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ROAD BREAKAWAY ROLLOVER MITIGATION WITH HIGH PERFORMANCE ELECTROMECHANICAL ACTIVE SUSPENSION SYSTEMS

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ABSTRACT

There have been several hundred rollovers in military vehicles in the last decade of deployment, of which approximately fifty percent are fall-based that occur during off-road operations. Off-road fall-based rollovers occur at lower speeds during road breakaway when the soft road gives way underneath the vehicle on one side as the soil is unable to support the vehicle load (Figure 1). A simulation-based study was conducted to explore potential off-road rollover mitigation benefits for the heavy vehicles with higher center of gravity such as MRAPs, MATV, and JLTV through the use of high performance active suspension systems. The study developed a system architecture based on the ElectroMechanical Suspension (EMS) technology and developed a medium fidelity MATLAB-Simulink-DADS model. Simulation results indicated substantial rollover mitigation benefits for MRAP/JLTV class vehicles, especially in road breakaway scenarios. Potential DoD beneficiaries include the Army and Marines, who rely on tactical and combat wheeled vehicles in off-road and on-road environments, potentially with unstable roadways/terrains. This paper describes fall-based rollover problem; active EMS technology based approach; and the simulation results.

INTRODUCTION

The topic of vehicle rollover has been widely researched over many decades by industry, academia, and the Government [1-3], due to its direct impact on human life. A vehicle is generally considered to have experienced a rollover when tires on one side of the vehicle have lost contact with the ground to the point of no return. The cause for rollover varies depending upon the operating conditions. The most commonly studied on-road rollovers occur at higher speeds and high lateral G's during maneuvers such as obstacle avoidance or J-turns. The vehicle during these rollovers pivots about the outside wheels in response to high lateral G's experienced at the vehicle CG where the outside wheels are laterally constrained by the cornering forces. Many techniques have been established to successfully characterize tire cornering data to accurately model on-road rollovers.

There is another type of rollover condition called fall based rollover that occurs at lower speeds over narrow terrains, near the edge of slopes of the terrains and often times near water. The soil on that side becomes softer and can suddenly break at the edge, causing the vehicle to rollover (Figure 1). These types of rollovers are more prominent among heavy vehicles with high CGs operating in mountainous regions where roadways are made up of narrow paths with steep side slopes and unstable soil. According to the report published by Rice [4], 2661 mishap events from multiple sources were recorded for MRAPs between November 2007, and March 2015. 987 of those mishaps events were recorded as some type of rollover with 527 rollovers (i.e. more than 50%) were recorded as fall-based rollover from uneven terrain or road breakaway and 221 rollovers were maneuver-based (ROM) on flat rigid ground that usually are the result of the high G cornering. Of 527 rollovers, 264 rollovers (50%) were due to road surface collapse near the edges of slopes near water. Twenty-one rollover events have resulted in 32 US fatalities; 14 drowning, 18 blunt force trauma to crewmembers. To date there have been 945 reported rollover related injuries.

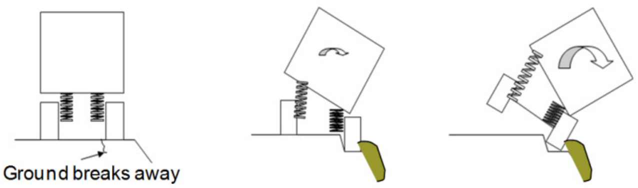

Figure 1 - Vehicle rollover due to soil breakaway

Many times such rollover-prone terrains offer significant strategic military advantage with surprising enemies, and other times, only are the viable option left to complete the mission. Therefore, developing solutions to mitigate rollover is important. The vehicle mobility on those rollover-prone terrains depends upon two factors: 1) how prepared the driver is to "correctly" respond to impending rollover condition, and 2) how prepared the vehicle is, technologically, to avoid the rollover. TARDEC took upon these two approaches to develop solutions to mitigate rollover issue. Since conducting experiments in the field or at the proving grounds is neither safe nor cost effective, TARDEC pursued M&S, lab experiments, and driving simulator to understand fall-based rollover to develop solutions.

BACKGROUND OF TARDEC'S EFFORT

Previously, TARDEC's Singh et al [5] investigated various driving styles to prevent rollover during road-collapse using real-time modeling in TARDEC's Ride Motion Simulator (RMS) environment. Both rigid terrain and Bekker-based soft soil modeling techniques were considered to demonstrate driving styles in real-time. The model was developed using a higher fidelity real-time simulation software, Simcreator, and was validated against test data collected on n-post shaker (Figure 2). The left tires were vertically actuated as a function of time to represent tire paths traced during the soil breakaway condition. The right tires stayed level.

