its maximum steering angle. This maneuver makes the vehicle turn slightly to the right with an induced yaw motion so that its right front wheel passes the high-friction part of the ground for a short distance, thus further increasing the yaw motion of the vehicle. In this phase, the simulation model has the steering system articulated to result in a 90 degree turn. This requires a trial and error approach to achieve the desired turning effect, and is sensitive to the surface friction, vehicle mass, center of gravity and tire properties
3) A rollover phase, in which the vehicle enters at the end of the low friction area into a sand pit with a yaw angle of approximately 40 degree and rolls. In this portion of the simulation, the vehicle model is allowed to freely move and interact with the road surface through contacts defined between the deformable road and the vehicle structure.

This study will focus on these two roll over events in order to determine the ability of a soil model to achieve a reliable simulation of a Ditch maneuver and a Soil Tripping condition.

Figure 3: Soil Tripping Event



Vehicle System Model

In order to control the boundary conditions more closely to the testing procedures, a VPG modeling approach was implemented. This makes use of a working suspension system and finite element tire models that interact with the road surface through a contact interface.

Vehicle Dynamics

A simplified vehicle model was developed to test the various road surface models. The model was developed from a 4 wheel independent suspension system, with a conventional upper/lower control arm and steering knuckle arrangement.

A finite element tire model was created the eta/VPG tire model. This tire model was correlated to an existing force deflection curve for vertical stiffness, and lateral force versus deflection curves for several tire slip angles. These tires were tuned using an iterative approach, modifying the Young’s Modulus of the tire sidewall.

Structural Model

The structural model of the vehicle used to study this behavior was a rigid model, with the mass and inertia properties of a typical sport utility vehicle. While the deformation of the vehicle structure will affect the interaction with the deformable road surface, this study is focused on the deformation of the road surface. In addition, the stiffness of the vehicle structure is significantly greater than that of the soil, and study is limited to the initial roll over and not subsequent impacts.

The structural model was attached to the suspension system by means of rigid connections at the suspension to vehicle interface areas. Locations which interface by means of shock absorbers and springs were modeled using a *DISCRETE_BEAM element which included the local stiffness of bushings and damping parameters associated with the shock absorber.

System Model Validation

The Simplified System Model was validated using road load measurements at the wheel centers for standard vehicle maneuvers. This data is proprietary and cannot be shared in this report.

Additional validation of the vehicle model was conducted by measuring the roll rate, yaw rate for corkscrew and SAEJ2114 tests conducted on the target vehicle.

Typical data used in the validation of this model is shown below.

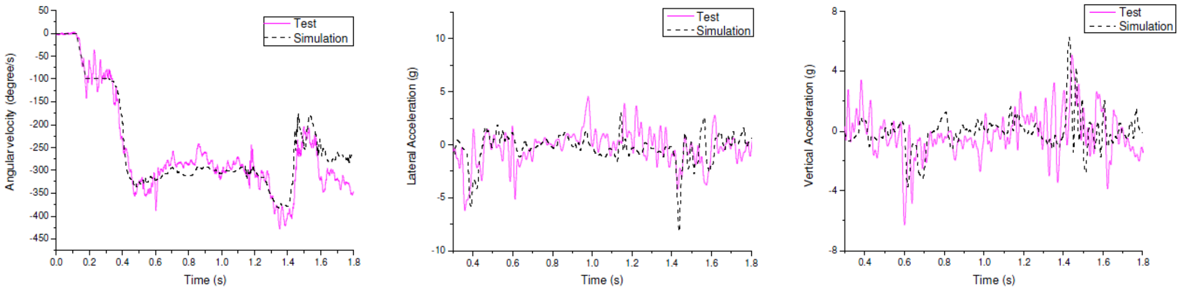


Figure 4: Validation Data for SAEJ2114 Roll Over Event – Typical Data

Soil Modeling

LS-DYNA has 23 different material models that provide the ability to simulate the behavior of soil in a structural analysis.

