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REDUCED ORDER MODELING FOR RAPID SIMULATION OF BLAST EVENTS OF A MILITARY GROUND VEHICLE AND ITS OCCUPANTS

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ABSTRACT

Due to the severity of forces exerted during an IED blast, ground vehicles undergo multiple sub-events including local structural deformation of the floor, blast-off, free flight and slam-down (including rollover). Simulation of the entire blast event is computationally intensive due to the high fidelity level of the model and the long duration of the event. The purpose of this project was to develop a computationally-efficient, reduced order model to simulate the blast event in one single simulation, to be used for rapid evaluation of military ground vehicles. Models were developed using MADYMO's rigid body and finite element integration techniques. Different methodologies used in MADYMO simulations, their performance results and comparisons are presented. A Hybrid III 50th Percentile male ATD model, enhanced for use in vertical loading conditions, was developed and validated to drop tower tests.

INTRODUCTION

Improvised Explosive Devices (IEDs) pose a significant threat to military ground vehicles and soldiers in the field. Full system end-to-end [8-12] models as well as Reduced Order [2,13-15] Modeling and Simulation (M&S) methodologies are extensively used for the development of blast-worthy ground vehicles in the Army Acquisition process.

Due to the severity of forces exerted by a blast, ground vehicles may undergo multiple sub-events subsequent to IED explosion including local structural deformation of the floor, blast-off, free flight and slam-down. Depending on the location of the IED under the vehicle, the vehicle may also be subjected to rollover. To understand injuries sustained by soldiers under all of the various loading conditions, it is imperative to analyze the impact of each sub-event on soldier injuries. Using traditional finite element analysis techniques to evaluate an entire event is inefficient, as calculation times may exceed several days for one simulation of up to 300 milliseconds. Therefore, there is a need for a computationally efficient tool or methodology to simulate the entire blast event in faster turnaround simulation time.

The main objective of this project was to develop a computationally efficient reduced order simulation model capable of analyzing end-to-end performance of military ground vehicles subjected to blast loading. This model will be used to determine the effects of blast loading on soldier injuries, including during the blast-off, potential rollover and slam-down phases.

MADYMO [1] is a leading design and analysis software for occupant safety systems in the safety/crashworthiness industry. MADYMO is known for its fast and accurate calculation of injury risks and safety system performance, and for its accurate library of crash dummy and human body computer models.

METHODS, ASSUMPTIONS AND PROCEDURES

Execution of the project was divided into four major tasks including development of the vehicle model, integration of occupant and restraint systems, implementation of several blast loading methods, and analysis of vehicle and occupant results and comparison of models, outlined below.

Development of vehicle model

- Integrate a simplified generic ground vehicle model in MADYMO using a combination of rigid body and finite element techniques equivalent to the LS-Dyna [4,5] full finite element ground vehicle model.

- The integration shall consist of required geometric details of each component and sub-assembly of the vehicle, material properties of the structure and seats, and energy absorption characteristics of the seats.
- Select typical suspension and seat models, and integrate them into the MADYMO ground vehicle model developed in Task 1.

Integration of occupant and restraint systems

- Integrate a commercial 50th Percentile Hybrid III occupant model into the MADYMO ground vehicle model.
- Route a standard seatbelt around the occupant model and connect it to the vehicle anchor locations.

Implementation of various blast loading methods

- Develop and implement different loading methods in MADYMO to apply representative blast loading to the underbody of ground vehicle model.
- Loading methods identified are:
    a) Impulse based vertical loading into the vehicle
    b) Prescribed accelerative vertical motion
    c) Prescribed effective blast pressure map to the vehicle structure

Analysis of vehicle and occupant results and comparison of models

- Integrate the modified ground vehicle model with the loading method to develop a reduced order blast simulation model.
- Conduct an analysis to capture sub-events of floor deformation, vehicle rigid body response and occupant response during the blast-off phase, and vehicle/occupant response consisting of potential rollover during the slam-down phase.

DEVELOPMENT OF VEHICLE MODEL IN MADYMO

The first task was to develop a vehicle model in MADYMO based on an LS-Dyna full finite element model.

LS-Dyna FE hull model converted to MADYMO

A MADYMO model of the hull was built to capture the geometric details and material properties of the FE hull model. An LS-Dyna full finite element model of the hull structure was converted to MADYMO using the TASS LS-Dyna to MADYMO Converter. All nodes and elements, materials and properties were converted. The result of the conversion was a full FE model of the hull in MADYMO, shown in Figure 1.

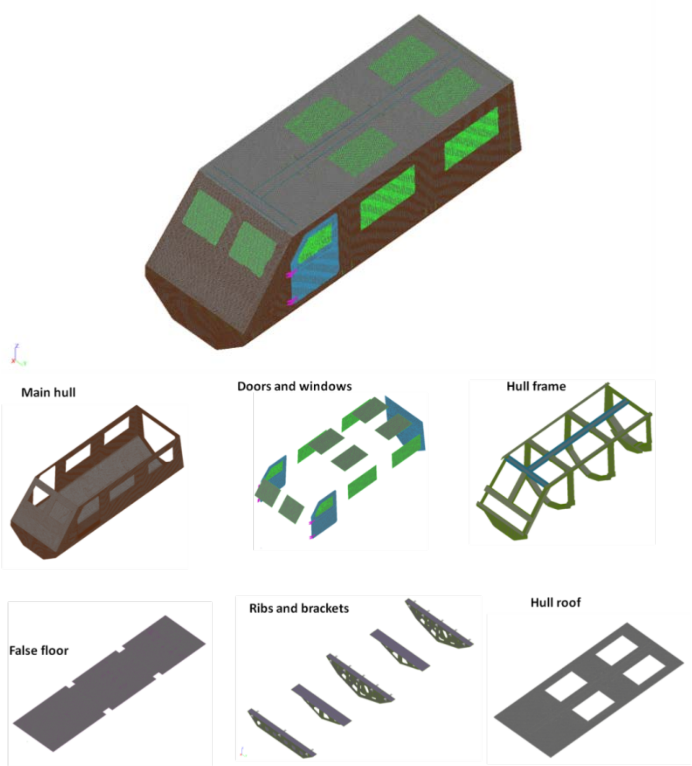


Figure 1: Hull full FE model in MADYMO

Simplified Models

Based on the full finite element vehicle model converted to MADYMO, three simplified models were created to run in MADYMO, using 1) planes, 2) rigid facets, and 3) a combination of rigid facets and deformable finite elements. The purpose of the plane vehicle model, shown in Figure 2, was to create an efficient model with reduced runtime which captures the important information from the detailed FE model for the motion of the vehicle during the blast-off and slam-down phases.