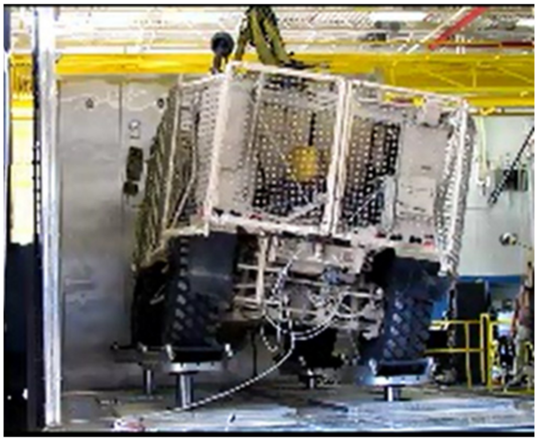

Figure 2 - n-post Shaker simulating soil breakaway condition

Vehicle accelerations in all three directions and suspension travels were compared between test and the model and were found to be reasonable close [5]. The vehicle model was driven on Ride Motion Simulator (RMS) and many experiments were run to understand driving styles over various soil types and slopes.

Figure 3 shows Ride Motion Simulator used for the study. Although research in terramechanics has been active for many decades, most of it addresses straight-line mobility. A real-time terramechanics model focused on slope maneuvering was developed that utilized Bekker's theory, Mohr-Coulomb equations, and bulldozing effects. The terramechanics model was incorporated into the full vehicle model as a C library.

Figure 3 - Ride Motion Simulator (RMS)

Driving simulation experiments revealed certain driving styles that are intuitively used by drivers to correct the fall-based situation may actually be more detrimental. For example, as soon as the driver realizes that the vehicle is beginning to roll down due to road collapse, he would try to "correct" the situation by steering up the road as shown in

Figure 4. This in reality introduces roll inertial effects and speeds up the rollover process. A better path, depending upon the soil condition, may actually be steering down the hill.

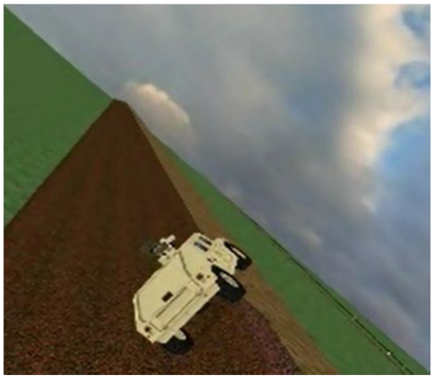

Figure 4 - Vehicle roll over while the driver corrects

Many times steering the vehicle down the hill may not be the best choice due to the presence of water canal or a cliff on the other end. For the other slope situations, even if the driver chooses to go down that may still induce rollover due to undesired soil conditions and speed. This requires a more robust and reliable vehicle or a suspension design solution that could detect the rollover situation and automatically mitigate it.

Brake-based Electronic Stability Control (ESC) has proven to be effective in reducing maneuver-based rollover (ROM) of high CG vehicles. ESC helps dampen the yaw energy; if not controlled would feed into roll energy causing vehicle to rollover. However, due to relatively small yaw energy during road breakaway event, ESC is not effective in mitigating rollover. Computer simulations and laboratory tests on TARDEC's n-post "shaker" have demonstrated the feasibility of road breakaway rollover mitigation by active suspension systems. Active suspension systems, by pushing (extending) on the downhill side and simultaneously pulling inward (retracting) on the uphill side when road breakaway is sensed, can reduce rollover incidents caused by road breakaway as opposed to sudden maneuvering, i.e. lane change. In one test on the TARDEC shaker, an experimental active suspension actuator demonstrated successful mitigation of what would have been rollover upon encountering an 8" drop on one side. In the current research, the focus is on employing active suspension technology that detects and intelligently manages forces at all vehicle corners to prevent rollover during road collapse. The active solution was developed as part of SBIR–phase I in collaboration with University of Texas Center for Electromechanics.

MODELING / SIMULATION APPROACH

A medium fidelity full vehicle model was developed using DADS (Dynamic Analysis and Design System) software that handles the kinematic simulation of vehicle hardware and tire-terrain interactions. It was run in co-simulation mode with MATLAB Simulink used to represent the active suspension, steering control, and speed control with various differential configurations. The model was developed to represent a vehicle with independent suspension, similar to weight class of MRAP, JLTV, and MATV type vehicles. The vehicle mass used for this series of simulations was 10,500 kg.