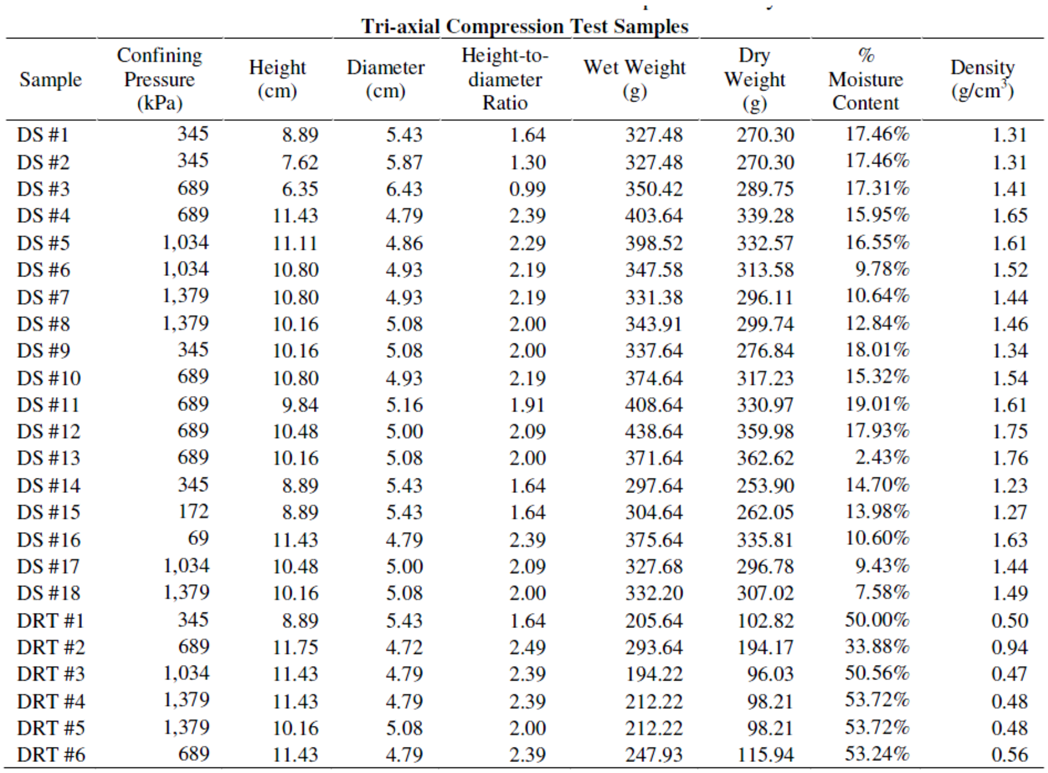
Soil behaviors under impact has been described by various studies, demonstrating that a MAT 5 _Soil_and_Foam, is both reliable for the prediction of soil compaction and has reasonable testing requirements in order to define the material properties.

The MAT 5 model describes a pressure dependent shear strength envelope or yield function. This material has the option to use an unloading curve to more accurately define the material behavior.

MAT 5 requires the user provide: *Density, Shear Modulus, Bulk Modulus for Unloading, Pressure Cutoff for Tensile Fracture, Yield Function* (a_0, a_1, a_2)*, Pressure-Volumetric Curve*

Three materials; a dry sand, a moist sand and a wet sand were identified as soil materials that would be studied and included in the Ditch and Soil Tripping simulations.

Soil testing was conducted for a variety of damp sand and damp dirt samples under tri-axial compression with confining pressures of 344.74, 689.48, 1,032.21 and 1,378.95 kPa (50, 100, 150 and 200 psi respectively). Moisture content ranged from 2.4% to 53.7% and was the primary variable in the material samples.



Tri-axial Compression Test Samples

Sample	Confining Pressure (kPa)	Height (cm)	Diameter (cm)	Height-to-diameter Ratio	Wet Weight (g)	Dry Weight (g)	% Moisture Content	Density (g/cm^3)
DS #1	345	8.89	5.43	1.64	327.48	270.30	17.46%	1.31
DS #2	345	7.62	5.87	1.30	327.48	270.30	17.46%	1.31
DS #3	689	6.35	6.43	0.99	350.42	289.75	17.31%	1.41
DS #4	689	11.43	4.79	2.39	403.64	339.28	15.95%	1.65
DS #5	1,034	11.11	4.86	2.29	398.52	332.57	16.55%	1.61
DS #6	1,034	10.80	4.93	2.19	347.58	313.58	9.78%	1.52
DS #7	1,379	10.80	4.93	2.19	331.38	296.11	10.64%	1.44
DS #8	1,379	10.16	5.08	2.00	343.91	299.74	12.84%	1.46
DS #9	345	10.16	5.08	2.00	337.64	276.84	18.01%	1.34
DS #10	689	10.80	4.93	2.19	374.64	317.23	15.32%	1.54
DS #11	689	9.84	5.16	1.91	408.64	330.97	19.01%	1.61
DS #12	689	10.48	5.00	2.09	438.64	359.98	17.93%	1.75
DS #13	689	10.16	5.08	2.00	371.64	362.62	2.43%	1.76
DS #14	345	8.89	5.43	1.64	297.64	253.90	14.70%	1.23
DS #15	172	8.89	5.43	1.64	304.64	262.05	13.98%	1.27
DS #16	69	11.43	4.79	2.39	375.64	335.81	10.60%	1.63
DS #17	1,034	10.48	5.00	2.09	327.68	296.78	9.43%	1.44
DS #18	1,379	10.16	5.08	2.00	332.20	307.02	7.58%	1.49
DRT #1	345	8.89	5.43	1.64	205.64	102.82	50.00%	0.50
DRT #2	689	11.75	4.72	2.49	293.64	194.17	33.88%	0.94
DRT #3	1,034	11.43	4.79	2.39	194.22	96.03	50.56%	0.47
DRT #4	1,379	11.43	4.79	2.39	212.22	98.21	53.72%	0.48
DRT #5	1,379	10.16	5.08	2.00	212.22	98.21	53.72%	0.48
DRT #6	689	11.43	4.79	2.39	247.93	115.94	53.24%	0.56

