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LATERAL ROLLOVER SIMULATION OF HIGH MOBILITY MULTIPURPOSE WHEELED VEHICLE (HMMWV) AND EFFECTIVENESS OF RESTRAINTS SYSTEMS ON OCCUPANT RESPONSES

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ABSTRACT

Non-combat tactical vehicle incidents such as rollover are one of the major causes of soldier injuries and deaths. Rollover incidents are usually associated with multiple impacts which result in complex interactions between occupants and hard structural components. Detailed information of occupant responses in such rollover incidents are lacking, and to design effective occupant protection system and safety restraints systems, understanding the vehicle to occupant interaction is essential. The performance of ground vehicles during a rollover event is an important safety and occupant protection requirement for military vehicles. Modeling and simulation are a very useful tool in study and investigation of vehicle rollover characteristics and countermeasure concepts.

The main goal of this research is to develop an M&S model of a HMMWV full vehicle system and evaluate the effectiveness of the different restraints systems in a lateral 25 mph rollover tests and its effect on occupant response such as head, chest, pelvic accelerations and neck forces and moments. This M&S analysis will aim to correlate to the PM LTV and IMMI conducted lateral 25 mph rollover test with set of restraints systems and evaluate Analysis of Alternatives.

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1. INTRODUCTION

According to findings published by Government Accountability Office or GAO released in July 2021, it was found that 123 soldiers and Marines died in 3753 non-combat tactical vehicle incidents between 2010 and 2019. The report reveals that training inconsistencies and overconfidence contributed significantly to the loss of life & related injuries. The report also found that rollovers were by far the deadliest kind of accident. Despite being responsible for one-quarter of the accidents, they accounted for 63% of the deaths reviewed in this study (source military.com).

A 2017 study [1] in the Military Medicine journal reveals that reports of rollover fatalities involving the High-Mobility Multipurpose Wheeled Vehicle (HMMWV) increased between 2003 & 2005. This timeframe coincides with the military's HMMWV up-armoring program which made vehicles more capable of protecting their occupants from IED blasts & small arms fire. Unfortunately, the added weight of the vehicle armor destabilized the HMMWVs & altered their center of gravity, making them harder for drivers to control. The now-armored turret was especially troublesome because it made the vehicles top heavy and therefore more likely to rollover. If a rollover did occur, it was now much harder for troops to egress from the HMMWV due to additional weight of the doors from the bolted-on armor. The threat posed by IEDs may have been reduced, but now the rough terrain and poorly maintained roads of Iraq and Afghanistan had become a dangerous antagonist for troops attempting to negotiate steep inclines or unfamiliar routes.

The over-encumbered up-armored HMMWVs were a far cry from the vehicles in their original form, which were maneuverable in off-road conditions and not especially prone to rollovers thanks to their light weight and wide wheelbase. Indeed, according to statistics from a 2017 Military Medicine study [1], a greater proportion of the more severe class A and class B HMMWV accidents between 1991-2013 involved the up-armored M1114 variant of the vehicle, at 35 percent.

There are currently more than 5,000 older HMMWV's, also called legacy vehicles, in use on U.S. military bases. The military plans to continue operating them until the 2040s. The aging fleet of military vehicles is another issue that can put lives at risk. These HMMWVs typically are decades old and lack modern safety technology like anti-lock braking and electronic stability control systems, which are standard on all modern civilian vehicles. Retrofit of some of these technologies may not be feasible, but opportunities exist to improve the interior safety by incorporating smart restraints systems, stroking pretensioners and if possible, a stroking seat system to mitigate soldier's injuries.

The Army is pursuing materiel upgrades and retrofits to decrease ground vehicle mishaps. The Joint Light Tactical Vehicle will include cab structural requirements (crush resistance), five-point seat belts, an antilock brake system (ABS), electronic stability control (ESC), an automatic fire extinguishing system (AFES), front and rear driver display cameras, a driver visual enhancement system, and self-adjusting ride height and tire pressure. There will also be upgrades to all new HMMWVs, including improved door mechanisms, upgraded restraints and ABS/ESC retrofit kits. Legacy HMMWVs will be retrofitted with ABS/ESC. Finally, the Army is developing troop kits for cargo vehicles, providing restraints and rollover protection for Soldiers riding in the backs of trucks.

A rollover is a type of vehicle crash in which a vehicle tips over onto its side or roof. Types of rollovers can be classified into two categories: untipped and tripped. Untipped rollovers are relatively rare events resulting from high lateral friction forces between the tires and road. Tripped rollovers are the result of lateral forces caused by the tire or wheel digging into the road or ground or from striking a curb or other obstacles. In both cases, the rollover event is preceded by the vehicle going into a maneuver, that has a relatively high lateral velocity [3].

Among all the vehicle rollover test procedures, the SAE J2114 dolly rollover test is the most widely used. However, it requires the test vehicle to be seated on a dolly with a 23° initial angle, which makes it difficult to test a vehicle over 5,000 kg without a dolly design change, and repeatability is often a concern. A new dynamic rollover test methodology was developed and implemented, that can be used for evaluating crashworthiness and occupant protection without requiring an initial vehicle angle. To do that, a custom cart was designed to carry the test vehicle laterally down a track. The cart incorporates two ramps under the test vehicle's trailing-side tires. In a test, the cart with the vehicle travels at the desired test speed and is stopped by a track-mounted curb. While the cart is being stopped by two honeycomb blocks, the vehicle slides laterally from the cart with the far-side wheels sliding up the ramps, which generates the desired lateral roll rate. The vehicle near-side wheels slide onto a high-friction surface, which generates an additional strong roll moment around the vehicle center of gravity. To design the testing procedure, computational simulations were conducted to select values for several testing parameters, including ramp height, ramp length, ground surface friction, vehicle traveling speed, cart height and stopping distance to ensure desired roll rate and number of quarter turns. Three physical tests using three armored military vehicles were conducted using the procedure. All tests resulted in the desired 5 to 8 quarter-turns of the vehicle, and the instrumented tests showed repeatable initial roll rates. The tests demonstrated that the newly designed rollover procedure is suitable for vehicles that are generally too large/heavy for other dynamic rollover methods and may also be useful for lighter vehicles when a well-controlled, directly lateral roll is desired [2].

