2010 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
MODELING & SIMULATION, TESTING AND VALIDATION (MSTV) MINI-SYMPOSIUM
AUGUST 17-19 DEARBORN, MICHIGAN

AN INTEGRATED ROLLOVER MITIGATION STRATEGY FOR MILITARY TRUCKS

Brad Hopkins
Saied Taheri, PhD
Mehdi Ahmadian, PhD
Department of Mechanical Engineering
Virginia Tech
Blacksburg, VA

Alexander Reid, PhD
U.S. Army RDECOM-TARDEC
Warren, MI

ABSTRACT

Military vehicles in the field are often required to perform severe emergency maneuvers to avoid obstacles and/or escape enemy fire. This paper proposes a combined direct yaw control (DYC) and emergency roll control (ERC) system to mitigate rollover in the studied military vehicle. The DYC uses a differential braking strategy to stabilize the vehicle yaw moment and is intended to reduce the risk of untripped rollovers and also help prevent the vehicle from skidding out, thus allowing the driver to maintain control of the vehicle. The ERC uses actuators located near the vehicle suspension to apply an upward force to the vehicle body to counter the roll angle. An off-road tire model was used with the overall vehicle model in commercially available vehicle simulation software to simulate emergency maneuvers on various driving surfaces. Simulation results show that the proposed control strategy helps prevent both tripped and untripped rollovers on various driving surfaces.

INTRODUCTION

Severe driving maneuvers performed by a military vehicle on unexpected terrain can cause the vehicle to be prone to rollover. Several stability control algorithms exist that provide yaw and roll stability control, which have the potential of improving the off-road stability of a military vehicle. [1] proposes a yaw-roll stability control scheme that uses lateral acceleration measurements as feedback to generate a control signal applied by a differential braking strategy. [2] and [3] present yaw stability control schemes that utilize active front steering and direct yaw-moment control to stabilize the vehicle yaw moment. [4] discusses the use of electronic brake system (EBS) for vehicle rollover prevention. [5] proposes a Roll Stability Control (RSC) system that can be easily integrated into an existing electronic stability control (ESC) system which can improve vehicle roll stability. [6,7] present a yaw stability control algorithm based on Lyapunov direct method that uses a differential braking strategy to apply a corrective yaw moment to the vehicle. [8] presents a lateral acceleration based roll coefficient that warns of an impending rollover.

In developing a rollover prevention control algorithm and testing it in a virtual environment, it is important to include a tire model. [9] discusses the Magic Formula (MF) tire model, which is a semi-empirical tire model that can provide the forces and moments acting on the tire for various vertical loads, slip angles, camber angles, forward speeds, and driving surfaces. [10] presents the determination of scaling factors for the MF for various driving surfaces, including dry asphalt, wet asphalt, ice, and snow.

This paper presents an integrated roll stability control strategy for enhanced military vehicle stability and rollover avoidance. The strategy consists of two parts, the first being a direct yaw-moment controller (DYC) [6,7] that uses a differential braking strategy to stabilize the vehicle yaw moment. This helps the driver to maintain control over the vehicle to steer clear of potential obstacles or uneven terrain, as well as reduces the vehicle lateral acceleration and lateral velocity, decreasing the risk of untripped and tripped rollovers, respectively. The second part of the control strategy is an additional layer of protection called emergency roll control (ERC), which was added to improve the roll stability of the vehicle. ERC utilizes a roll coefficient [8] related to vehicle static stability factor (SSF) to detect an impending rollover and applies an upward force to the vehicle body through actuators located near the vehicle suspension as necessary. The proposed control strategy is evaluated on a military vehicle driven on various driving surfaces in a virtual environment. Dry asphalt, dirt, and gravel driving surfaces are simulated by utilizing a developed off-road tire model for the studied military vehicle.

This paper is organized as follows. First, the off-road tire model is presented. Next, the development of the rollover mitigation control strategy is presented. Finally, the control strategy is tested by simulating potential tripped and untripped rollovers on dry asphalt, dirt, and gravel driving surfaces.