Table 1: Material Test Samples for Tri-Axial Compression Tests

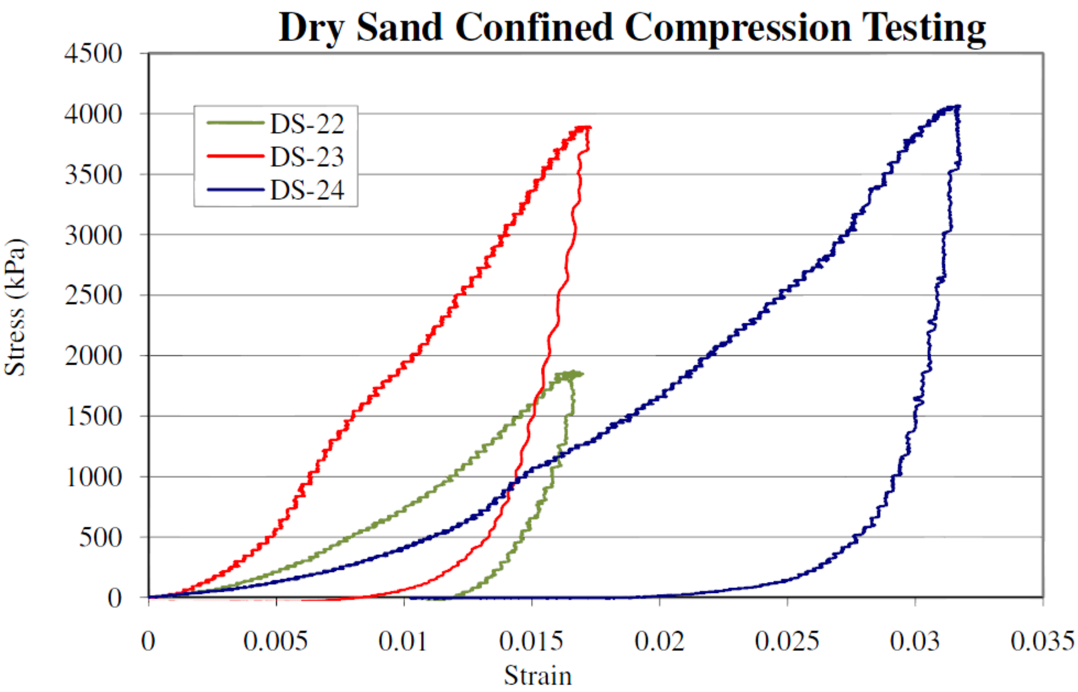


Figure 5: Stress vs. Strain Behavior of Low Moisture Sand Material Samples

Additionally, in order to find the remaining necessary material properties to complete the MAT_005 material card in LS-DYNA, constrained compression tests were also conducted. From the constrained compression tests it is be possible to determine the bulk modulus for unloading, *K*, as well as volumetric strain values and their corresponding pressures to allow unloading through optional volumetric crushing. From these values a shear modulus, *G*, may also be calculated and compared to data acquired using the unconstrained tri-axial compression tests to ensure test method independence. The graphs below contain a summary of the damp sand (DS) and damp dirt (DRT) samples tested.