In 2021, GVSC-Analytics investigated a reduced order analysis of HMMWV rollover with CAPE fixture and compared with test results from IMMI [7]. Analysis and research presented in this paper is an M&S effort to correlate to an IMMI lateral 25 mph rollover event on a 26.4-degree ramp, with restraints systems insertion and evaluate analysis of alternative (AoA) restraints systems.

2. MOTIVATION FOR RESEARCH

Numerical simulation of military vehicle rollover events is very rare and even if there are, very few exist. This work is a collaborative effort between PM LTV, IMMI and GVSC Analytics group, to evaluate the effectiveness of different restraint systems on occupant responses. According to literature, there is so much statistical information available on occupant injuries (soldier) from rollover incidents, but not much valuable insight into the details of the injury mechanism. This research and study attempt to reduce the knowledge gap by focusing on occupant responses from different restraint systems and augment the statistical information in lateral rollover scenarios and other types of rollovers which is not covered in this study.

3. OBJECTIVE AND SCOPE

The main objective of this research and study, is to help parameterize the seatbelts and further evaluate the efficacy of the pre-tensioning. To evaluate this GVSC Analytics developed a comprehensive HMMWV vehicle and integrated with 4-point seat belts, dual pretensioners, and neck airbags. Occupant responses from these restraints systems were evaluated in a 25-mph lateral rollover test to understand the contribution of each of these restraints systems. One of the 25 mph lateral rollover tests from IMMI is available with all the necessary data to establish a correlation between test and developed M&S models. Successful development and evaluations of all the Analysis of alternatives (AoA) will be relevant to the ground vehicle development missions of the U.S. Army and its affiliates.

4. EXPERIMENTAL ROLLOVER TEST

IMMI had conducted a 25-mph lateral rollover test. Cart specifications and dimensions of the test fixture are shown in Figures 1 and 2. Trailing side and leading sides are coated with Teflon surface for easy slide. Loading ram is 26.4 degrees.

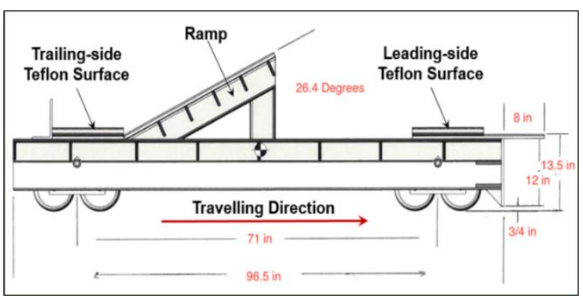

Figure 1: Cart dimensions

Test was conducted with vehicle lateral velocity of 25 mph and stopping distance of the cart at 200 mm. Cart will impact the 8-inch honeycomb attached to the curb with Hexcel blocks adjacent to the concrete ground surface. Figure 3 shows the curb ramp, Hexcel blocks and HMMWV vehicle.

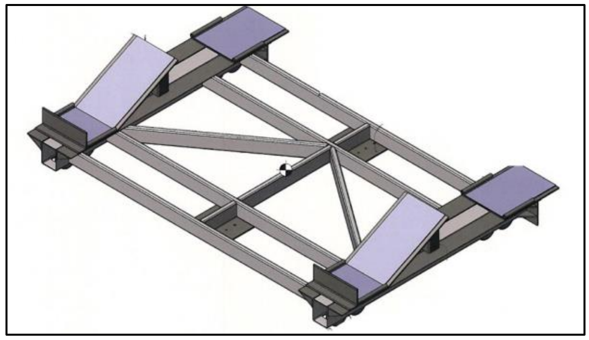

Figure 2: Cart with ramps

This results in vehicle to slide on the curb ramp and the tires to contact the raked concrete surface. This causes the vehicle roll rate of 200 degrees/second and vehicle roll 11 quarter turns for a total of 315 degrees. Vehicle will roll on the cart and drop. Figure 3 shows the curb ramp with HMMWV vehicle.

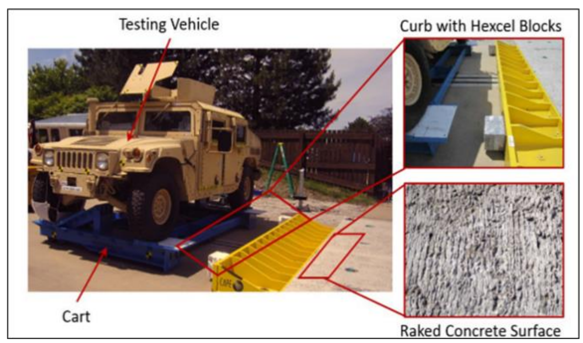

Figure 3: HMMWV on the cart

5. NUMERICAL MODEL

Numerical simulation models were developed for HMMWV and up weighted appropriately as needed to match the total weight.

5.1. Tire and suspension model

Tire is modelled as a simple AIRBAG MODEL with mass flow rate and temperature as inputs. Tires are of 37 x 12.5-inch radial tires modeled in this analysis. The models did not include any run flat devices & are mounted on to a 4 x 4 independent suspension and pressures at 75 Psi. Suspension rates used in the simulation is shown in Figure 4. Two sets of suspension rates are used in the simulation, one measured from the Vehicle Inertia Parameter Evaluation Rig, (VIPER) and another generic one which has higher rates. Inertia and suspension properties are the keys to vehicle handling and Military vehicles are often subject to tough driving conditions need to drive up, down, across hills and many different terrains. The simulation model of suspension and tire are shown in Figure 4.

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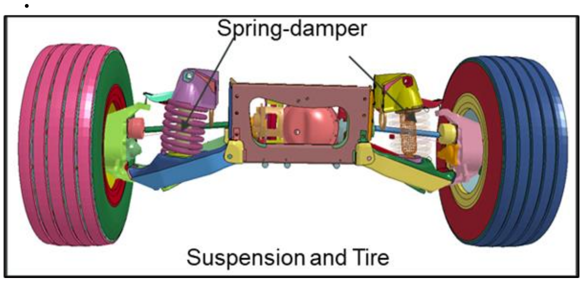

Figure 4: Suspension and tire models

Viper measurement was made for two sets of suspension rates, and a generic rate used in this simulation are shown in Figure 5.