Figure 5 shows the modeled suspension geometry at the front of the vehicle. The frame, subframe, and tires are shown in grey, steering knuckles in blue, sway bar and end links in purple, steering linkage in green, and control arms in red. The rear suspension is of similar construction but lacks the steering idlers and centerlink, the inner tierod ends are connected to fixed brackets on the vehicle frame. The tire / terrain interaction is handled by tire specific elements in DADS that generate the coupled interactions between forces and torques in the normal, longitudinal, and lateral directions. Empirical relationships are used to relate lateral and longitudinal forces to Normal force coupled with the system kinematics governing steering and rotational slip from applied wheel spindle torque, as well as the aligning and overturning moments [6]. The friction ellipse concept is used to manage the magnitude of the net tangential force as a combination of longitudinal and lateral forces. Tire stiffness is assumed to dominate the vertical response as opposed to terrain deformation or deflection. A more detailed flythrough animation of the model is available here: https://goo.gl/WG7i2I

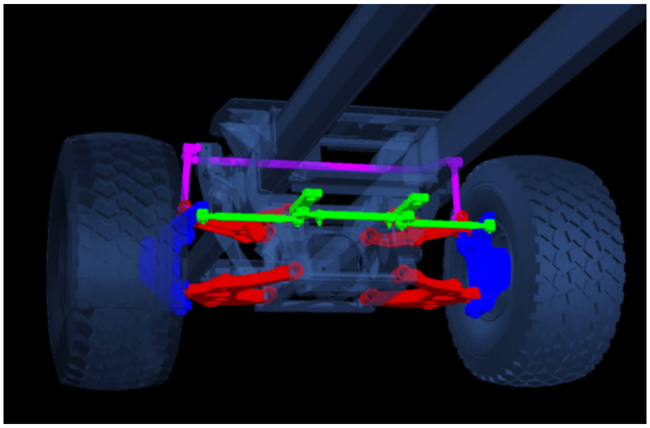

Figure 5 - Modeled suspension system geometry

The CEM EMS (ElectroMechanical Suspension) system is the active suspension technology used in this study. It replaces conventional shock absorbers with electromechanical actuators that can operate in all four motor control quadrants to insert and extract energy from the suspension system to provide controlled motoring force and damping as required by the system controller. Passive springs are retained so there is no energy consumption to support the sprung mass. Energy storage supplies the power required during motoring and captures energy regenerated during damping. Figure 6 shows the EMS control architecture. CG sensors collect data about the motion of the vehicle body and feed it to the System Controller through the Sensor Interface Unit. The optimal control forces are then computed and sent to the servo amplifiers that regulate the power flow into and out of the ElectroMechanical Actuator's respective motor.

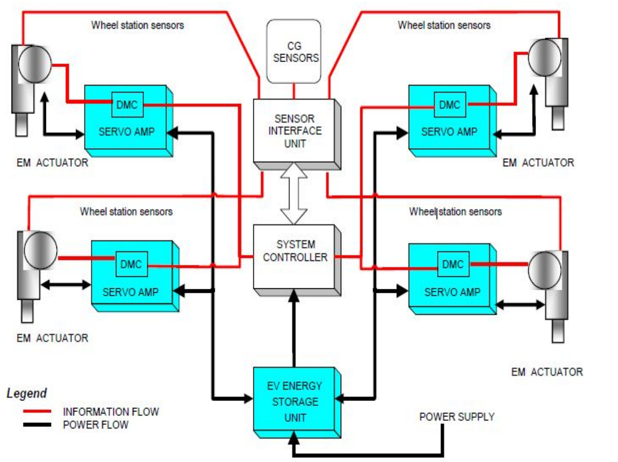

Figure 6 - EMS control architecture

RESULTS

Terrain profiles were generated to represent one road breakaway and two stuck vehicle scenarios. Table 1 lists the scenario permutations analyzed in this study and a brief summary of the results.

Scenario	Steering Control	Suspension Config.	Differential Config.	Result
Road Breakaway @ 20 MPH	Follow	Passive	Open	Fail
		Active	Open	Pass
	Free	Passive	Open	Pass
		Active	Open	Pass
Front-End Extraction	Manual	Passive	Open	Stuck
		Active	Open	Free
Frame Bottomed Extraction	Manual	Passive	Open	Stuck
		Active	Open	Stuck
		Passive	Locked	Stuck
		Active	Locked	Free

Table 1 - Senario Permutations and Results

For the road breakaway simulations, the terrain starts initially flat and then abruptly drops away on the right side of the vehicle to a steep lateral slope. This attempts to represent the vehicle driving on a level road and the right side suddenly breaking away to where the vehicle is now essentially driving partially on side slope. The angle of the slope in the breakaway simulation was increased until the active suspension showed increased capabilities over passive, this angle ended up being approximately 35 degrees. Figure 7 shows how this event appears as the front wheel leaves the terrain flat and begins to engage the sloped portion of the road profile.