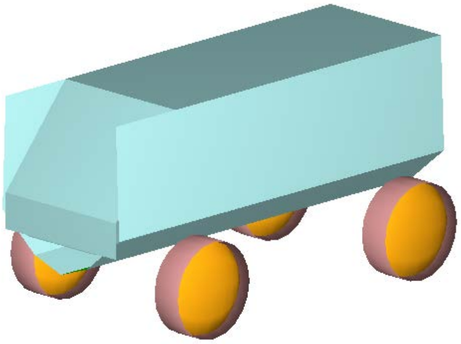


Figure 2: Plane Vehicle Model

A zero time MADYMO run of the finite element hull model calculated the mass, center of gravity and moments of inertia of the hull. These values were assigned to a vehicle rigid body in the MADYMO plane model. The basic hull geometry was defined by planes, rigidly attached to the vehicle body. The hull was defined using non-deformable null materials. The density, Young's modulus and Poisson's ratio were taken from the finite element model and assigned as contact properties for the multi-body model to be used for contact stiffness calculations.

The purpose of the facet vehicle model, shown in Figure 3, was to create an efficient model with reduced run time which captures the important information from the detailed FE model for the motion of the vehicle during the blast-off and slam-down phases and can be used for contacts of the vehicle with the ground on rollover.

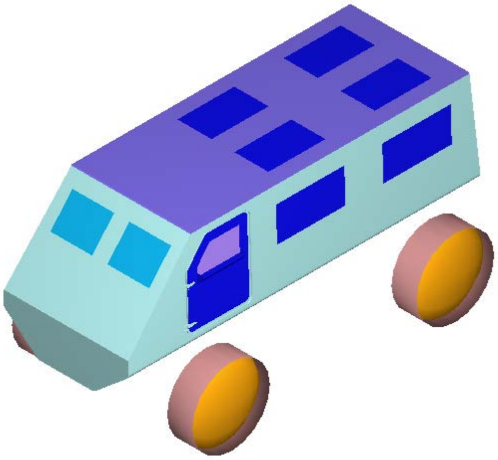


Figure 3: Facet Vehicle Model

Facets are used instead of planes to better represent the features of cab structure and allow more realistic contact of the vehicle with the ground plane due to possible rollover and slam-down.

The purpose of the combined facet and FE model was to create a model which would capture the deformation of the hull due to the blast pressure load, as well as the vehicle rigid body motion. To do this as efficiently as possible, a combination of facet and finite elements were used. The parts that deform most due to the blast force were made of deformable finite elements and the rest of the parts were made of rigid facet elements. To further reduce required CPU times, the deformable parts were switched to rigid after the simulation ran for 30 msec. The main hull was split into two parts – rigid walls and deformable floor, as shown in Figure 4.

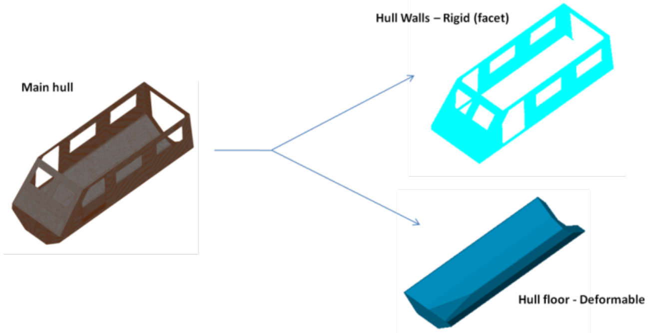


Figure 4: Main hull split into Rigid and Deformable Parts

The deformable parts of the FE model are then the hull floor, hull frame, floor, UB ribs and floor-rib brackets, as shown in Figure 5.

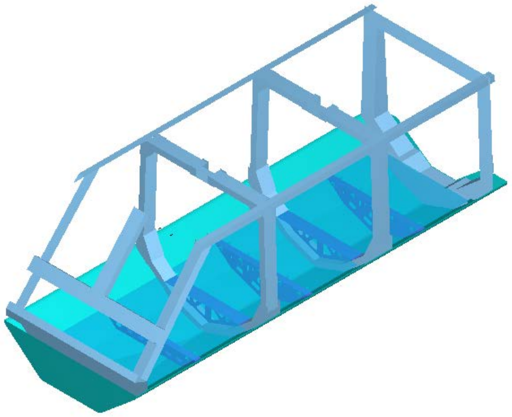


Figure 5: Deformable Parts of FE Model

Suspension and Stroking Seat Models

MADYMO models of the suspension, using joints, and the tires, using rigid bodies, ellipsoids and cylinders, were developed and integrated with the full vehicle model. Tire dimensions used in this model were (from Michelin 335/80R20): diameter – 40.7", tread width – 338 mm, and tire weight – 106 lb. At the center of each tire there are three joints. The support joint is a bracket joint with zero degrees of freedom which connects the support body to the vehicle body. The suspension joint is a translational joint with one degree of freedom, which is translation along the z-axis. This joint connects the suspension body to the support body. The wheel joint connects the tire body to the suspension body with a universal joint with two degrees of freedom, with rotation about the y-axis and bending about the x-axis. This is shown in Fig. 6.

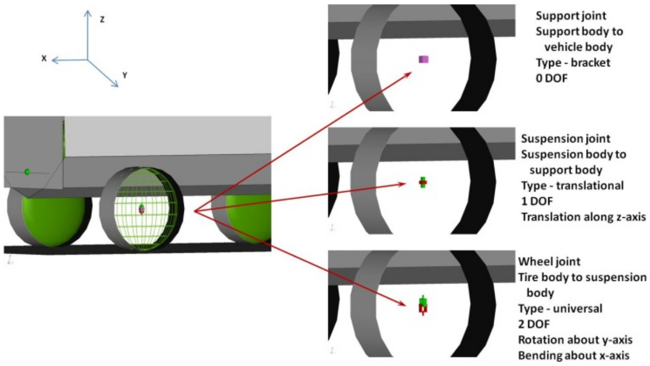


Figure 6: Suspension Joints

A suspension spring model which allows reasonable stroke of the suspension was used. The spring function is shown in Figure 7.