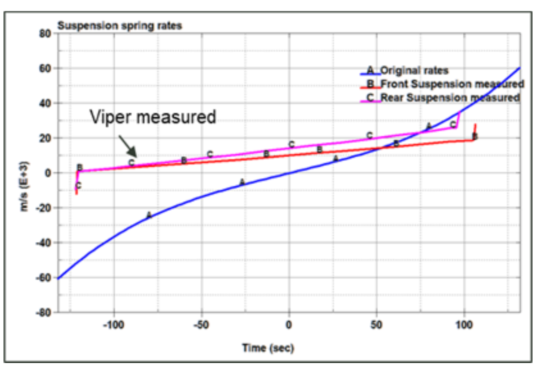

Figure 5: Suspension rates

5.2. Gunner protection kit

Gunner protection kit (GPK) model was not available during the time of the development, but later modeled (Figure 6) by measuring the overall geometry of the GPK. GPK and attachment turret ring mount several components and has bearings which are not modelled in the simulation. It is worth mentioning that this influences the yaw and pitch of the HMMWV during rollover events. Overall, the model is well represented with the GPK and turret assembly.

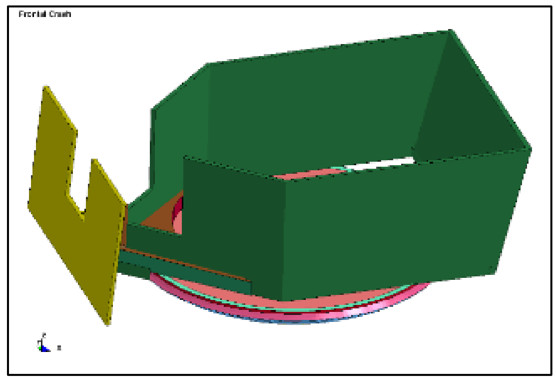

Figure 6: Gunner protection kit

5.3. 4-point seat belt model

HMMWV restraints models consists of lap and shoulder belts with automatic lock retractors. It does not have smart retractors or pretensioners. The 4-point seat belt used in this study is shown in Figure 7. Both inboard and outboard belt segments are attached to the buckle which has pretensioners. The shoulder belt is routed behind the seat back to a tube connected to the seat structure instead of the HMMWV vehicle structure. This will enable the seatbelt to move along with the seats. A hybrid approach with 1-dimensional (1D) MAT SEATBELT and a 2-dimensional (2D) MAT FABRIC was used in representing the 4-point seatbelts. Details of all the materials representations can be found in LS-DYNA user's manual [4].

5.4. Buckle pretensioner model

Pretensioners are well known safety devices for seat belt systems, used to rapidly remove belt slack in vehicle crash and rollover events. Pretensioners are one way pull in only whereas retractors are two-way pull-in and pull -out. In LS-DYNA there are several ways to represent the retractor- pretensioners, force-time or force-displacement are two most widely used. In this study IMMI provided the force-time (FT) curves for the pretensioners, hence FT based pretensioner model was utilized.

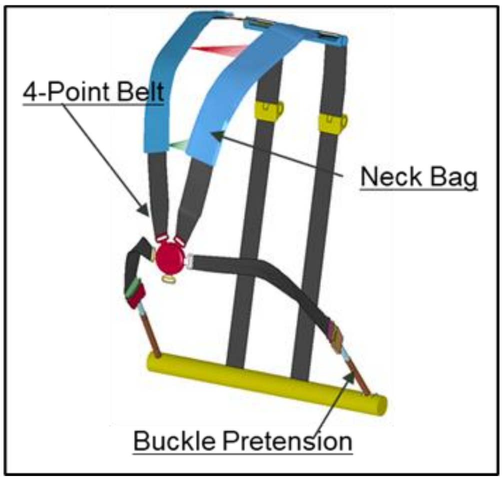

Figure 7: 4-point seat belt with neck airbag

Figure 8 shows the pretension load curve. Pretensioner has a very high pull in load of 15 kN at the onset of sensor triggering. This requires a proper modelling of the pretensioners and damping to avoid unwanted noises from the spring elements. In the simulation model proper mass was assigned to these pretensioner elements.

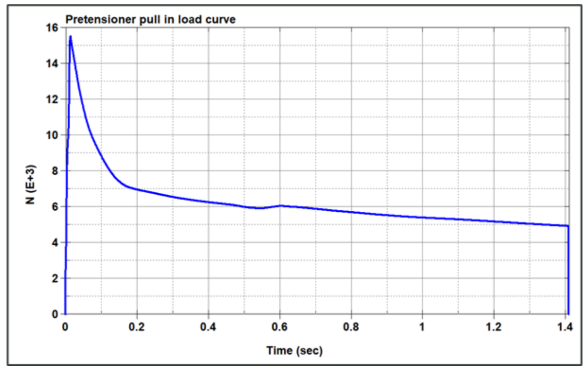

Figure 8: Pretensioner load curve

5.5. Neck airbag model

Airbags are widely used in modern automobiles as a vehicle safety system to protect occupants during vehicle crash. An airbag system consists typically of a fabric bag, a gas-generating inflator, crash sensors and control modules. The fabric bag could be sealed or non-sealed, and usually has vents for gas leaking to absorb impact energy. Modern vehicles might contain different airbag systems in various configurations, such as driver, passenger, side or curtain, knee bolster, inflatable seat belt, and pedestrian airbags. The proposed airbag in HMMWV rollover injury mitigation concept is an inflatable seat belt system, where the bag is folded and wrapped around the shoulder belts near the occupant neck. During the rollover events, the airbag is deployed around the neck, and would potentially support and protect occupant's neck. For a given bag design with bag volume, shape and fabric material, the bag inflating process is determined by the inflator output, including inflator nozzle gas mass flow rate, temperature, and gas thermal properties. The inflator output can be experimentally determined by using a tank test. On the other hand, if the inflator output is already given or assumed, the airbag deployment characteristics can be simulated with proper numerical models.