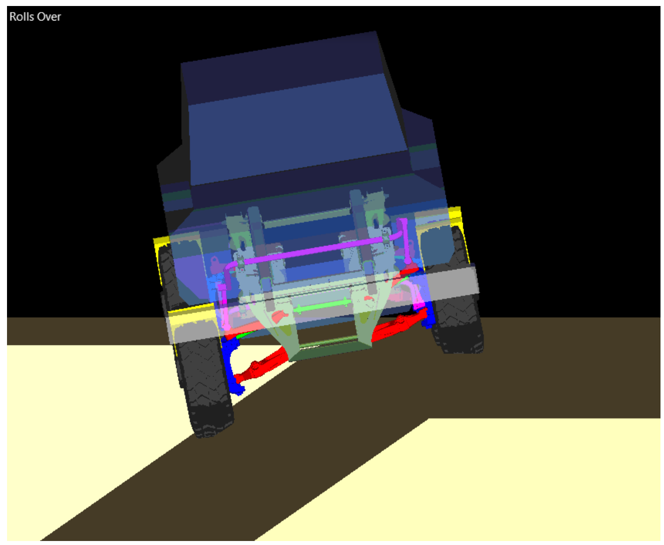

Figure 7 - Vehicle encountering terrain drop

The combination of roll momentum from the abrupt drop and side slope angle puts the vehicle at the verge of tip-over, whether the vehicle rolls is determined by the drivers steering input. If the driver lets go of the steering wheel, the modeled vehicle will naturally steer down the slope into the rollover direction and counter the roll momentum. If the driver attempts to recenter the vehicle on the road, they will be steering against the roll momentum and the passive vehicle will overturn.

The active suspension equipped vehicle does not suffer from this behavior, as the suspension controller attempts to minimize the rolling motion as part of its normal operation. This dramatically lowers the accumulated roll momentum and provides the driver with the ability to continue to steer the vehicle however they choose. Figure 8 and Figure 9 show angular rate and displacement comparisons between the passive and active suspension systems. Both experience a similar magnitude of response in pitch as the front tire leaves the edge, with the active settling much more quickly.

The active experiences a much more controlled roll transition and settles into a gentle roll rate that does not overcome the lateral stability of the vehicle.

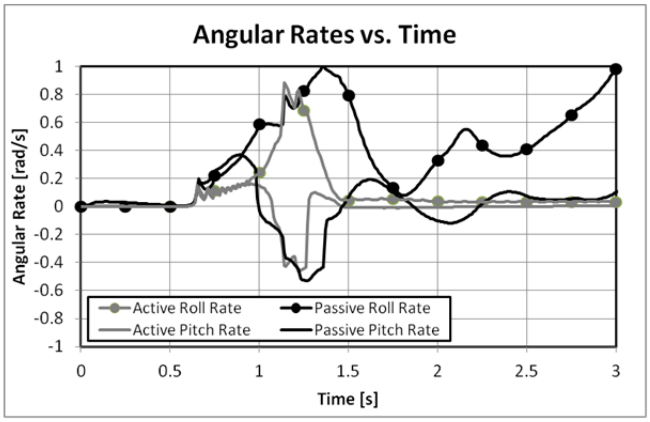

Figure 8 - Angular rate comparison

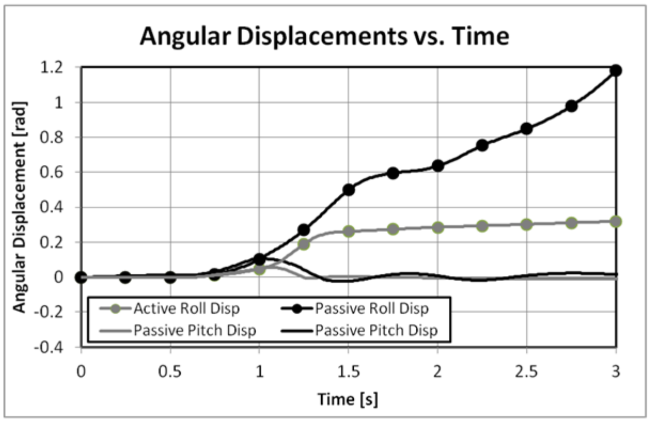

Figure 9 - Angular displacement comparison

The active suspension keeps the tires in better contact with the terrain through the event, within the limits of the suspension travel. Figure 10 and Figure 11 show the passive tire forces and active tire forces, respectively. This provides the driver additional ability to steer or stop the vehicle in a controlled manner.