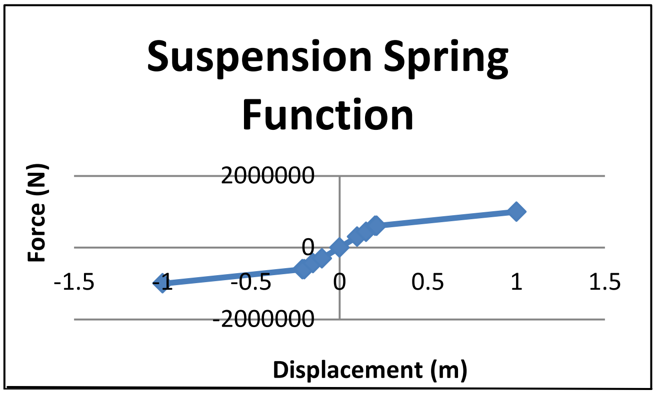


Figure 7: Suspension Spring Function

A joint restraint which prevents bending of the wheels about the y-axis was used. This can be modified by users of the model if some bending is desired. The function is shown in Figure 8.

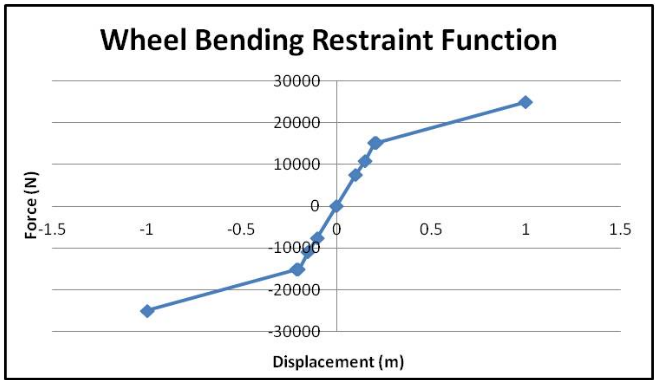


Figure 8: Wheel Bending Restraint Function

A generic model of a stroking seat was built, shown in Figure 9, with the energy absorbing function shown in Figure 10. Contact forces for interaction with the dummy are based on dummy -characteristics. Stroking of the seat is limited by contact of the seat bottom cushion ellipsoid to the seat stop plane. The position of the seat stop plane was adjusted to limit stroke to approximately 6 inches.

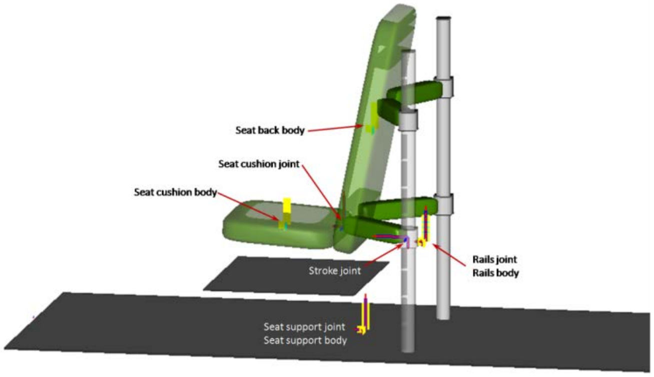


Figure 9: Stroking Seat Model

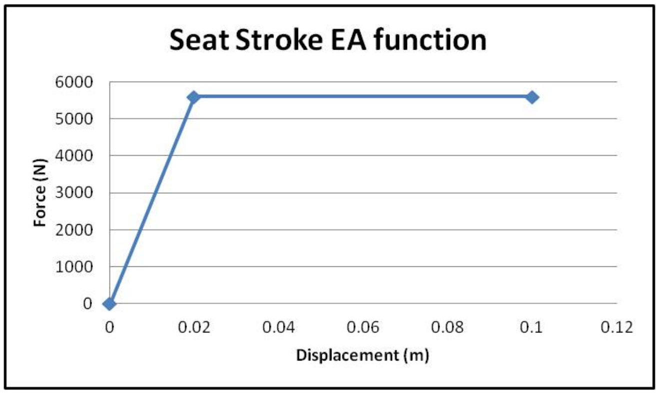


Figure 10: Stroking Seat EA Function

INTEGRATION OF OCCUPANT AND RESTRAINT SYSTEMS

A 50th percentile male dummy model was added to the MADYMO model. Occupant positioning data was not specified, so the dummy model was placed in a seat in the center front part of the vehicle. The position of the seat and the dummy can be adjusted when this information is available. A 4-point harness system including lap and shoulder belts and center buckle was positioned on the dummy, as shown in Figure 11.

Figure 11: Dummy and Harness System Setup

Seatbelts were modeled with 2-dimensional finite element parts and 1-dimensional multi-body parts, with a generic stiffness. The stiffness of the 1-D parts was calculated by multiplying the stiffness of the FE parts by the area of the cross-section of the belt material. The FE portions of the belt are in contact with the dummy, and the MB parts connect the ends of the FE belts to the buckle and the anchor points. The stiffness functions for FE and 1-D belts are shown in Figure 12 and Figure 13.