Figure 9 depicts the schematic of an airbag inflation process. With assumption that within the airbag all thermal properties of the gas or gaseous mixture are well mixed and uniformly distributed (i.e., a lumped parameter approach), and that the gas behaves as an ideal gas or gaseous mixture, the governing equations for the airbag inflation process can be summarized as below [5, 6]:

$$\begin{aligned} P_b &= P_o & \text{if} \quad V_b \le V_{bo} \\ P_b &= P_o + \frac{1}{c_s}\left(V_b / V_{bo} - 1 \right) & \text{if} \quad V_b \ge V_{bo} \end{aligned} \qquad (1)$$

$$m_b c_{v,b} \frac{dT_b}{dt} = \dot{m}_e \left(h_e - \sum e_{k,b} Y_{k,e}\right) - \left(\dot{m}_{vent} - \dot{m}_{leak}\right) \frac{R_u}{\overline{W}_b} T_b - P_b \dot{V}_b - Q$$

(2)

$$P_b V_b = \sum \frac{m_{k,b}}{W_k} R_u T_b \qquad (3)$$

$$\dot{V}_b = \frac{1}{P_b}\left(\sum \frac{\dot{m}_{k,b}}{W_k} R_u T_b + m_b \frac{R_u}{\overline{W}_b} \dot{T}_b \right) \qquad \text{if} \quad V_b \le V_{bo}$$

$$\dot{V}_b = \frac{1}{P_b}\left(\sum \frac{\dot{m}_{k,b}}{W_k} R_u T_b + m_b \frac{R_u}{\overline{W}_b} \dot{T}_b - \dot{P}_b V_b \right) \qquad \text{if} \quad V_b > V_{bo}$$

(4)

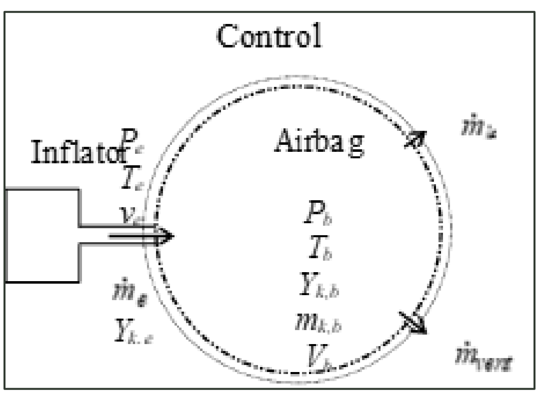

Figure 9: Airbag inflation process

Relation among bag pressure, volume and fabric material characteristics is given in Eq. 1 for a simple airbag model. Energy conservation is expressed in Eq. 2. Equation of state along with its derivative form are shown in Eqs. 3 and 4, respectively. In these equations, P is pressure, T is temperature, Y represents species mass fraction, and Q is the heat loss rate from gas to fabric or environment. Please note that here P, T, h and e are stagnation properties. For the airbag inflation process, the inflator exit nozzle mass flow rate and temperature are usually provided, and we can rearrange the above equations and integrate them to get time histories of bag pressure Pb, temperature Tb, bag volume Vb, etc.

For our HMMWV rollover injury mitigation concept, the preliminary inflator output requirement is simply that at the end of free bag deployment, the bag pressure should be about 50 kPa. With given belt airbag taut-volume Vbo=0.0145 m3, realistic fabric stretch factor cs = 1E-6 1/Pa, and inflator nozzle gas k = 1.29, cv = 1023.4 J/kg-K, we adjusted typical inflator nozzle mass flow and temperature curves and ran an in-house code to generate new inflator nozzle mass flow rate and temperature curves which satisfy the required 50 kPa free bag deployment. The resulted inflator curves, for bag pressure, temperature and volume in a simple bag model are shown in Figure 10 and Figure 11.

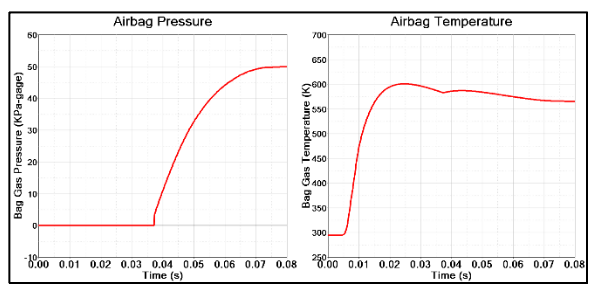

Figure 10: Airbag gas pressure and temperature

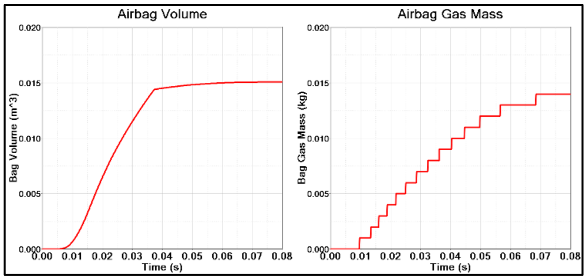

Figure 11: Airbag volume and mass

5.6. Pull down seat model.

Figure 12 shows the pull-down seat structure used in the test. Due to proprietary nature of the pull-down seat, geometry or the model was not available, but IMMI had provided with seat pull down, load time-history curve (Figure 13). To accommodate this, pull down seat, existing HMMWV seats had to be modified, by removing the existing seat structures. In simulation this pull-down seat mechanism is represented as two pneumatic piston cylinder type design with spring-damper as a stroking mechanism (Figure 14). Having two pneumatic piston-cylinders are not sufficient to avoid the shearing or wobbling of the seat during the rollover event, since the force to pull down is very high for the non-linear represented spring-dampers. Four more null piston-cylinders are integrated to the four corners of the seat with piston connected to the seat structure and the cylinder attached to the floor.

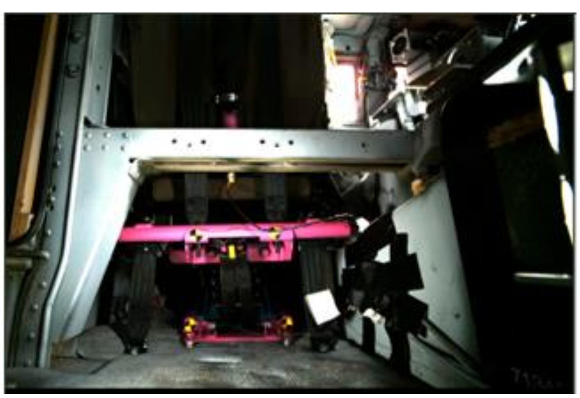

Figure 12: Pull down seat.

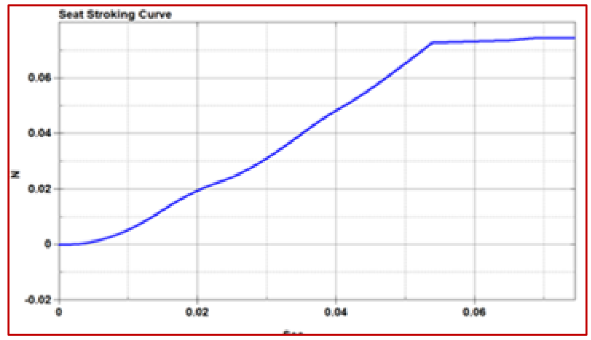

Figure 13: Pull down seat stroking load time history curve.