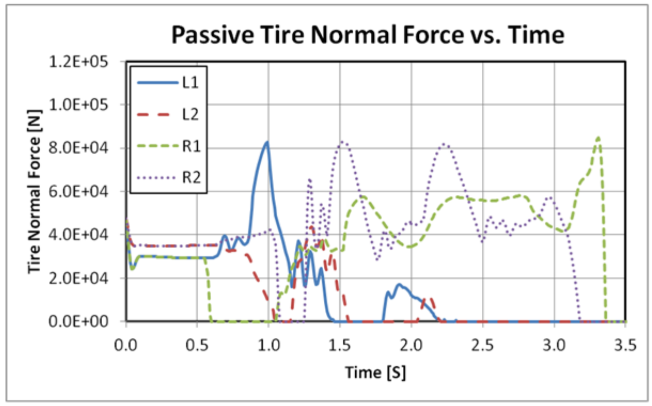

Figure 10 - Passive tire forces

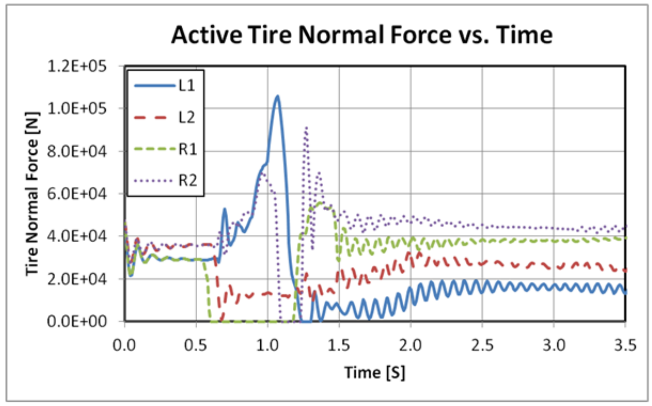

Figure 11 - Active tire forces

The active system also kept the strut more centered in its travel through the event compared with the passive as shown in Figure 12 and Figure 13. This would provide additional advantage to the active system in more realistic operating conditions where the terrain is not smooth and may contain additional features that would further destabilize the already compromised passive vehicle.

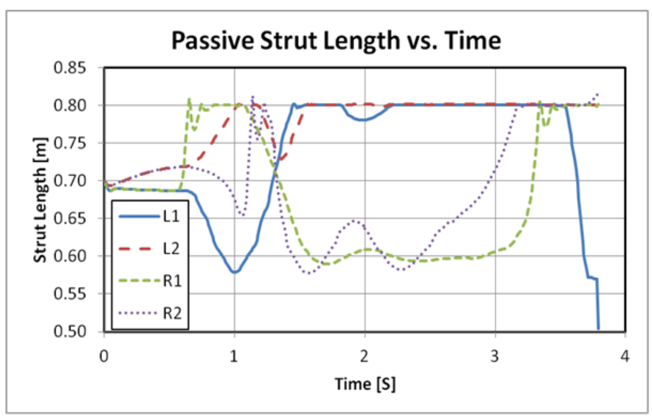

Figure 12 - Passive strut length

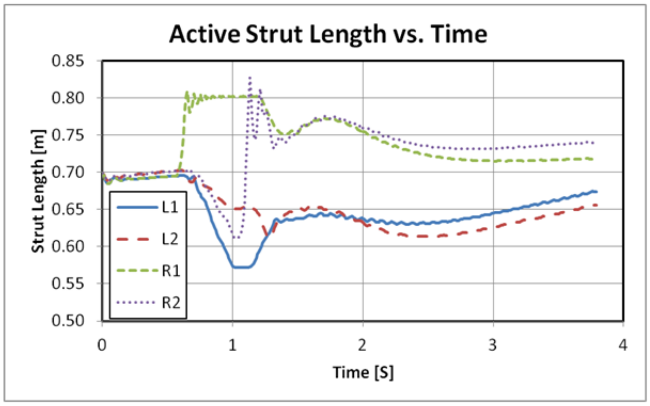

Figure 13 - Active strut length

Figure 14 shows the comparison of the vehicle CG position as it travels down the course. The passive vehicle slides uncontrollably down the hill and eventually rolls over while the active is able to better maintain its position relative to the center of the road. The Active vehicle does not attempt to move the vehicle CG back to the course centerline, it is only attempting to maintain a fixed reference point in front of the vehicle on the course centerline. The lateral slip of the tires maintains a small constant yaw offset, thus the steering controller holds the vehicle in this position.