OFF-ROAD TIRE MODEL

A tire model was developed to simulate vehicle response on dry asphalt, dirt, and gravel driving surfaces. The tire of the studied military vehicle was first tested on a rolling road in an indoor tire test facility to develop a dry asphalt tire model. The tire was driven on a stainless steel flywheel that closely resembles a dry asphalt driving surface and was subjected to 20 degrees slip angle sine wave sweeps and 16 degrees camber angle sine wave sweeps at each combination of seven different vertical loads (7200, 7650, 9000, 10800, 12600, 14400, 15300 lbs.) and four different forward speeds (5, 20, 40, 65 mph). All three forces and all three moments were measured in response to the various conditions previously described. The collected data was then curve fitted to the Magic Formula [9] to obtain a tire model. Equations (1-8) show the formulas for the lateral force MF tire model:

$$F_y = D\sin\left(C\arctan\begin{pmatrix} B(\alpha+S_H)- \\ E(B(\alpha+S_H)-\arctan(B(\alpha+S_H))) \end{pmatrix}\right)+S_V \tag{1}$$

$$C = a_0 \tag{2}$$

$$D = \left(a_1F_z^2 + a_2F_z\right)\left(1-a_{15}\gamma^2\right) \tag{3}$$

$$E = \left(a_6F_z + a_7\right)\left(1-\left(a_{16}\gamma + a_{17}\right)\operatorname{sign}\left(\alpha + S_H\right)\right) \tag{4}$$

$$K = a_3\sin\left(2\arctan\left(F_z/a_4\right)\right)\left(1-a_5|\gamma|\right) \tag{5}$$

$$B = K/(CD) \tag{6}$$

$$S_H = a_8F_z + a_9 + a_{10}\gamma \tag{7}$$

$$S_V = a_{11}F_z + a_{12} + \left(a_{13}F_z + a_{14}\right)F_z\gamma \tag{8}$$

where F_y is the tire lateral force, F_z is the tire vertical load, α is the tire slip angle, γ is the tire camber angle, B, C, D, E, S_H, S_V are Magic Formula parameters, and a_0, a_1,…, a_{17} are Pacejka coefficients for lateral force. For each forward speed the Pacejka coefficients were solved for by using a curve fitting routine. Table 1 shows the Pacejka coefficients that give the lateral force tire model for the military tire on dry asphalt. They can be used with equations (1-8) to predict the lateral force that will occur for a given vertical load, slip angle, and camber angle.

Table 1. Lateral force Pacejka coefficients for the military tire on dry asphalt

	Speed (mph)			
	5	20	40	65
a_0	1.048	1.239	1.500	1.200
a_1	-5.498	-6.600	-6.753	-5.899
a_2	-1038.015	-1004.756	-845.097	-899.234
a_3	-4043.512	-4519.586	-5397.504	-5134.564
a_4	-68.628	-73.647	-72.248	-70.403
a_5	-0.022	-0.016	0.030	0.033
a_6	-0.001	-0.018	-0.002	-0.005
a_7	0.347	-0.284	1.140	1.200
a_8	0.009	-0.013	-0.007	-0.004
a_9	2.307	0.815	0.306	0.556
a_{10}	-0.021	-0.008	-0.090	-0.043
a_{11}	-10.913	-80.998	-10.858	-10.918
a_{12}	4184.959	-580.249	-698.940	-207.210
a_{13}	-0.188	0.091	0.007	-0.012
a_{14}	-31.433	-17.417	-11.998	-15.814
a_{15}	0.000	0.000	0.000	0.000
a_{16}	4.075	3.912	-1.964	-16.404
a_{17}	2.361	1.036	0.008	0.019

Off-road tire testing was then performed on a passenger tire to develop scaling factors that could be applied to the dry asphalt tire model to make it applicable for off-road terrain. It was found in [10] that the majority of the scaling in lateral force between two driving surfaces can be quantified in the peak value (D, equation (3)) scaling factor and the cornering stiffness (K, equation (5)) scaling factor. It was also found that the lateral force scaling factors are primarily independent of vehicle type, vehicle forward speed, or tire type. As a result, the current research attempts to determine universal peak lateral force and cornering stiffness scaling factors that can be applied to any tire to transform a dry asphalt lateral force tire model into a dirt or gravel lateral force tire model. Equation (3) then becomes:

$$D = \lambda_D \cdot \left(a_1 F_z^2 + a_2 F_z\right)\left(1 - a_{15}\gamma^2\right) \tag{9}$$

$$K = \lambda_K \cdot a_3 \sin\left(2\arctan\left(F_z / a_4\right)\right)\left(1 - a_5|\gamma|\right) \tag{10}$$

where λ_D and λ_K are the peak value and cornering stiffness scaling factors, respectively.

To determine the scaling factors, a passenger tire was tested on dry asphalt, dirt, and gravel driving surfaces using a portable tire test rig. Slip angle sweeps were performed at six different vertical loads on all three driving surfaces and the lateral force response was measured. Peak value and cornering stiffness were extracted from each vertical load test and these values were used with equations (9-10) to determine the scaling factors for each driving surface. The results are shown in Table 2.