Figure 14: Pull down seat model.

5.7. Cart model

IMMI geometry and specifications were used in developing the cart, curb, and Hexcel block models (Figure 15), due to unavailability of CAD or meshed models. Few iterations were needed to establish the right stop distance by observing the roll angle and tire to ground contacts. Initial sets of analysis were run with tire to ground friction of 0.30 and optimized to 0.94.

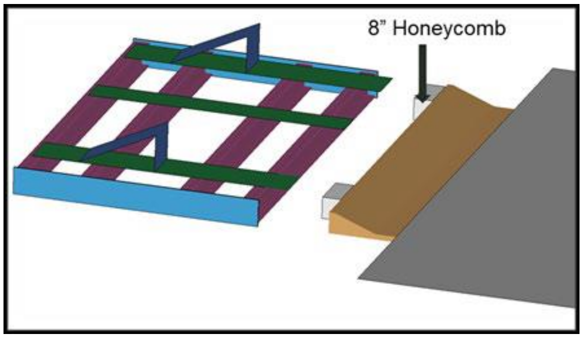

Figure 15: Numerical cart model

5.8. Anthropomorphic Test Dummy (ATD) models

Three different dummies with soldier gears were positioned in this HMMWV model. A 50th Driver, 95th Commander and a 50th Passenger rear. Soldier gears for the dummies were developed for blast simulations and are more generic in nature. It is possible that the soldier gears in the tests and simulations could differ. This may not affect the overall signature of the occupant responses but certainly influences the seat belt loading and some of the peak values. Figure 16 shows the 50th % driver position. Clearances between the head and the roof is very narrow as shown in Figure 17, 68 mm (~3") for 50th % driver and 20 mm (~1") for the 95th % Commander position. Initially, the Driver head slides along roof with foam padding and hence the load does not speak during the head contact with roof.

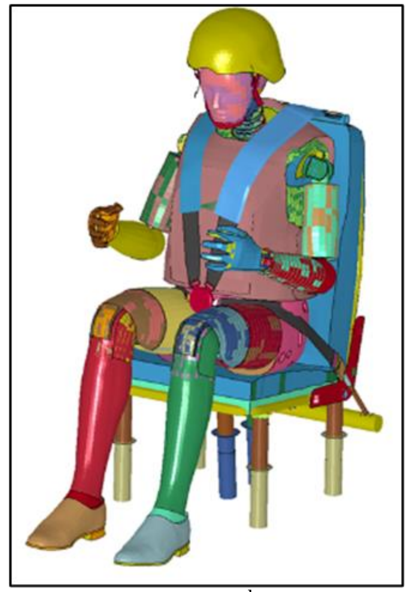

Figure 16: 50^{th} Driver

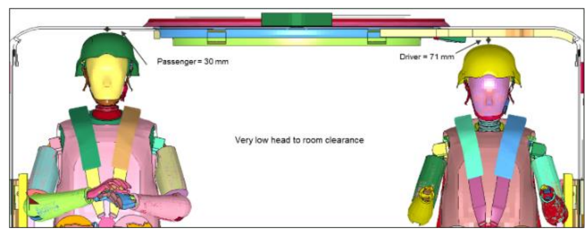

Figure 17: Head to roof clearance

5.9. Integrated HMMWV rollover model

Figure 18 shows the integrated HMMWV rollover model with all the subsystems in position. Dimensions and center of gravity of the simulated HMMWV is shown in the table 1.

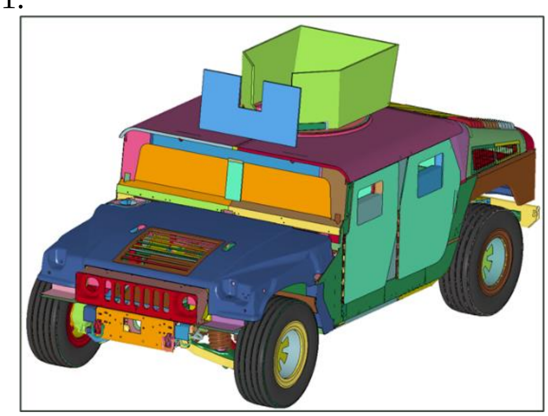

Figure 18: Integrated HMMWV model

Table 1: Dimensions and Center of Gravity

	Overall Dimension (m)
Length	4.76
Width	2.16
Height	1.83
Heigh with GPK	2.36
Wheelbase	3.3
Total Weight (kg)	5600
CG	**Location (m)**
L (from front axle)	1.791
W (from center line)	0.00346
H (ground)	0.961

6. SIMULATION METHOD

Numerical simulation of a fully loaded HMMWV with 3 ATD with soldier gears are rolled at 25 mph on the cart. Once cart hits the Hexcel honeycomb, the cart stops, and the vehicle continues to move laterally on the 26.4 degrees Kevlar ramp and rolls on the curbside on to raked concrete surface. Once the tire contacts the very high friction (0.94) concrete surface, the vehicle rolls and continues to move both laterally and with angular motion. Since there are many safety and restraints systems inserted in the model, understanding the influence of each of the restraints system is necessary. The analysis matrix is shown in Table 2.

Table 2: Analysis matrix

	Speed	**Pre-tensioners**	**Pull down seat**	**Neck Airbag**
Baseline	25 mph	NO	NO	NO
Run 1		YES	YES	NO
Run 2		YES	YES	50 kPa
Run 3		YES	YES	60 kPa
Run 4		YES	YES	70 kPa

The first set of analysis performed was with the 4-point enhanced seatbelt restraints (referred baseline in this document) without the pretensioners, seat pull down and the neck airbags. The second set of analysis performed was with only pretensioners activated. The next 3 sets are with the neck airbag inflators of varying capacities 50 kPa, 60 kPa and 70 kPa.

7. RESULTS AND ANALYSIS

Structural kinematics and occupant responses are summarized in detail for all the chosen matrix.