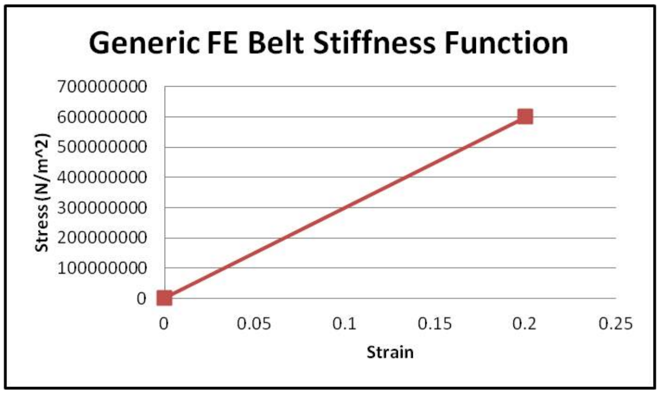


Figure 12: FE Belt Stress-Strain function

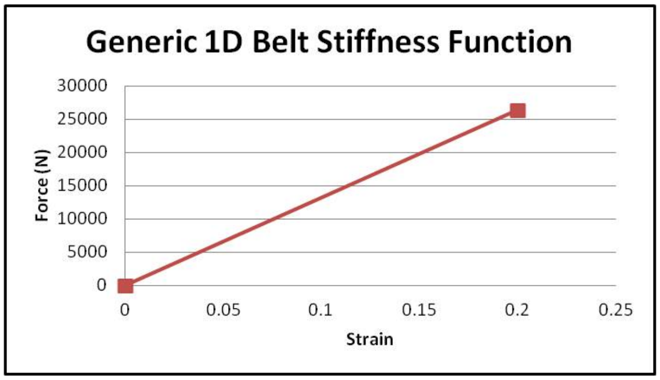


Figure 13: 1D Belt Force-Deflection function

Occupant response output was requested for the following: lower and upper tibia forces, head, chest and pelvis accelerations, lumbar spine load and upper neck load [7].

IMPLEMENTATION OF DIFFERENT BLAST LOADING METHODS

Several different methods were attempted to model the blast loading on the vehicle and the occupant in MADYMO.

Simple pulse based vertical loading

A vertical acceleration pulse [3] was applied to the vehicle rigid body. The sample pulse has a maximum acceleration of approximately 180 g's, as shown in Figure 14. When the model ran with this applied acceleration, the motion of the vehicle was not changed when the mass of the vehicle was changed. Another limitation of this loading method would be the need to include the effect of gravity in the prescribed motion pulse to generate the vehicle free flight and return to ground events.

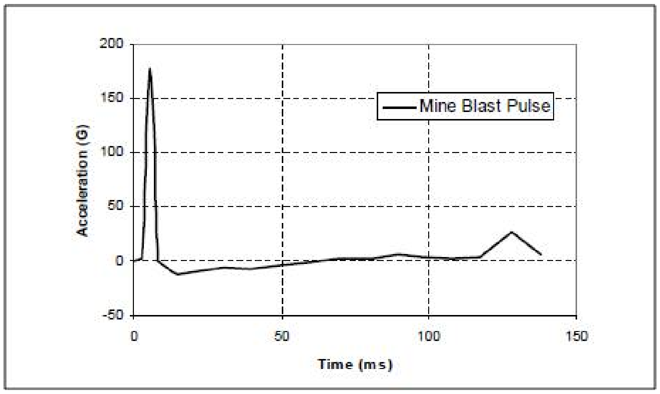


Figure 14: Mine Blast Acceleration Pulse

Due to the limitation of acceleration pulse based loading method, a force (or impulse) based loading method was developed. In this method, instead of prescribing the vehicle motion through acceleration pulse, a force profile (time-history) would be applied to the vehicle. For example, a force based on the 180 g acceleration pulse was generated by multiplying the acceleration by the mass of the vehicle, as shown in Figure 15. This type of loading was simulated by applying an Actuator Load in MADYMO.

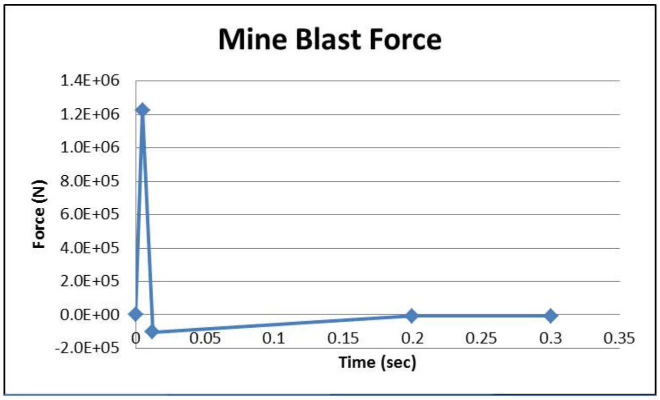


Figure 15: Mine Blast Force

An important advantage of this method is that the force can be applied to any specified location on the underbody of the vehicle. In this project, blast loading was applied to three different locations. In the first case, loading was applied to the center of gravity of the vehicle, causing blast-off and slam-down. Next a load was applied to the center of the hull side edge, causing blast-off, partial rollover and slam-down. Finally, a load was applied to the lower front corner of the vehicle, which also caused lift-off, partial roll-over and slam-down. These load application points and the results of the vehicle kinematics during the full event as well as the injury responses, with the load applied to the lower front corner of the vehicle, are shown in Figure 16a-c.