Pressure (psi)	σ_{yield} (kPa)
50	7
100	1,663
150	1,750
200	1,750

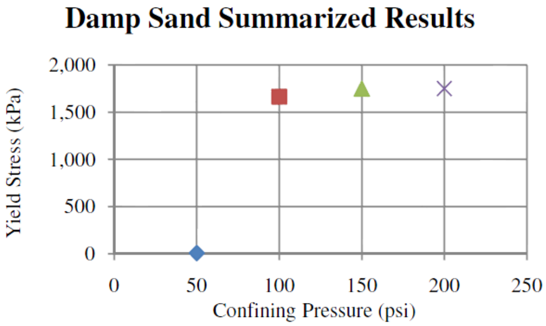


Figure 6: Summary of Sand Samples

MAT_5 Material Card

Further calculations are needed to determine the material property parameters from these curves, the theoretical background of which is presented in the LS-DYNA Keyword User’s Manual [5]. The parameters calculated for damp sand are presented below.

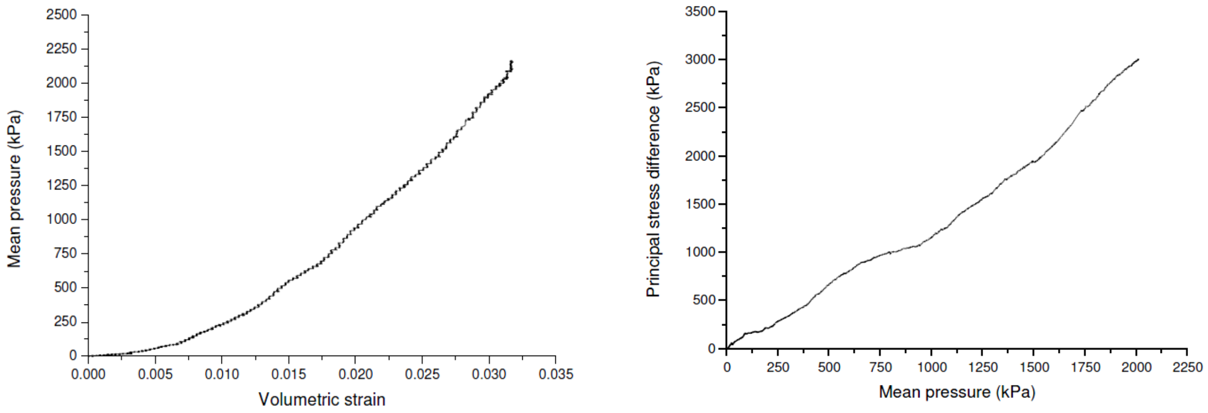


Figure 7: Mean Pressure vs. Volumetric Strain and Principal Stress vs. Mean Pressure for the DS-24 Material Sample

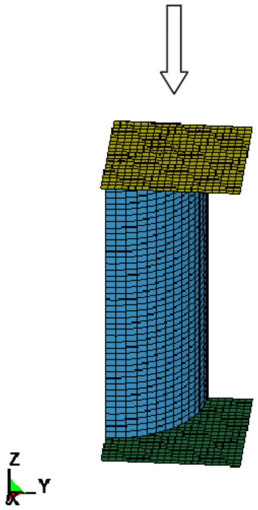
Based on the two curves, all of the parameters required are determined from the derivation described in the LS-DYNA User’s Manual and listed in the following Table.

Variable	Value	Units
G	11.8	MPa
BULK	107.5	MPa
A0	0	-
A1	0	-
A2	0.6	-
PC	0	MPa
VCR	0	-
EPS1	0	-
EPS2	-0.006	-
EPS3	-0.009	-
EPS4	-0.012	-
EPS5	-0.015	-
EPS6	-0.018	-
EPS7	-0.021	-
EPS8	-0.024	-
EPS9	-0.027	-
EPS10	-0.030	-
P1	0	kPa
P2	79.2	kPa
P3	194.4	kPa
P4	329.2	kPa
P5	548.5	kPa
P6	740.5	kPa
P7	1024.5	kPa
P8	1284.7	kPa
P9	1562.2	kPa
P10	1925.2	kPa

To validate these experimentally-determined values, a finite element model representing the test condition was developed. Rigid, shell plates confined the ends of the cylinder and nodal constraints confined the circumferential direction. The sand was modeled with 2.4 mm hexahedral solids with one-point integration.

To apply confining pressure, the top plate was prescribed a displacement time history measured during testing. Figure 8 shows the quarter cylinder model. Principles of symmetry were used to simplify the model.