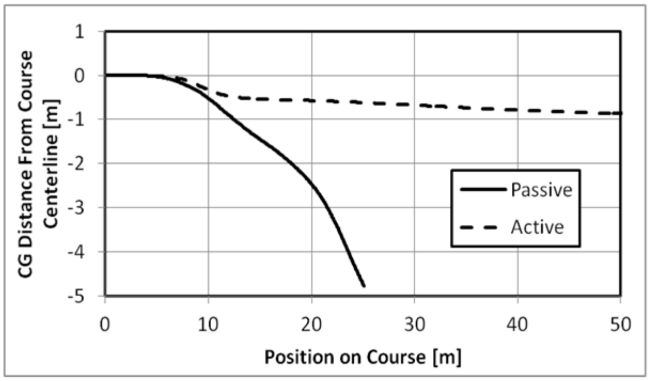

Figure 14 - Vehicle path comparison

Figure 15 shows the side-by-side comparison of the stock passive vs. the Active EMS system on the road breakaway simulation. An animation of this result comparison is available here: https://goo.gl/YNyrjN

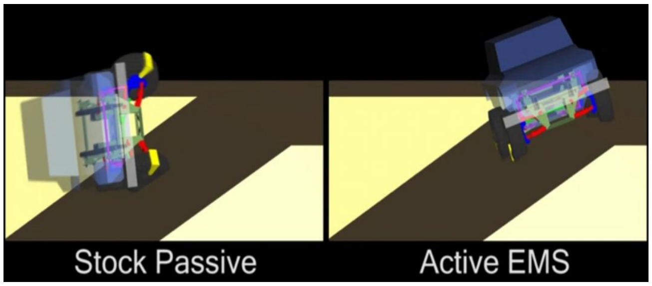

Figure 15 - Road breakaway comparison

Stuck Vehicle Extraction

The stuck vehicle extraction simulations followed a different methodology. For the front-end extraction simulation, the vehicle was driven in a straight line at 5 mph with the steering locked to keep the front wheels pointed straight ahead. The terrain was setup such that the right front tire encountered a near vertical drop off, leaving it without any possibility of ground contact. Dummy elements were added to the DADS model to allow the lower control arm and vehicle sub-frame to interact with the terrain edge and "catch" the vehicle as it fell. Figure 16 shows the vehicle as it would appear when stuck. The right front wheel is no longer in contact with the ground and the vehicle is resting on its lower control arm. The left rear tire is also in the air as the vehicle has pivoted over on the left front and right rear wheel stations, as if it was leaning into the hole that has captured the right front wheel.

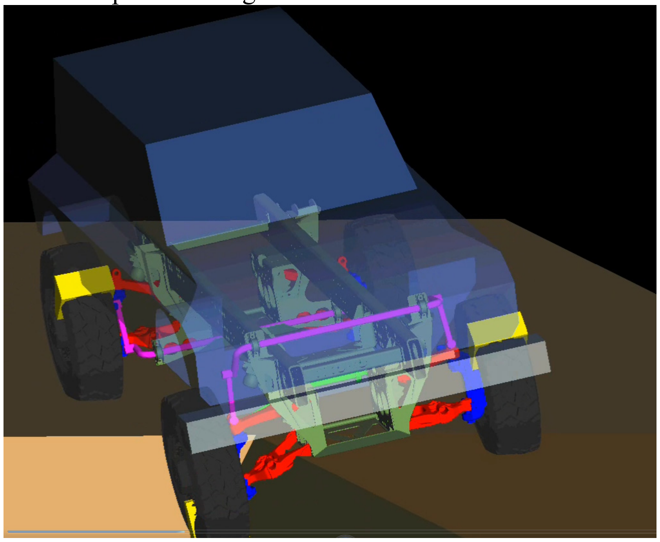

Figure 16 - Stuck vehicle extraction, right front tire no longer in contact with terrain

This vehicle configuration has open front and rear differentials, thus is unable generate any effective tractive effort with the right front and left rear tires not in contact with the ground. While the passive vehicle is unable to free itself, the active vehicle can manipulate its actuators to force both rear tires into sufficient contact with the ground to be able to drag the front end free. This option is not available on a vehicle with a passive or semi-active suspension system. A passive vehicle with adjustable ride-height may be able to self-extract at a much slower rate than the full active suspension, but it was not attempted to simulate this operation. Figure 17 shows a comparison of extraction attempts for the front end stuck simulation. An animation of this result comparison can be found here: https://goo.gl/pTCAIJ

