DEVELOPMENT OF MADYMO-BASED MODEL FOR SIMULATION OF LABORATORY ROLLOVER TEST MODES

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ABSTRACT

Types of vehicle rollovers can be classified into two categories: untripped and tripped. Untripped 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. As reported in the open literature, various test methods for conducting rollover events such as SAE J2114, Side Curb Trip, Critical Sliding Velocity, and Corkscrew have been used. This paper presents the development of MADYMO-based models for simulating vehicle kinematics in these four modes.
The CAE methodologies using MADYMO is interactively developed with the test methodologies. Experimental data obtained from these test modes are used for developing rollover CAE models for replicating vehicle motions under similar test conditions. Analyses of simulated results provide feedback to improve the test procedures. Testing with improved procedures provide additional new data for continued model refinements. MADYMO-based CAE tools thus provide quality models with better simulated and/or predicted results. MADYMO rollover models consist of sprung and un-sprung masses, suspension systems and tires, whose characteristics are extracted from ADAMS-based vehicle handling model. Use of the MADYMO-based models to support rollover testing, rollover sensing algorithm development, and rollover protection system development will be described. Since MADYMO modeling described in this paper is a rigid-body based approach, model limitations and issues associated with rollover simulation will also be discussed. In addition, model correlations with test data in these four modes and future areas of improvement will be presented.

INTRODUCTION

For many years, NHTSA has conducted research investigating the underlying causes of vehicle rollover accidents, developing rollover test procedure, and developing vehicle and roadway design criteria to help reduce both the number and the severity of rollover accidents. The rollover process, which involves a complex interaction of forces from suspension systems, tires, power-trains, and road surface, is one of the most complicated types of safety analysis. To study the vehicle and/or occupant kinematics during rollover crashes, mathematical models are useful tools for understanding essential rollover mechanics and evaluation of restraint system performance in mitigating occupant ejection. Tools available for such analysis include vehicle dynamic handling models, occupant gross-motion simulators [1-3] and finite element (FE) analysis programs.

A BRIEF REVIEW OF ROLLOVER MODELS

Rollover models are basically mathematical analyses which describe equations of motion derived for a simplified vehicle system consisting of one rigid body or two/three rigid bodies connected by joints and springs. Models are specifically developed for studying rollover mechanics under specific conditions. Jones [4] used a simple one-degree-of-freedom model to study the mechanics of vehicle rollover as a result of curb impact by treating the contact force at the curb as impulse forces in determining the vehicle kinematics. Ford and Thompson [5] developed a two-dimensional model as an initial attempt to predict the rollover characteristics of a vehicle. Their model is basically a 2D rigid-body of an automobile to allow simulation of vehicle ground contact and airborne motion. Lund and Bernard [6] developed a one-rigid-body model for analysis of simple rollovers to study the mechanics of the tilt table test and critical sliding velocity. Rollover simulation using a nonlinear model was reported by Eger et al. [7], using two rigid bodies with non-linear springs to represent suspension systems.

Other commercially available programs that have been used in vehicle dynamic handling are ADAMS by MDI [8] and PC-Crash by Maclnnis [9]. These models can simulate vehicle kinematics for inputs to Crash Victim Simulators (CVS), such as CAL3D/ATB and MADYMO for occupant kinematics simulations.

Both CAL3D/ATB and MADYMO programs are gross-motion simulators for vehicle occupant dynamics in three-dimensional motion in a crash environment. Prasad and Chou [10] published a detailed review of these models. Applications of these simulators in rollovers are presented below.

CAL3D/ATB.

Since the early 80's, CAL3D (later known as ATB which stands for Articulated Total Body), has been used for rollover studies. Rollover simulations were made possible in CAL3D with an improved option, which allows specification of vehicle angular motion. Kaleps et al. [11] and Obergefell et al. [12] conducted simulations of rollovers lasting up to 4 seconds. Use of ATB in the study of the occupant kinematics and the vehicle motion during rollover tests were presented in a series of papers. In the first paper of this series, Smith et al. [13] used ATB to study the occupant dynamics during a rollover by identifying some input parameters that were needed in the simulation. These included occupant' body segment shape and weight, moments of inertia, and body joint torque properties. In addition, vehicle interior geometry and its motion, the contact characteristics for the occupant and vehicle interactions, and the seat belt characteristics were also needed. The primary purpose of models developed by Ma et al. [14] and Cheng et al. [15] were developed to simulate occupant kinematics with or without restraint systems. The vehicle rollover motion was input to the models by describing its translational and rotational acceleration time histories. These time histories were obtained from rollover tests. Cheng et al. [16] further reported application of CAL3D/ATB to study vehicle and occupant kinematics in a rollover. Using the ATB models, evaluations of vehicle glazing materials were also made to study potential occupant ejection mitigation and head injuries reduction during rollover accidents

MADYMO.

The multi-body code MADYMO offers many options for defining the dynamic environment with interaction characteristics. This flexibility allows reasonable replication of some rollover tests. To simulate a rollover phenomenon, the vehicle model needs to be developed. In the development of rollover models, the contact between the vehicle and the ground plays a key role in determining the rollover consequence. Selection of appropriate contact parameters between the vehicle and the ground, such as stiffness, coefficient of friction, hysteresis and damping, is extremely important. However, lacking such data generally leads to "trial and error" methods to establish appropriate values for these parameters. In order for further application of the models, it is essential that their correlations with the test results be established.