Table 2. Peak value and cornering stiffness scaling factors for dirt and gravel

Driving Surface	λ_D	λ_K
Dry Asphalt	1	1
Dirt	0.573	0.690
Gravel	0.490	0.602

The scaling factors from Table 2 can be used with the Pacejka coefficients from Table 1 and equations (1-8) (with equation (9) substituted for equation (3) and equation (10) substituted for equation (5)) to determine the lateral force tire model for the military vehicle tire on dry asphalt, dirt, and gravel driving surfaces.

STABILITY CONTROL STRATEGIES

The roll stability control strategy for the military vehicle consists of a combined direct yaw-moment control (DYC) and emergency roll control (ERC) system. The DYC uses lateral acceleration and yaw rate measurements to calculate the corrective yaw moment required to get the vehicle yaw rate to match the desired (stable) yaw rate. The corrective yaw moment is applied through a differential braking strategy. The goal of the DYC is to stabilize the yaw behavior of the vehicle so that the driver can maintain control, which is necessary for obstacle avoidance and escape maneuvers. The DYC also helps to reduce high vehicle lateral accelerations which is beneficial for preventing untripped rollovers, and also helps to reduce high vehicle lateral velocities, which can help to prevent potential tripped rollovers. The ERC is added as an extra layer of roll protection for the military vehicle. The ERC operates on lateral acceleration measurements and if a potential rollover is detected, applies an upward force to the vehicle body via actuators located near the suspension. The combined DYC and ERC system is intended to assist the driver in maintaining control of the vehicle and helping to prevent rollovers during severe maneuvers.

Direct Yaw Control

The DYC algorithm was derived using a two degree of freedom bicycle model with lateral velocity and yaw rate motions considered. The equations of motion for the vehicle are:

$$A\dot{x} + Bx + W = 0\,, \tag{11}$$

where

$$x = \begin{bmatrix} v \\ r \end{bmatrix},\ A = \begin{bmatrix} m & 0 \\ 0 & I_z \end{bmatrix},\ W = \begin{bmatrix} C_{\alpha-f}\delta_f \\ aC_{\alpha-f}\delta_f \end{bmatrix},$$

$$B = \begin{bmatrix} \dfrac{C_{\alpha-r} - C_{\alpha-f}}{u} & \dfrac{bC_{\alpha-r} - aC_{\alpha-f}}{u} + mu \\ \dfrac{-aC_{\alpha-f} - bC_{\alpha-r}}{u} & \dfrac{-a^2C_{\alpha-f} - b^2C_{\alpha-r}}{u} \end{bmatrix},$$

v is the vehicle lateral velocity, r is the vehicle yaw rate, m is the vehicle mass, I_z is the yaw moment of inertia, $C_{\alpha-f}$ is the front axle cornering stiffness, $C_{\alpha-r}$ is the rear axle cornering stiffness, a is the distance from the vehicle center of gravity to the front axle, b is the distance from the vehicle center of gravity to the rear axle, u is the vehicle forward speed, and δ_f is the front wheel steer angle.

The control algorithm is then derived by first adding a control law, $U = [0\ \ M_s]^T$, to the right hand side of equation (11) to get

$$A\dot{x} + Bx + W = U\,, \tag{12}$$

where M_s is the corrective yaw moment required to stabilize the vehicle.

The control law, U, and an adaptation law are derived by using Lyapunov Direct Method as found in [6,7]. The following candidate Lyapunov function is considered:

$$V(x,t) = \frac{1}{2}\left[\tilde{x}^T A\tilde{x} + \tilde{p}^T \Gamma \tilde{p}\right] + \int \tilde{x}^T B\tilde{x}dt \tag{13}$$

Where $\tilde{x} = x - x_d$ is the state error vector, x is the state vector, x_d is the desired state vector, $p = \left[\hat{C}_{\alpha-f}\ \ \hat{C}_{\alpha-r}\right]^T$ is the adaptive parameter vector, and Γ is the adaptation gain matrix.

In order to ensure system asymptotic stability, it is necessary to choose the control law and adaptation law such that $V(x,t)$ is positive definite and $\dot{V}(x,t)$ is negative definite. These criteria are fulfilled when the control law is chosen to be:

$$U = \hat{A}\dot{x}_d + \hat{B}x_d + \hat{W} - \Lambda\tilde{x} \tag{14}$$

where Λ is the control gain matrix, $\tilde{A} = \hat{A} - A$, $\tilde{B} = \hat{B} - B$, $\tilde{W} = \hat{W} - W$, and ^ denotes an estimated value,

and the adaptation law is chosen to be:

$$\dot{\tilde{p}} = -\Gamma^{-1}H^T\tilde{x} \tag{15}$$

Λ must be a positive diagonal matrix and Γ must be a positive definite matrix in order to ensure asymptotic stability of the system.