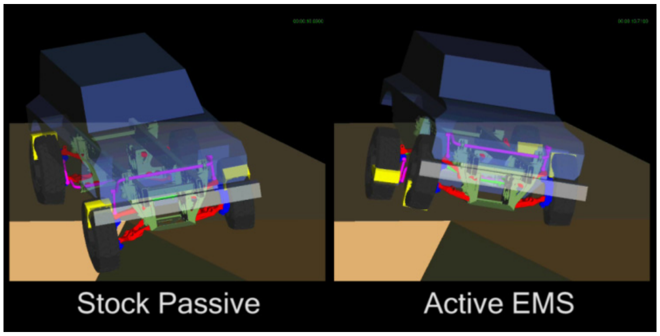

Figure 17 - Front-end stuck extraction comparison

The second stuck vehicle scenario has an additional feature added to the terrain model to represent a large mound in the center of the road that catches and supports the vehicle subframe when the right front tire drops off the initial starting flat. This center mound limits the downward travel of the right front wheel station by supporting the lower control arm or front subframe assembly depending on the roll angle of the chassis, subsequently limiting the amount of additional vehicle body roll and forward pitch. Thus, the open differential of the rear axle is able to continue to push the vehicle forward until the right rear wheel falls off the terrain edge and the vehicle is fully engaged against and supported by the center mound on the right side lower control arms. This approach attempts to represent the vehicle operating in deep ruts and becoming "high-centered" on the sub-frames against the middle "un-rutted" section of the road. In this condition, even locking the front and rear differentials is unable to allow the vehicle to free itself for the passive suspension. The left tires simply cannot generate enough traction to overcome the friction of the sub-frame against the road mound.

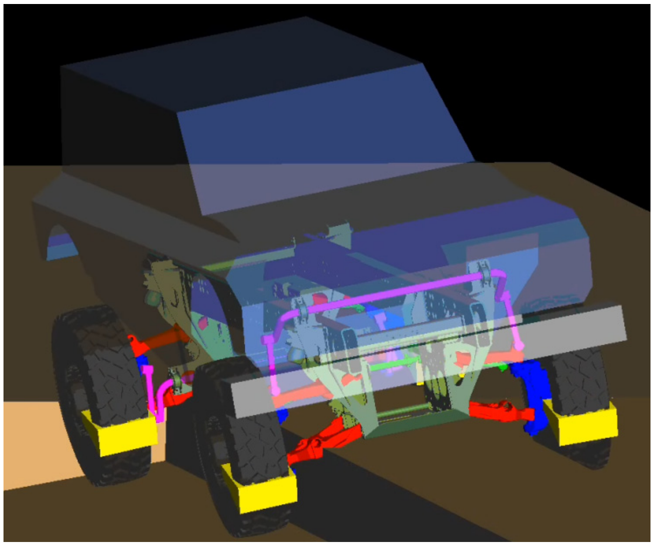

Figure 18 - Frame-bottomed stuck state

However, the active vehicle can manipulate its actuators to rock the vehicle enough to momentarily let the left hand side tires dig in and pull the vehicle far enough back that the right rear wheel can climb back onto the flat ground and drag the vehicle from the obstacle. Again, this is an option that is not available on a vehicle with a passive suspension system. From the dynamic nature of this simulation, it is not likely that a passive suspension with adjustable ride height would have the speed required to rock the vehicle free in the same manner that was performed here with the active suspension. Figure 19 shows a side by side comparison of the passive vs. active vehicles attempting to self extract from the frame bottomed condition. An animation of this result comparison can be found here: https://goo.gl/mhLL8Z

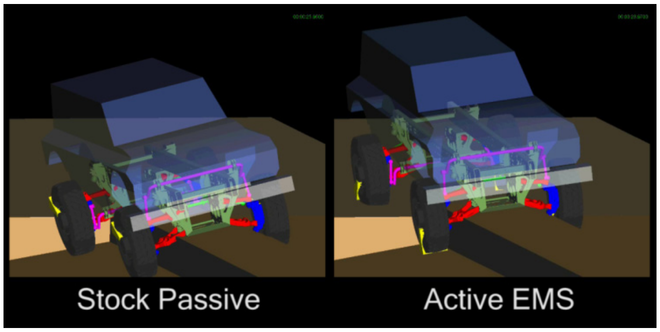

Figure 19 - Frame-bottomed extraction comparison

It is important to note that in both of the stuck vehicle simulations the driver was operating the suspension actuators manually. This manipulation to extricate a vehicle is not part of the current active suspension control algorithm. While manual manipulation could be carried out if necessary in the field, it would be preferable to develop an automated system that would extract a vehicle from a full range of stuck conditions with minimal input from the driver.