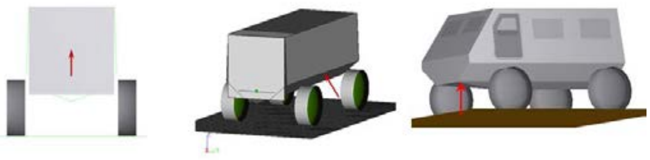


Figure 16a: Actuator Load Points of Application

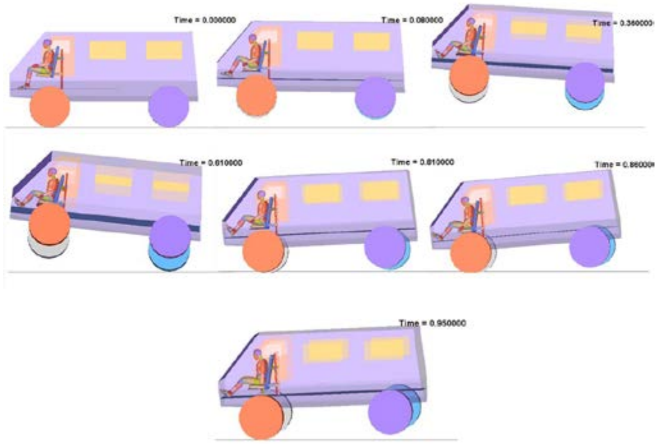


Figure 16b: Vehicle Kinematics during the Entire Blast Event

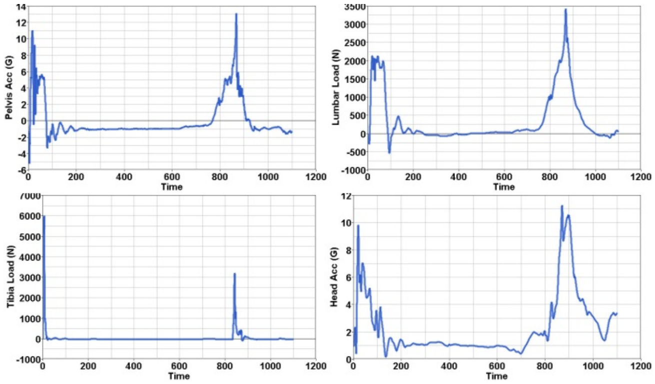


Figure 16c: Injury responses during the entire blast event, 0-100ms (blastoff), 800-1000ms (slam-down)

Prescribed accelerative vertical motion / PSM

Prescribed structural motion was used to model the deformation of the hull due to blast. An LS-Dyna model which included the ConWep function [6] was run, with a charge mass corresponding to a STANAG level threat, located approximately 0.26 meters below the hull of the vehicle, as shown in Figure 17.

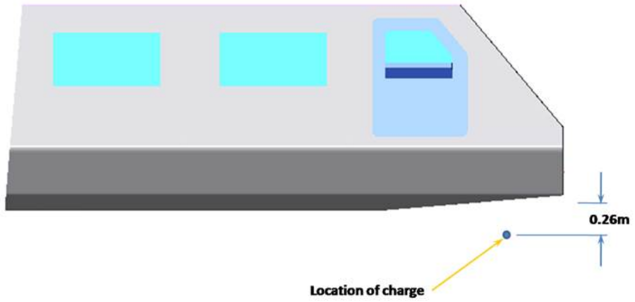


Figure 17: Charge Location

The blast load from ConWep caused deformation of the hull floor structure, underbody ribs, hull frame, floor and floor-rib brackets. The blast force interface pressure contours output by LS-Dyna are shown in Figure 18. The deformation of the hull floor and floor were captured in a prescribed structural motion (PSM) file to be input to MADYMO. The deformation of the hull floor in MADYMO is shown in Figure 19. PSM captures the deformation of the structure in the model, but it does not allow the deformed parts of the model to move with the rest of the vehicle. In other words, the PSM method when applied to partial structural content of the vehicle could represent the local deformations of the vehicle structure, however cannot transfer the vehicle global motion. Modifying the PSM method so that it could capture both the deformation and the gross motion of the vehicle, though possible, would be a complicated and time-consuming process. Due to its inability to capture global vehicle motion, at present, PSM is not considered to be a valid blast loading method.

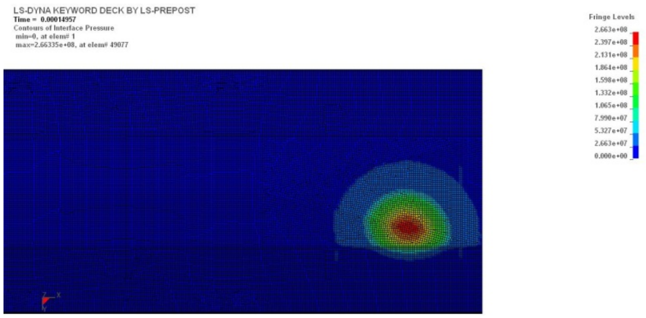


Figure 18: Contours of Interface Pressure from Blast

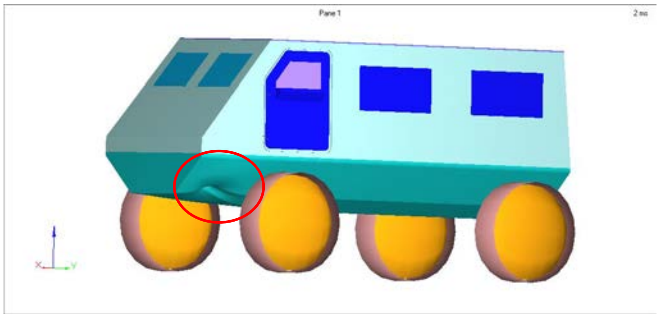


Figure 19: Deformation of Hull due to Blast

Blast pressure

In the pulse-based or actuator force based loading methods that were developed thus far, an aggregate load was applied to a single point on the vehicle. However, in order to capture local deformation of the hull more accurately along with global motion of the vehicle, a blast pressure based loading method was developed. In this method, basically a pressure profile from a blast event would be applied on the underbody hull surface. The pressure profiles can be generated using a number of Finite Element based simulations of vehicles including ConWep, Fluid Structure Interactions in LS-Dyna. For this project, the blast pressure profile was obtained from a ConWep simulation in LS-Dyna. In MADYMO, there are two ways to apply the pressure data on the structure: 1) through nodal forces or 2) through pressures on element faces. Hence, in this project both nodal forces and pressure on elements were investigated as a way to model the effects of the blast on vehicle hull deformation and vehicle rigid body motion. Initially, a simple plate model was used to test this loading method and also to determine the best way to apply pressure. A blast load was applied in LS-Dyna using ConWep, producing deformation of the plate and motion of the plate as a whole. Outputs from the LS-Dyna model included nodal forces (NODFOR) and blast pressure (BLSTFOR). In MADYMO, nodal forces can be modeled using LOAD.NODE cards, and pressure can be modeled using LOAD.PRES cards. Each were tried to see if either could be used to simulate the blast in MADYMO. Kinematics from the simulations using each of these methods was compared to the LS-Dyna model output. The nodal forces produced much less deformation and motion of the plate, while element pressures produced similar results to LS-Dyna. So, blast pressure on elements, as a pressure vs. time curve for each requested element, was used. Figure 20 shows a comparison of plate deformation and motion from LS-Dyna and MADYMO using pressure on the elements. Based on the plate simulation results, applying pressure on elements, as a pressure versus time curve, was selected for full vehicle simulation.