We can then define

$$H\tilde{p} = \tilde{A}\dot{x}_d + \tilde{B}x_d + \tilde{W} \tag{16}$$

where H is the adaptation matrix. If we insert equation (16) into the derivative of equation (13) we can solve for H, which is:

$$H = \begin{bmatrix} \dfrac{-v_d - ar_d}{u} + \delta_f & \dfrac{v_d + br_d}{u} \\ \dfrac{-av_d - a^2 r_d}{u} + a\delta_f & \dfrac{-bv_d + b^2 r_d}{u} \end{bmatrix} \tag{17}$$

where v_d is the desired lateral velocity and r_d is the desired yaw rate, defined by:

$$r_d = \frac{u\delta_f}{(a+b)(1 + K_{us}u^2)} \tag{18}$$

where K_{us} is the understeer gradient.

Emergency Roll Control

The emergency roll control operates on a rollover coefficient that is presented in [8], which can be approximated by:

$$R \approx \left(\frac{2h_{CG}}{t_w}\right)\left(\frac{a_y}{g}\right) \tag{19}$$

where R is the rollover coefficient, h_{CG} is the height of the center of gravity of the vehicle, t_w is the vehicle track width, g is acceleration due to gravity, and a_y is the lateral acceleration of the vehicle. When $|R| = 1$, it is expected that the vehicle will begin to rollover. A rollover coefficient reference value, $\hat{R}$, is chosen such that the ERC preventative strategy deploys when $|R| \geq \hat{R}$. So if $|R| \geq \hat{R}$ and the vehicle is rolling to the left, the ERC will apply a 6000 N upward force to the vehicle body via an actuator located near the suspension on the front left and rear left of the vehicle; and if $|R| \geq \hat{R}$ and the vehicle is rolling to the right, the ERC will apply a 6000 N upward force to the vehicle body via an actuator located near the suspension on the front right and rear right of the vehicle.

VECHICLE ROLLOVER SIMULATIONS

Potential tripped and untripped rollovers were simulated in a virtual environment by using commercially available vehicle simulation software. The software contains non-linear multiple degrees-of-freedom models for various vehicle components, including steering, tires, suspension, and aerodynamics. Dry asphalt, dirt, and gravel driving surfaces were simulated using the off-road tire model. In both the untripped and tripped rollover simulations the vehicle was given a NHTSA standard 140 degree fishhook steer input. During the untripped simulations the military vehicle was driven at a constant forward speed of 90 km/h and during the tripped simulations the vehicle was driven at a constant forward speed of 75 km/h. To simulate the vehicle striking an obstacle for the potential tripped rollover, a x20 multiplier was applied to the lateral friction during the constant steer angle portion of the fishhook maneuver. For both the tripped and the untripped rollover simulations, the vehicle was driven on dry asphalt, dirt, and gravel for the cases where it was uncontrolled (not equipped with DYC or ERC), equipped with just DYC, and equipped with both DYC and ERC. Table 3 shows the results from the untripped rollover simulations. The table displays the maximum yaw rate (deg/s) and the maximum vehicle roll angle (deg) for the fishhook maneuver for each driving surface and controller condition. The results show that the addition of DYC can decrease both the maximum yaw rate and roll angle. The results show that the further addition of the ERC to the DYC slightly improves the vehicle yaw stability, and significantly improves the vehicle roll stability. In such a case where there is a potential untripped rollover, like the dry asphalt case, the combined DYC + ERC system can prevent vehicle rollover. The friction coefficient of the dirt and gravel driving surfaces is too low for the vehicle to rollover without hitting something.

Table 3. Results from untripped rollover simulations on dry asphalt, dirt, and gravel

Max yaw rate (deg/s) / max roll angle (deg)		Controller		
		Uncontrolled	DYC	DYC + ERC
Surface	Dry Asphalt	30.44 / rolls over	24.73 / rolls over	22.70 / 6.70
	Dirt	20.32 / 5.74	17.00 / 5.34	16.90 / 4.72
	Gravel	17.03 / 3.95	10.08 / 3.79	10.00 / 3.01

Table 4 shows the results from the tripped rollover simulations. As was illustrated in the untripped rollover simulations, the DYC + ERC system both reduces the vehicle yaw rate and roll angle during severe maneuvers. The affect of the proposed control system on the military vehicle when it strikes an object while moving laterally can be seen in table 4. The DYC significantly improves the yaw response of the vehicle so that when the vehicle strikes the lateral obstacle, the vehicle is already moving at a slow enough lateral velocity such that the obstacle will not cause a tripped rollover. The addition of the ERC does not significantly improve the vehicle yaw stability; however, it does continue to provide additional roll protection which is beneficial both before and after the vehicle strikes the obstacle.