Power and Force Limit Evaluations

Additional simulations of road breakaway were performed to investigate the effect of realistic power and force limits on the EMS system's ability to prevent rollover. Previous analysis had allowed the actuators to develop as much force as required to stabilize the vehicle and consume as much power as necessary during road breakaway events. Simulations were rerun with the existing vehicle model at 20 mph with the "smart driver" attempting to maintain the original path as the right side of the pavement dropped away onto a steep side slope to investigate actuator force and power requirements. These new simulations indicated that, compared with historical design guidelines for EMS system sizing, approximately a 40% increase in EMS actuator force would be required to adequately control the vehicle in difficult road break-way scenarios. Figure 20 shows a representative comparison between the original simulation with unlimited actuator force vs. applied limits that still prevented rollover on the road breakaway. It is typical to see large momentary spikes far above the applied force limit in simulation and operation of active suspension systems, they are of brief duration and their negation does not detract from the overall system performance as they do not usually carry significant energy.

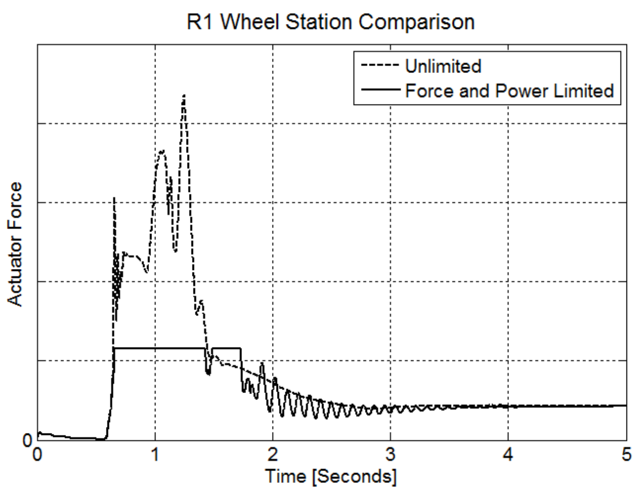

Figure 20 - Limited vs. unlimited actuator force comparison

Since this is a very short-term event, continuous power requirements for the system do not need to be increased significantly beyond typical EMS sizing guidelines. This analysis confirmed that, while EMS actuator force capacity will need to increase to address road breakaway events, the increase is reasonable and well within the realm of current actuator designs with the proper modifications. Additionally, it is likely that most of this increase can be obtained by optimizing actuator gear ratios so size and mass increases will be compatible with typical military mass and volume constraints. It is reasonable to assume that the enhanced actuator performance would also improve the vehicle extraction capability of the vehicle but this has not yet been simulated.

CONCLUSIONS

Fall-based rollovers are serious mobility issues for the Army that require mitigation via driver training and advanced vehicle technologies. The simulations presented here show promise that Active Suspension systems can significantly reduce the likelihood of rollovers due to road-breakaway, and provide enhanced ability for a stuck vehicle to self-extract without the need for the crew to dismount. This report will serve as a future comparison for analysis of alternative active suspension systems, semi-active systems, or advanced passive systems with auxiliary support or rollover mitigation systems. Future work should focus on refining intelligent algorithms that automatically detect the vehicle and soft terrain conditions and overcome the issue with minimal human intervention. The system's effectiveness should be demonstrated on actual vehicle via further experimentation in lab and/or proving grounds.

ACKNOWLEDGEMENTS

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TABLE OF ACRONYMS NOT IN COMMON USE

Acronym	***Definition***
CEM	Center for Electromechanics
CG	Center of Gravity
DADS	Dynamic Analysis and Design System
EMS	ElectroMechanical Suspension
ESC	Electronic Stability Control
JLTV	Joint Light Tactical Vehicle
MATV	MRAP - All Terrain Vehicle
MRAP	Mine Resistant Ambush Protected
RMS	Ride Motion Simulator

REFERENCES

[1] Winkler, C., "Rollover of Heavy Commercial Vehicles," University of Michigan Transportation Research Institute Report, ISSN 0739 7100, 2000.

[2] Hac, A., "Detection of Vehicle Rollover," Proceedings of SAE World Congress, #2004-01-1757, 2004.

[3] Peters, S., Iagnemma K., "Stability Measurements of High Speed Vehicles," Vehicle System Dynamics, 47-6, p701-720, 2009.

[4] Rice, A., "MRAP Mishap Trends, 1 Nov 07- 31 Mar 2015," Deployment and Operations Working Group, Pentagon, 2015.

[5] Singh, A., Holtz, D., Megiveron, M., Paul, V., "Modeling Off-road rollover using terramechanics for real-time driving simulator," GVSETS, Dearborn, MI, USA, 2014.

[6] DADS, Revision 9.60, Online Help System, 12.16.1.1: General Tire-Ground Interaction.