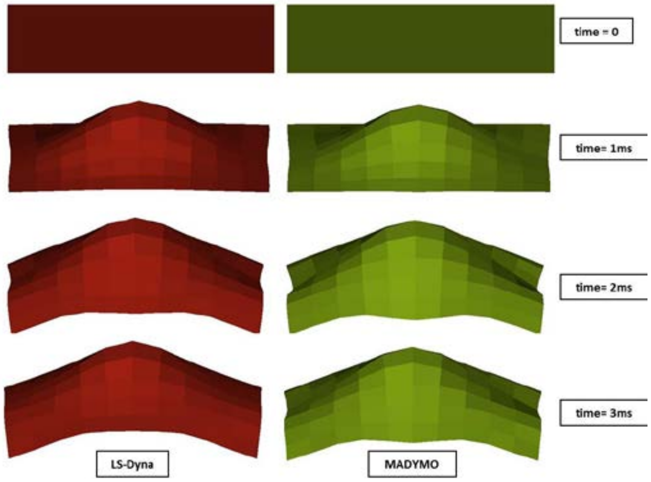
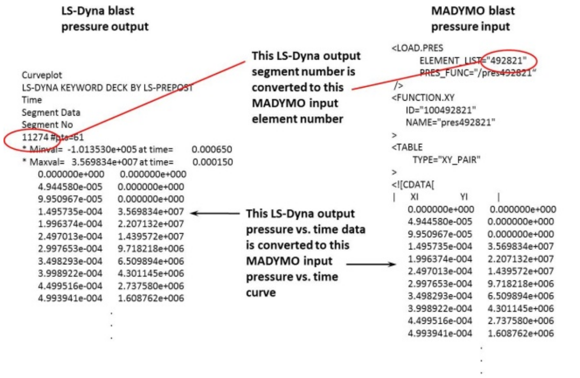


Figure 20: Plate Kinematics Comparison from LS-Dyna and MADYMO

A Python script was written to convert pressure vs. time curves from LS-DYNA output file BLSTFOR applied to segments, to MADYMO input format applied to the corresponding elements. Because LS-Dyna outputs pressure on segments rather than elements, the script had to find the elements in the input which correspond to the segments in the output and apply the output pressure to the corresponding elements, as shown in Figure 21. It was also noted during the script development that, depending on the grid size and volume of data to be processed, care should be taken to select only hull elements that are near the charge and would be subjected to non-negligible blast pressure loads. The script runs prohibitively long if too many elements are chosen on which to apply the pressure. If the time efficiency of the script can be improved in the future, more nodes/elements can be chosen for pressure application, and the deformation and motion of the vehicle can be modeled more precisely.



LS-Dyna blast pressure output

```
Curveplot
LS-DYNA KEYWORD DECK BY LS-PREPOST
Time
Segment Data
Segment No
11274 #pts=61
* Minval=  -1.013530e+005 at time=     0.000650
* Maxval=   3.569834e+007 at time=     0.000150
    0.000000e+000    0.000000e+000
    4.944580e-005    0.000000e+000
    9.950967e-005    0.000000e+000
    1.495735e-004    3.569834e+007
    1.996374e-004    2.207132e+007
    2.497013e-004    1.439572e+007
    2.997653e-004    9.718218e+006
    3.498293e-004    6.509894e+006
    3.998922e-004    4.301145e+006
    4.499516e-004    2.737580e+006
    4.993941e-004    1.608762e+006
                .
                .
                .
```

This LS-Dyna output segment number is converted to this MADYMO input element number

This LS-Dyna output pressure vs. time data is converted to this MADYMO input pressure vs. time curve

MADYMO blast pressure input

```
<LOAD.PRES
    ELEMENT_LIST="492821"
    PRES_FUNC="/pres492821"
/>
<FUNCTION.XY
   ID="100492821"
   NAME="pres492821"
>
<TABLE
    TYPE="XY_PAIR"
>
<![CDATA[
|    XI           YI         |
    0.000000e+000    0.000000e+000
    4.944580e-005    0.000000e+000
    9.950967e-005    0.000000e+000
    1.495735e-004    3.569834e+007
    1.996374e-004    2.207132e+007
    2.497013e-004    1.439572e+007
    2.997653e-004    9.718218e+006
    3.498293e-004    6.509894e+006
    3.998922e-004    4.301145e+006
    4.499516e-004    2.737580e+006
    4.993941e-004    1.608762e+006
                .
                .
                .
```

Figure 21: Script Example Input and Output

The script accomplishes its purpose with the following steps:

1. Reads nodal coordinate data from the original LS-Dyna input keyword file.
2. Reads nodal coordinate data from a keyword file based on the LS-Dyna pressure output.
3. Finds matching coordinates in the two files and changes the node numbers in the output file to the node numbers from the matching nodal coordinates in the input file.
4. Changes the node numbers in the element data of the output file to the node numbers with the matching coordinates.
5. Reads element data from the original LS-Dyna input file.
6. Finds elements in the input file with matching nodes in the output file and changes the elements numbers in the output file to the matching element numbers from the input file.
7. Changes the segment numbers on which the pressure is applied in the blast force pressure output file to the corresponding element numbers from the input file.
8. Outputs the element pressure vs. time curves for the correct elements in MADYMO format.

This process is illustrated in the flowchart in Figure 22.