Table 3 and 4 illustrate the capabilities of the DYC and ERC control systems. The DYC helps the vehicle maintain yaw stability, decreasing dangerous levels of lateral velocity and lateral acceleration, thus decreasing the likelihood of potential tripped and untripped rollovers. The ERC provides an extra layer of roll protection that is not otherwise available from the DYC system. A good example is the case of the untripped rollover simulation on dry asphalt where the DYC system is applying full braking in order to decrease vehicle yaw rate due to the severe maneuver. The vehicle equipped with only DYC rolls over despite the fact that a maximum control signal is already being applied. The further addition of ERC in this situation provides an extra layer of roll protection that prevents the vehicle from rolling over.

Table 4. Results from tripped rollover simulations on dry asphalt, dirt, and gravel

Max yaw rate (deg/s) / max roll angle (deg)		Controller		
		Uncontrolled	DYC	DYC + ERC
Surface	Dry Asphalt	27.20 / rolls over	21.29 / 14.84	21.05 / 10.82
	Dirt	19.18 / rolls over	16.08 / 7.13	15.97 / 6.53
	Gravel	19.66 / 6.33	15.08 / 5.45	14.87 / 4.87

CONCLUSIONS

A combined direct yaw-moment control and emergency roll control algorithm was proposed to improve the yaw and roll stability of a military vehicle. The algorithm was tested on off- and on-road driving surfaces by utilizing a developed on- and off-road tire model for the military vehicle tire. Results of potential untripped and tripped rollover simulations show that the proposed control algorithm improves the vehicle yaw and roll response on a variety of driving surfaces, and has the potential to prevent both tripped and untripped rollovers.

REFERENCES

[1] Chen, B-C., Peng, H., "Differential-braking-based rollover prevention for sport utility vehicles with human-in-the-loop evaluations." Vehicle System Dynamics, Vol. 36 (4-5), p. 359-389, 2001.

[2] Guvenc, B.A., Acarman, T., Guvenc, L., "Coordination of steering and individual wheel braking actuated vehicle yaw stability control." IEE Conf., 2003.

[3] Karbalaei, R., Ghaffari, A., Kazemi, R., Tabatabaei, S.H., "A new intelligent strategy to integrated control of AFS/DYC based on fuzzy logic." International Journal of Mathematical, Physical and Engineering Sciences 1; 1, p.47-52, 2007.

[4] Palkovics, L., Semsey, A., Gerum, E., "Roll-over prevention system for commercial vehicles – additional sensorless function of the electronic brake system." Vehicle System Dynamics, Vol. 32, p.285 – 297, 1999.

[5] Lu, J., Messih, D., Salib, A., "Roll rate based stability control – the Roll Stability Control ™ system."

[6] Tamaddoni, S.H., Taheri, S., "Yaw stability control of tractor semi-trailers", SAE Technical Paper 2008-01-2595, 2008.

[7] Tamaddoni, S.H., Taheri, S., "A new control algorithm for vehicle stability control", ASME Proc. Of 10th Intl. Conf.

on Advanced Vehicle and Tire Technologies (AVTT), NY, USA, 2008.

[8] Odenthal, D., Bunte, T., Ackerman, J., “Nonlinear steering and braking control for vehicle rollover avoidance”, in European Control Conference, 1999.

[9] Pacejka, H.B., *Tire and Vehicle Dynamics*. Second ed. 2006: SAE International.

[10] Braghin, F., Cheli, F., Sabbioni, E. (2006). “Environmental effects on Pacejka’s scaling factors.” Vehicle System Dynamics **44**(7): 547 – 568

ACKNOWLEDGEMENTS

This project was supported in part by a grant from the Tank and Automotive Command (TACOM) of the U.S. Army, with Dr. Alexander Reid as Program Manager. The views expressed in this paper are those of the authors, and not the U.S. Government, the U.S. Army, or TACOM. The authors would also like to thank the Department of Animal and Poultry Sciences at Virginia Tech and Danville Regional Airport in Danville, VA for providing facilities for tire testing.