Comparison of the simulation results with the experimental force-deflection curve is shown in Figure 9. The calculated material property parameters yield good agreement and provide validation of this sand model.



Quarter cylinder finite element model geometry and mesh

Figure 8: FE Model for Material Validation

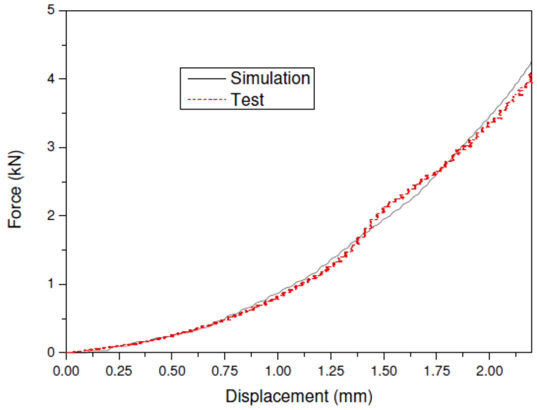


Figure 9: MAT5 Comparison to Testing Results

Implementation into Simulation Models:

The Ditch Maneuver was executed using the simplified vehicle model, approaching the ditch surface at an angle of 15 degrees with respect to the ditch edge.

As the vehicle enters the ditch, the maximum steering angle is applied, in order to attempt to steer the vehicle away from the ditch.

The vehicle travels through the ditch, and eventually rolls over. The soil material allows a compaction of the road under the tires, and allows the vehicle to slide down the incline, laterally.

The vehicle tires interact with the soil elements and are also required to interact with the rigid approach areas for both the Ditch and Soil Trip conditions.

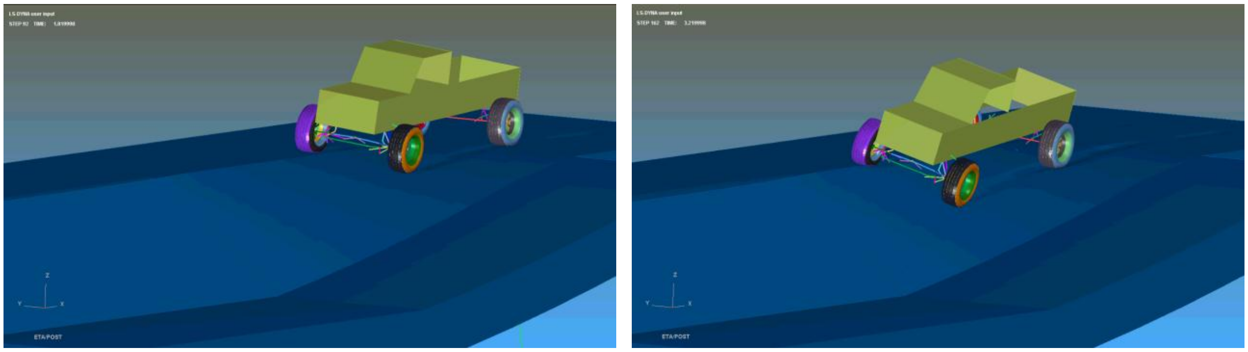
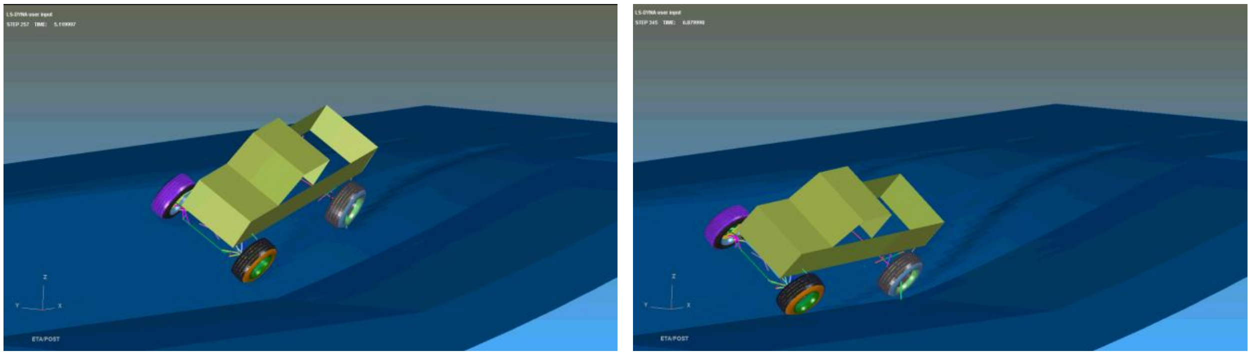