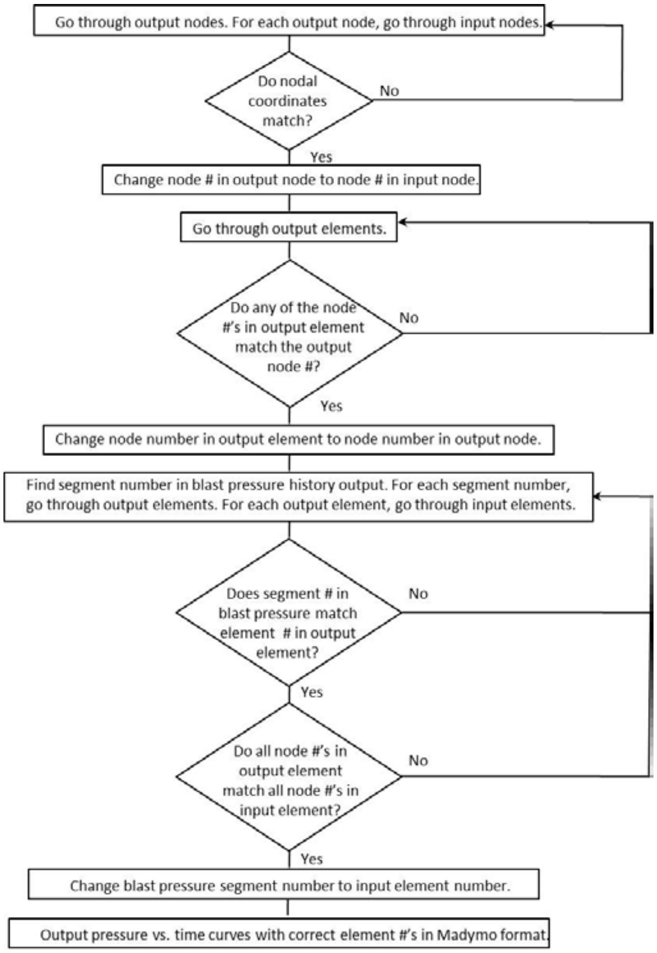
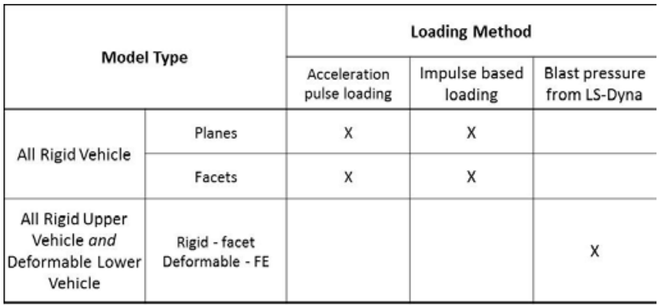


Figure 22: Script Flowchart

The pressure vs. time curves resulting from the script were used as input to MADYMO with an include file.

ANALYSIS AND COMPARISON OF SIMULATION RESULTS

In this work, three different vehicle model types were developed and were integrated with three different loading methods for reduced order simulation of full blast events. Table 1 shows the various vehicle models and applicable blast loading methods. Due to the limitation of pulse methods, only impulse based loading is included in discussions hereafter.



Model Type		Loading Method		
		Acceleration pulse loading	Impulse based loading	Blast pressure from LS-Dyna
All Rigid Vehicle	Planes	X	X	
	Facets	X	X	
All Rigid Upper Vehicle *and* Deformable Lower Vehicle	Rigid - facet Deformable - FE			X

Table 1: MADYMO Models

Model 1: Plane model with impulse based loading

The first model used planes to model the vehicle structure, and used actuator load to model the blast load. This model was used to model blast-off and slam-down when the load was applied to the center of gravity of the vehicle. A second load application point with this model, at the center side of the vehicle, was used to model blast-off, partial roll-over and slam-down.

Model 2: Facet model with impulse based loading

This model used rigid facet elements to model the vehicle structure, and used actuator load to model the blast load. This model was used to model blast-off, slam-down and partial roll-over. Facets were used in this case instead of planes in order to model the potential contact of the vehicle walls to the ground.

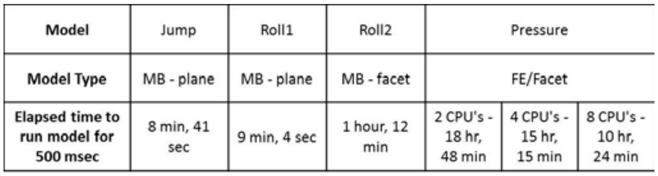
Model 3: FE/Facet model with blast pressure loading

The third model used rigid facet elements to model the upper vehicle structure and deformable finite elements to model the lower vehicle structure. The vehicle hull floor, floor, UB ribs, hull frame and floor-rib brackets were deformable for the first 30msec of the MADYMO simulation. After 30 msec, when the deformation is complete, a switch was used to turn the deformable parts to rigid, to reduce computation time. The load was modeled using blast pressure applied to elements, using LOAD.PRES in MADYMO.

As a check on the validity of the multi-body models, load case 3 was applied to both the plane model and the facet model to determine if there would be any difference in the results. The results for both simulations were the same.

Model evaluation/comparison

A comparison of run times for all of the models is shown in Table 2. All models were run on 2 CPU’s on Linux Cetos 6.X. The FE/facet model was also run using 4 CPU’s and 8 CPU’s to determine the speed-up possible with more CPU’s. A 19% speed-up was obtained by using 4 CPU’s, and a 45% speed-up was obtained by using 8 CPU’s.



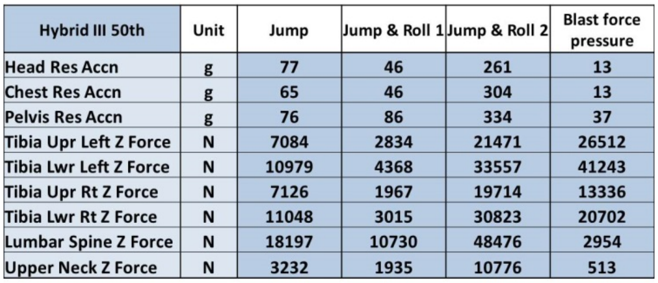
Model	Jump	Roll1	Roll2	Pressure		
Model Type	MB - plane	MB - plane	MB - facet	FE/Facet		
Elapsed time to run model for 500 msec	8 min, 41 sec	9 min, 4 sec	1 hour, 12 min	2 CPU's - 18 hr, 48 min	4 CPU's - 15 hr, 15 min	8 CPU's - 10 hr, 24 min

Table 2: CPU Time Comparison

The MADYMO rigid body models provide quick run times, and work well for modeling the overall vehicle motion. However, they cannot simulate the deformation of the hull and floor due to the blast load. The occupant response from these models does not include the effects of the contact of the deforming floor with the occupant’s feet. Occupant injuries are due only to the global acceleration of the vehicle and contacts of the dummy with vehicle interior surfaces, seat and harness system due to the motion of the vehicle.