7.1. Structural responses

When the vehicle turns, the vehicle wants to go straight according to Newton's First Law, so the tires mut create a lateral centripetal force due to friction between the tires and the concrete surface. Lack of sufficient friction between the road and concrete surface will cause the vehicle to slide rather than roll. On the far side, (passenger) there exists the opposite centrifugal force which forces the vehicle upward and outward about the center of gravity of the vehicle. The vehicle has a center of gravity, plus any added mass such as occupants, in this case which has its own center of gravity will raise the overall CG of the vehicle. Figure 19 shows the forces acting on the vehicle.

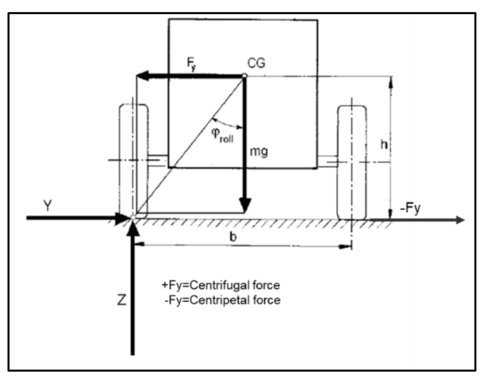

Figure 19: Forces on the vehicle

The first sets of analysis were performed with tire to ground friction of 0.30 and generic suspension rates. Lower friction resulted in roll angles of 120 deg/sec, 4 quarter turns of roll and the vehicle started to slide on the concrete surface, whereas the test shows 8 quarter turns in total and a roll rate of 220 deg/sec. Literature survey shows that concrete surface friction varies from 0.82 and higher. Tire to ground friction was increased from 0.30 to 0.94 in the next sets of analysis. Increasing the friction to 0.94 resulted in a roll rate of 218 deg/sec. very close to the test measurements. Numerical simulation was carried up to 3.5 seconds to get at least 8 quarter turns. Figure 20 shows the roll rates and Figure 21 roll angles.

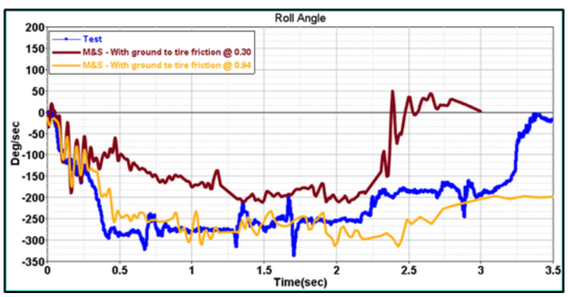

Figure 20: Roll rates

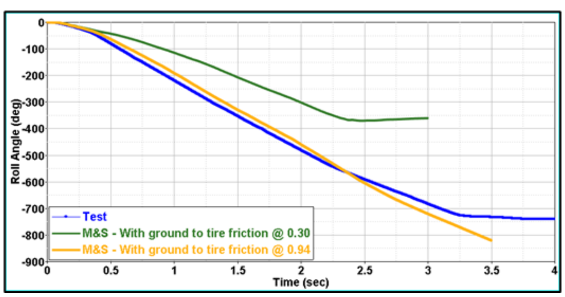

Figure 21: roll angles.

Vehicle and ground surface characteristics such as mass, tire and suspension rates, structural stiffness and road friction are the main influencers of vehicle kinematics of rollover. Initial impact conditions such as velocity, roll, yaw, and pitch rates dictate the outcomes of the rollover events such as number of quarter turns, deceleration rate and distance travelled.

Figure 22 (a & b) shows the simulated vehicle at different quarter turns compared against the test. Simulation result captures the test responses at every time stamp very closely. The suspension's kinematics in simulations do not match the test. This can be attributed to the 1D beam representations of Tie-rod and spring-dampers. Overall, the vehicle kinematics from numerical simulation correlates very well.

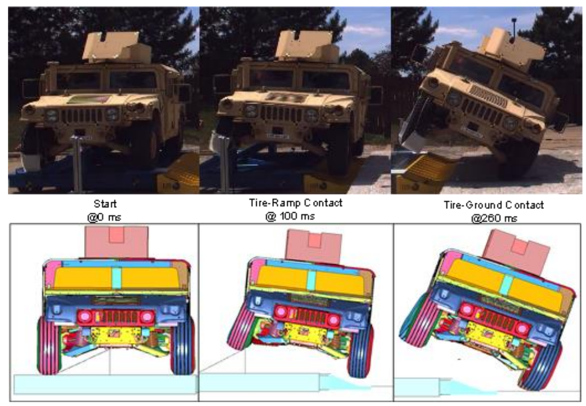

Figure 22 a: Vehicle Quarter Turns

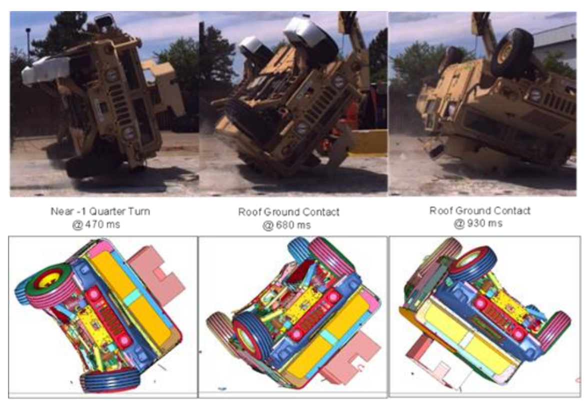

Figure 22 b: Vehicle Quarter Turns

7.2. Occupant response – Driver side

All the occupant responses are captured from the simulation & compared to that of the test responses. Few selected accelerations, forces and moments are presented here in this report. Figures 23, 24 & 25 shows the driver head resultant, chest resultant and pelvis resultant accelerations. Simulation responses are for baseline, with buckle pretensioner only, and the test response is with the airbag and a 50Kpa inflator. It is interesting to note that peak values from the baseline simulation with 4-point seatbelt responses are well below the test peaks. Since there is no spool out of seatbelts in this case, occupants are tied to the seat & rolls along with the vehicle resulting in lower chances of head contacting hard structural components. When the buckle pretensioner are fired with retractor spooling also shows similar lower responses. This tells us that having the occupant tied to the seat throughout the rollover event will mitigate higher forces & accelerations and limit contacting with hard structural components. Both the buckle pretensioner & seat pull-down sensors were triggered at about 95 deg/sec roll rate which corresponds to approximately 42 degrees at 450 milliseconds. Neck airbags are triggered 100 milliseconds after the pretensioner is triggered at 650 milliseconds.