Figure 10a-d Ditch Maneuver Simulation Results



The Soil Trip Rollover Test simulation setup is shown in Figure 3. The parameters for this simulation are based on a test method developed by Berg, et al. (2007),[3] The simulation includes a rigid road surface with a single friction coefficient region and a deformable road soil/sand trap. The vehicle is given an initial velocity and driven toward the low-friction region of the road. As the vehicle passes over the low-friction region, the steering system is moved to maximum steering travel. As maximum steering travel is reached, the vehicle passes over a small region of high friction, inducing yaw before passing over another portion of low-friction road and into the deformable soil/sand trap.

Variables for these simulations include vehicle initial velocity, tire pressure (20-50psi), and may include soil/sand material properties. Contact definitions for Tire-to-Road Interaction and Vehicle Body-to-Road Interaction are applied.

The high-friction area makes use of the soil model described previously. Soil was modeled using solid elements. Model sensitivity to mesh size and though-thickness mesh density was investigated through a trial and error approach. It was found that elements should be no less than 1/3 the total distance of the thickness of the deformable section of the road, in order to achieve a reasonable deformation of the read. The approach area is a rigid surface 121 feet in length. The deformable section of the road was 102 feet in length.

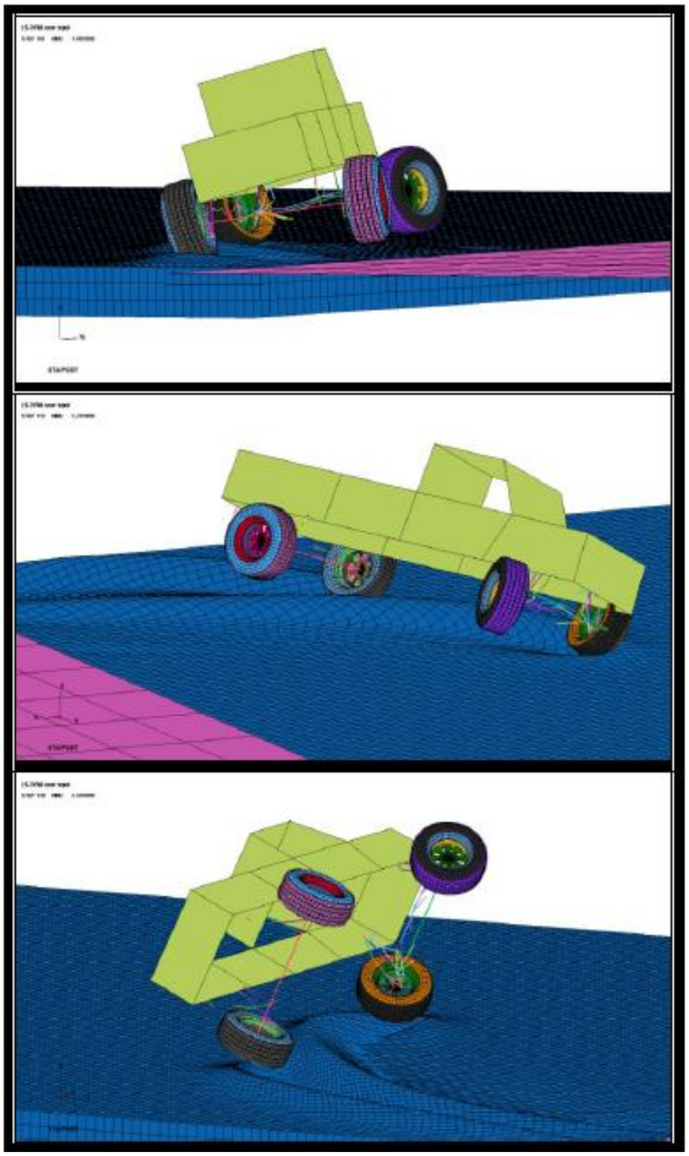


Figure 11: Soil Tripping Results

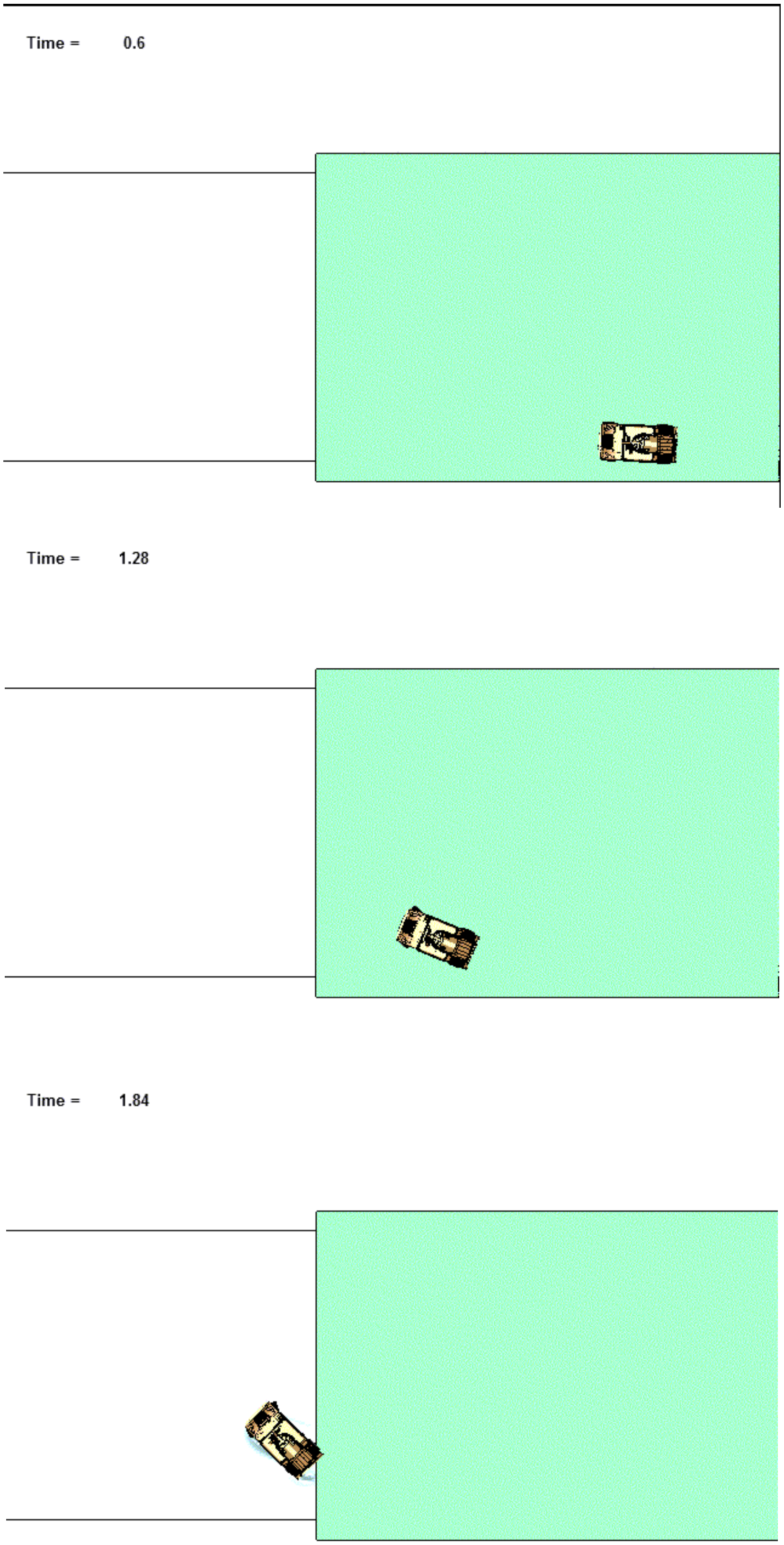
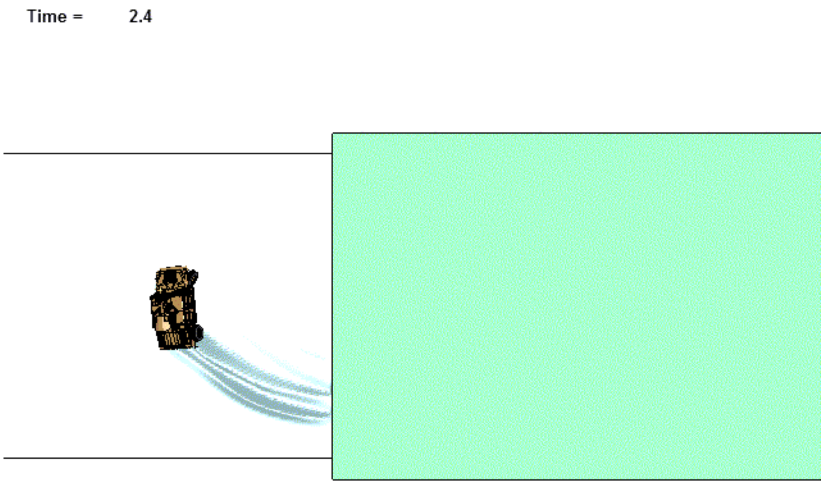
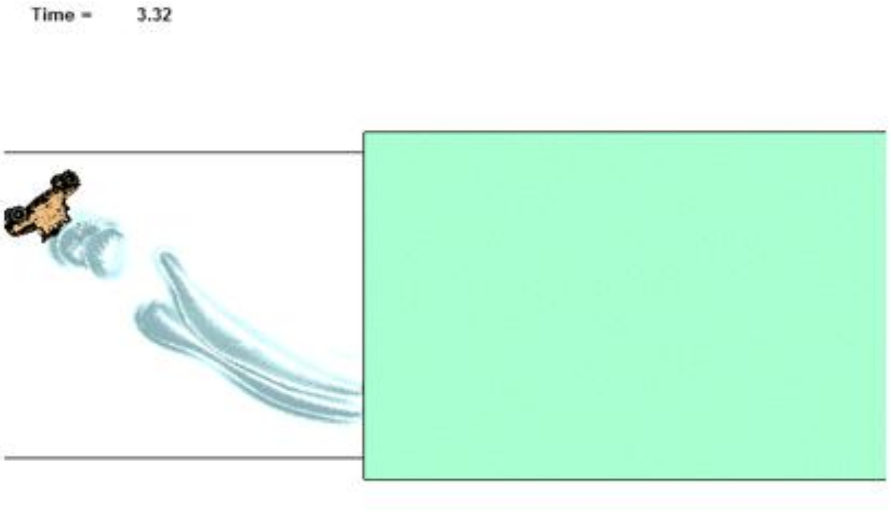