The finite element/facet model has longer run times, but can be used to model both deformation of the vehicle hull structure and gross vehicle motion. Occupant injuries in this model include the effect of the floor deformation on the tibia loading as well as the effect of vehicle acceleration and interior contacts.

Occupant responses for different models and blast loadings are shown in Table 3. These responses are based on generic seat properties and assumed dummy position, which can be modified for different vehicle configurations. These occupant injury numbers can be used to show trends for the various models. For example, for the blast pressure model with the given charge mass, the head, chest and pelvis accelerations are relatively low. The tibia forces are high due to the deformation of the floor, which contacts the feet, applying force. On the other hand, for the second jump and roll model, which simulates blast-off, partial rollover and slam-down, the head, chest and pelvis accelerations are high due to the acceleration of the vehicle.



Hybrid III 50th	Unit	Jump	Jump & Roll 1	Jump & Roll 2	Blast force pressure
Head Res Accn	**g**	**77**	**46**	**261**	**13**
Chest Res Accn	**g**	**65**	**46**	**304**	**13**
Pelvis Res Accn	**g**	**76**	**86**	**334**	**37**
Tibia Upr Left Z Force	**N**	**7084**	**2834**	**21471**	**26512**
Tibia Lwr Left Z Force	**N**	**10979**	**4368**	**33557**	**41243**
Tibia Upr Rt Z Force	**N**	**7126**	**1967**	**19714**	**13336**
Tibia Lwr Rt Z Force	**N**	**11048**	**3015**	**30823**	**20702**
Lumbar Spine Z Force	**N**	**18197**	**10730**	**48476**	**2954**
Upper Neck Z Force	**N**	**3232**	**1935**	**10776**	**513**

Table 3: Preliminary Injury Results

Kinematic Comparison between MADYMO and LS-Dyna models

An LS-Dyna model with ConWep blast force applied to all segments of the hull floor and a MADYMO model with PSM (prescribed structural motion) for all nodes of the vehicle were both run for 50 msec. Then deformation of the hull and motion of the vehicle were compared. Applying PSM to all nodes in the MADYMO model produced the same kinematics of the vehicle, both for deformation and motion, as in the LS-Dyna model, as shown in Figure 25. However, extracting structural motion of all the finite element nodes in the vehicle and importing is neither feasible nor valid as the entire finite element part of the MADYMO model will behave as a rigid body at any instant. Furthermore, PSM needs to be input for the entire simulation event, blast-off to slam-down, which means the LS-Dyna full system simulation also needs to be run for the entire event.

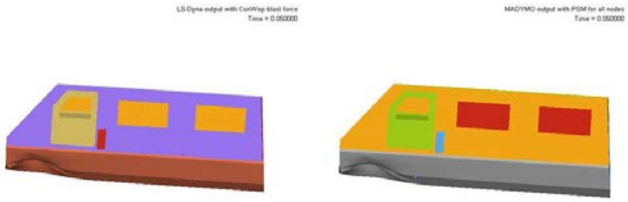


Figure 25: Kinematics at 50msec for LS-Dyna Output with ConWep Blast Force, and MAYDMO Output with PSM for all Nodes

An LS-Dyna model with ConWep blast force applied to some segments in the hull floor and a MADYMO model with pressure from script applied to the same elements were both run for 50 msec. Again, deformation of the hull and motion of the vehicle were compared. The MADYMO model with pressure input produced the same kinematics of the vehicle, both for deformation and motion, as in the LS-Dyna model, as shown in Figure 26.

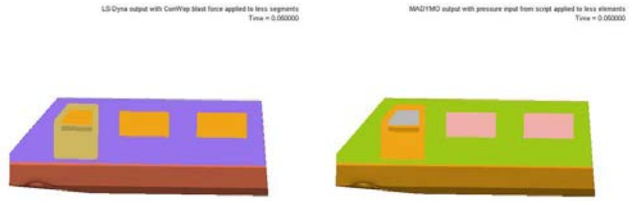


Figure 26: LS-Dyna Output with ConWep Blast Force applied to Fewer Segments, and MADYMO Output with Pressure from Script applied to Fewer Elements

The deformation and jump of the vehicle are less in the models where pressure is applied to fewer elements than in the models where the force or pressure is applied to more segments/elements. Less segments/elements were chosen for use with the script which produces the pressure input for MADYMO because of time limitations of running the script.

Standard MADYMO anthropomorphic test device (ATD) models originally developed and validated for frontal crash conditions were used in this project. At the same time, an enhanced Hybrid III 50th percentile male ATD model has been developed in a different project to improve correlation of injury results to tests of vertical loading conditions. By including the modified ATD model in the reduced order ground vehicle model, the prediction accuracy of the ATD injury results is expected to be higher. Multi-body models of Personnel Protection Equipment, vest and helmet, have also been developed. Results of studies using the enhanced ATD and PPE will be the focus of future paper.

CONCLUSIONS

Three models with varying degrees of complexity and different loading methods were built in MADYMO. The simplest model, using planes, can be used to capture sub-events of vehicle rigid body response and occupant response during blast-off and slam-down. The occupant response captured by this model is due to acceleration of the vehicle and occupant contact with vehicle interior structures, and seat and restraint systems. The slightly more complex facet model can do the same things, and add potential partial or full rollover response of vehicle and occupant. Forces due to contact of the vehicle with the ground upon rollover can be captured. The rigid body models run very quickly, with CPU times of less than 15 minutes for the plane models and less than 2 hours for the facet model to run a 500msec simulation. The most complex model, using finite elements and facets, can be used to capture all sub-events, including hull floor and floor deformation and its effect on occupant response. Using at least 8 CPU's, this model will run in less than 12 hours for the entire event from blast off to slam down.

Depending on whether hull and floor deformation and vehicle rollover are critical to an analysis, and how much time is available for the analysis, the MADYMO model to use should be chosen. For a given charge mass and location, the effect of changes to the hull on the vehicle response and occupant response can be evaluated. For different charge masses and locations, the effects on vehicle and occupant responses can be evaluated. Design iterations can be performed in a time-efficient manner using MADYMO.

Along with the chosen ground vehicle model, the enhanced Hybrid III ATD model can be used, as well as the multi-body PPE models.

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