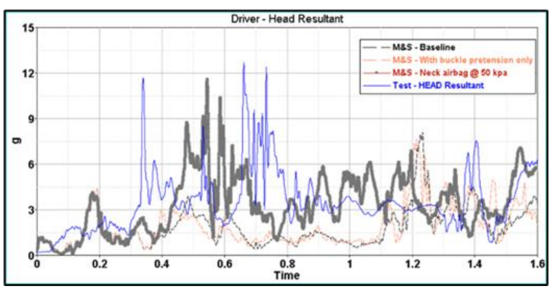

Figure 23: Driver head resultant g

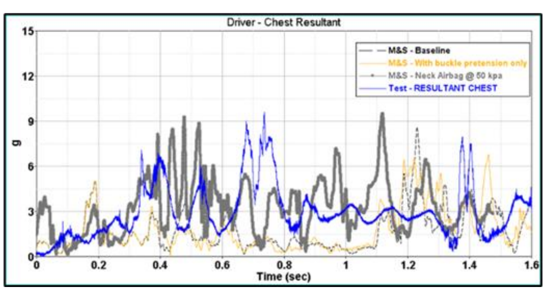

Figure 24: Driver chest resultant g

When the neck airbag is introduced into the seatbelt, all the head, chest and pelvis resultant accelerations show slightly improved responses over the baseline for 50 kPa inflator airbag. As the bag pressure is increased occupant responses tends to go higher. One of the main reasons for these higher accelerations is to do with non-permeable, non-venting bag results in a pressurized volume between the head-neck and the HMMWV head-roof structure. During the first quarter roll when the driver side structure is on the ground surface, inertial effects of occupant will impact the deployed airbag causing some of these accelerations and neck forces to go higher.

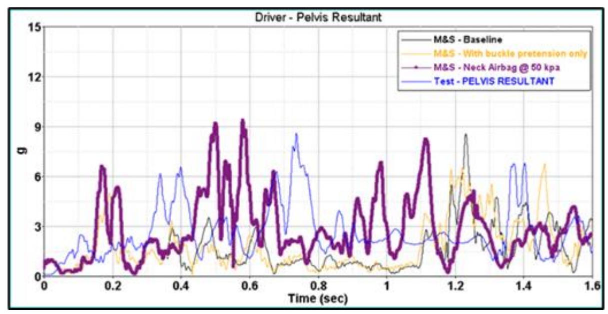

Figure 25: Driver Pelvis resultant g

Driver Neck FX, FZ and MX are shown in next three Figures 26, 27, 28. Neck airbag has the highest influence on Neck FZ forces. As mentioned in the previous section this is due to a pressure lock up situation during the 1st quarter turn when the occupant head is trying to move up against the inflated neck airbag. A vented and permeable bag may reduce the neck lock scenario and help reduce the forces.

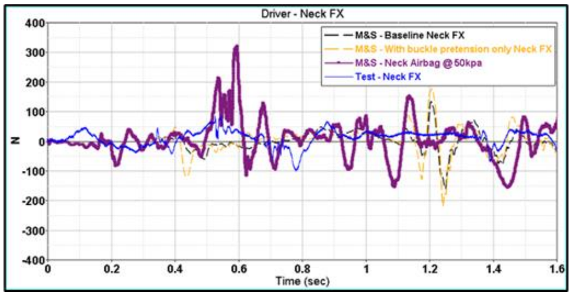

Figure 26: Driver Neck Fx

Airbag pressures and volumes for 50 kPa, 60 kPa, and 70 kPa inflator outputs are plotted in Figures 29 & 30. Left airbag is to the left side of the shoulder belt and right airbag is to the right-side shoulder belt. Average volume of the airbag from the simulation is 6 liters. 60 kPa and 70 kPa inflator outputs stretches the airbag fabric and the volume expands to 7 liters, but for 50 kPa output the volume remains at 5.5 liters. Net average pressure from the fully inflated bag varies from 50 kPa to 80 kPa.

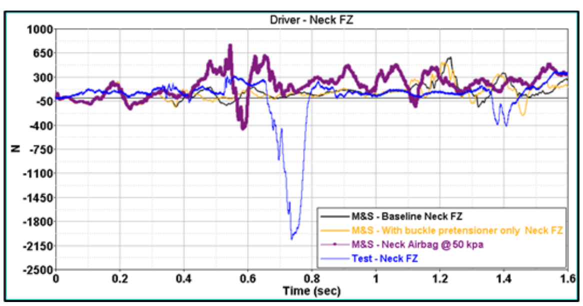

Figure 27: Driver Neck Fz

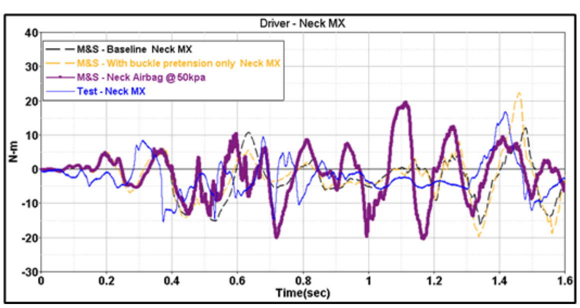

Figure 28: Driver neck Mx

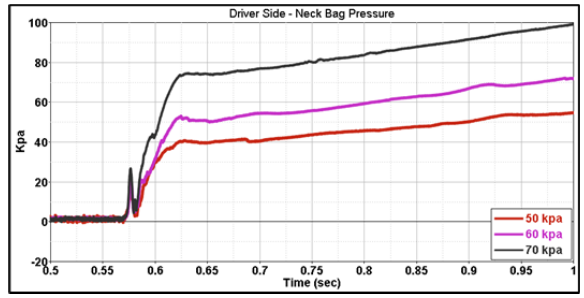

Figure 29: Neck airbag pressure

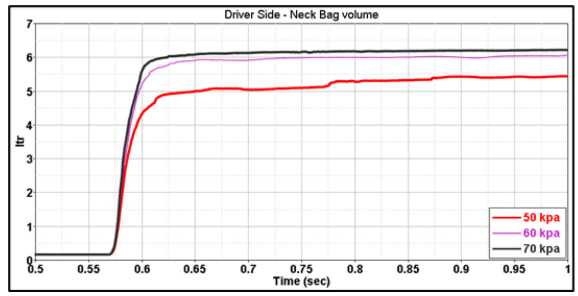

Figure 30: Neck airbag volume

There are several uncertainties in the numerical models from structures, occupants, seats, and restraints systems. Most of these uncertainties are quantified via valid engineering assumptions wherever applicable, some of them may correlate very well to the real time event but not all the assumptions. All the engineering assumptions are meticulously selected and limited to as minimal as possible. Just to name a few, suspension and tires assembly has 1D spring dampers and tie-rods with force-displacement as inputs, seat pull down modelled with conceptual piston-cylinder, neck airbags are close to the test specs. Overall, the numerical simulation captures the rollover event very successfully, both the vehicle kinematics and the occupant responses. A summary of structure and occupant responses from all the numerical simulation is shown in Table 3