Figure 12a –e: Soil Tripping Results (Top View)





Conclusions:

A MAT 5 SOIL_AND_FOAM model was implemented to simulate the behavior of a vehicle interacting with a deformable road surface. The testing of soil samples provided the necessary data to compute the volumetric stress/strain behavior of the soil material.

The implementation of the material model into the system level rollover model allowed for a realistic simulation.

This technique should be implemented and further validation conducted to assure that the material behaves in a robust manner for various vehicle types, vehicle speeds and deformation modes.

References:

[1] NHTSA Traffic Safety Facts 2005, National Center for Statistics and Analysis, National Highway Traffic Safety Administration, DOT-HS-810-631

[2] Mitchel, et.al., DATA ANALYSIS METHODOLOGY AND OBSERVATIONS FROM ROLLOVER SENSOR DEVELOPMENT TESTS , Society of Automotive Engineers, Paper Number 07-0308, 2007.

[3] Berg, A., Rucker, P. and Kroninger, M. (2007) A realistic crash test setup to assess the real world performance of advanced rollover sensing systems‟ , *The 20th International Technical Conference on Enhanced Safety of Vehicle*, Lyon, France, 8–21 June, Paper No. 07-0362

[4]Chou, CC., Wagner, CD., Yang, K.H., King, AI, Hu, J., Hope, K. and Arepally, S (2008). A Review of Math-based CAE Tools for Rollover Simulations, Int. J. Vehicle safety, Vol. 3, No. 3, pp. 236-275

[5] LS-DYNA Version 971 User's Manual. Livermore Software Technology Corporation, 2010.

[6]. Erin M Williams, Joe E. Windham, Steven S. Graham, and Paul A. Reed, " Laboratory Characterization of Near-Surface Soils from the AAD Iraq Site" U.S. Army Engineer Research and Development Center: Geotechnical and Structures Laboratory, ERDC/GSL TR-09-23, July 2009

[7] Erin M Williams, Joe E. Windham, Steven S. Graham, and Paul A. Reed, " Laboratory Characterization of Near-Surface Soils from the AAD Iraq Site" U.S. Army Engineer Research and Development Center: Geotechnical and Structures Laboratory, ERDC/GSL TR-09-29, September 2009

[8] Erin M Williams, Joe E. Windham, Steven S. Graham, and Paul A. Reed, " Laboratory Characterization of Near-Surface Soils from the AAD Iraq Site" U.S. Army Engineer Research and Development Center: Geotechnical and Structures Laboratory, ERDC/GSL TR-09-32, September 2009