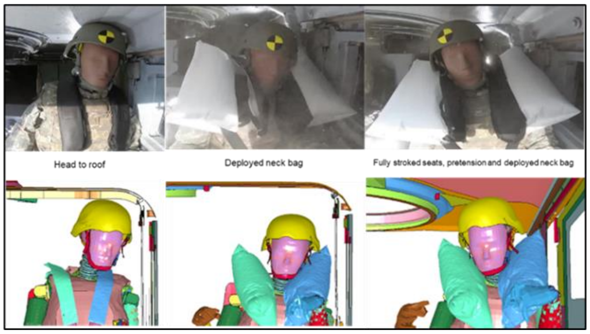

Figure 31: Deployed airbag and head-neck positions

7.3. Occupant responses – Passenger side

Passenger side occupant experiences centrifugal force, and the combination of pull-down seat and neck airbag will reduce the neck FZ and neck moments. Head, chest and pelvic accelerations did not show much improvements over baseline 4-point seat restraints systems with dual pretensioners.

Occupant positions with and without the pull-down seat and neck air bag are show in Figure 32. It shows that without the pull-down seat and neck airbag, passenger head is in contact with the roof and results in higher compressive forces. With the pull-down seat and neck airbag neck compressive forces are significantly reduced and the sharp peak is eliminated.

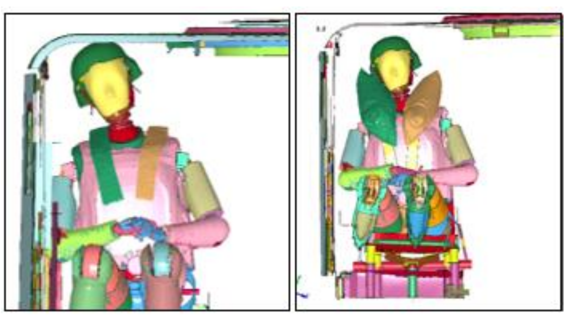

Figure 32: Passenger head with deployed neck bag

Table 3: Summary of test and simulation

		Numerical Simulation				
In g	Test	Baseline	With pretension	50 kpa	60 kpa	70 kpa
Head X	17.4	3.2	2.4	5.7	11.5	12.2
Head Y	61.5	7.6	12.4	5.9	9.1	12.4
Head Z	13.7	11.8	15.8	11.6	11.9	10.2
Head Resultant	61.8	22.3	16.9	11.7	12.7	17.9
In g						
Chest X	4.1	6.5	4.49	7.14	9.8	8.1
Chest Y	17.4	12.3	10.5	9.04	16.6	16.4
Chest Z	8.6	7.86	5.9	6.1	7.9	7.1
Chest Resultant	18.1	16.46	14.2	9.5	17.4	16.5
Pelvis X	6.8	5.56	5.3	5.9	6.2	4.9
Pelvis Y	13.8	7.9	8.7	7.9	7.8	7.8
Pelvis Z	7	4.7	4.07	4.65	5.32	5.5
Pelvis Resultant	13.7	16.7	14.7	9.3	8.5	8.2
In N,						
Upper Neck FX	223	176	131	319	211	177
Upper Neck FY	443	156	222	98	336	456
Upper Neck FZ	-2064	590	509	760	774	712
Upper Neck Mocx (n-m)	34	12	22	19	20	22
Vehicle roll (deg/sec)	336	316				

Buckle pulls in 70 mm and seats pulls down by 65 mm on an average. Buckle and seat pull in vs time curves are shown in Figure 33.

8. CONCLUSIONS

In this study, a numerical simulation was performed for a lateral 25 mph rollover of a HMMWV. Vehicle kinematics and occupant responses were compared to the responses from an IMMI test. Furthermore, numerical simulations were used for excursion analysis and AoA of several different restraints systems as identified in the analysis matrix in Table 1. The main objective of this analysis was to identify the effectiveness of the restraints systems on occupant responses. From this analysis it was found that a 4-point belt with dual pretensioners showed reductions in loads and accelerations. Adding neck airbag will increase the neck FZ forces especially if the airbag is non-permeable and non-vented as shown in the neck FZ curves. Further analysis is required to identify the proper venting and permeability. But the numerical simulation shows that Neck airbags have very minimal effect in mitigating the driver neck and head injuries in this rollover event. The pull-down seat also has small influence in mitigating neck and head injuries in the rollover event, but this may have much higher benefit in other blast/crash events which is not discussed in this report. On the passenger the neck airbag and the pull-down seat has reduced the neck FZ force and moment.

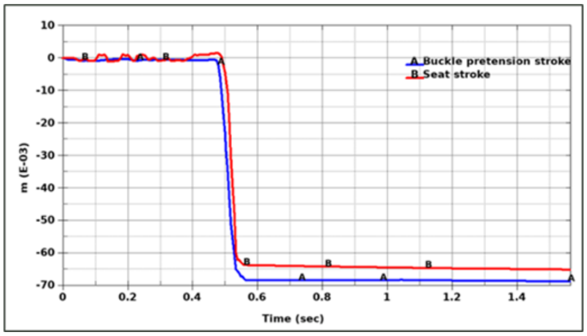

Figure 33: Buckle and seat pull in curves.

Vehicle initial velocity has a significant influence on vehicle roll outcomes. Ramp angle and drop height from the cart to the ground has a significant effect on vehicle kinematics. Ground friction has one of the most significant effects on the vehicle roll rate after the tire contacts the ground. The higher the friction, the higher the roll rate and the number of quarter turns.

Finally, numerical simulation is a very valuable tool to study the AoA in design and development phases and provided timely data for program managers to make effective decisions and avoided tests at a minimal cost with significant time.

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