MADYMO applications to rollover simulations have appeared in the literature. Blum [17] explored feasibility of using MADYMO to simulate rollovers in various conditions. Aljundi et al. [18] gave a brief description of rollover impact simulation using a MADYMO package. Yaniv et al. [19] developed a MADYMO model and validated against test results for restrained occupants with an inflatable tubular structure (ITS). Their model was then run to evaluate the effectiveness of ITS in preventing occupant ejection during rollover events. Sharma [20] used the model to help develop a rollover component test methodology for evaluating restraint systems under a NHTSA contract. Renfroe et al. [21] presented the MADYMO modeling of vehicle rollovers and resulting occupant kinematics. MADYMO models in general give fairly good predictions of vehicle kinematics at its initial and airborne phases during a rollover, and can be applied to (1) help establish threshold(s) for rollover sensor system development, and (2) guide and determine the initial conditions for rollover tests. Recently, Frimberger et al. [22] adapted MADYMO for occupant simulation in corkscrew type rollover situation. It should be mentioned that the rigid-body approach in the aforementioned simulations precludes itself from predicting vehicle structural crush and its effect on occupant kinematics during a rollover. In order for predictive structural model development, use of finite element analysis and test data from numerous rollover modes are needed.

In this paper, MADYMO-based models are developed to simulate certain full vehicle rollover test modes as described below.

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FULL VEHICLE ROLLOVER TESTS

Types of rollovers can be classified into two categories: untripped and tripped. Untripped 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. Different test methodologies such as SAE J2114, Side Curb Trip; Critical Sliding Velocity, and Corkscrew, as shown in Figure 1, for simulating rollover events have been used and reported in the open literature. A brief description of each mode is given below.

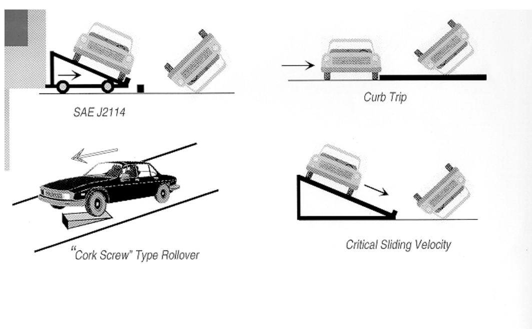

Figure 1 - Examples of various rollover test modes.

<u>SAE J2114 Test Mode</u>:

The SAE J2114 rollover test procedure is shown in Figure 1, along with other test modes to be described later. The test vehicle is placed laterally on a rolling cart at an angle of 23 degrees from the horizontal with the lower-side of the tires against a 4 inch (10.16 cm) high rigid flange so that the lower-side tires are 9 inches (22.86 cm) above the ground. The vehicle and rolling cart are accelerated to a constant velocity of 30 mph (50 kph) and the cart is then stopped in a distance of not more than 3 feet (0.914 m) without transverse or rotational movement of the platform during its deceleration. The cart deceleration must be at least 20 g's for a minimum of 40 milliseconds.

<u>Side Curb Trip Mode</u>:

The vehicle is placed laterally on a sled against a curb, which is about 6 inches (15 cm) high or high enough to allow rim interaction with it. The sled is towed to a pre-determined velocity (which is determined by a CAE rollover model of the specific vehicle) and released from the tow device prior to impact with the curb. In this test mode, the vehicle will experience a lateral acceleration of approximately 7 to 12 g's.

<u>Critical Sliding Velocity Mode</u>:

In this mode, the test vehicle is laterally placed at the top of a slanted ramp, which can be adjusted to any slanted angle. The wheels of the vehicle sit on "frictionless padding", which are guided in the slanted ramp. The vehicle slides down the ramp if the slanted angle is large enough, and initiates rollover when the tires impact the flange located at the bottom of the ramp as shown in Figure 1.

<u>Corkscrew Mode</u>:

This test mode requires a test ramp. Figure 2 shows various ramp configurations with different height, width, and length that appeared in the literature. It should be pointed out, however, that the SAE J857 test is currently obsolete. During the test, a vehicle with sufficient longitudinal velocity runs over the ramp, with wheels from one side of the vehicle on the ramp, while wheels from the other side of the vehicle on the ground. The vehicle gains a high asymmetric acceleration from the z-direction. When it leaves the ramp, the vehicle rotates along its longitudinal axis until it impacts against the ground.

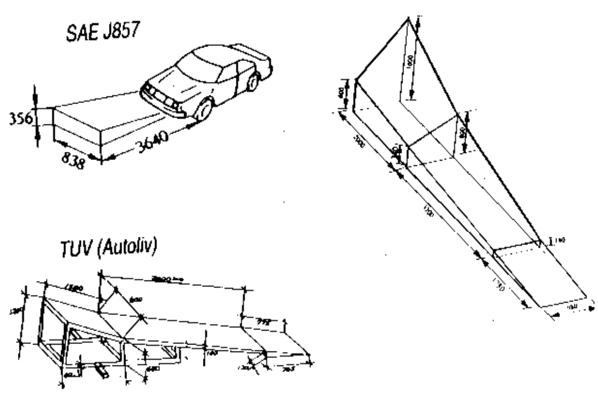

Figure 2 – Various ramp configurations.

TYPICAL TEST DATA

Some typical data obtained from the afore-mentioned rollover tests are shown in Figure 3. These data are the angular rate time histories, which can be integrated to yield angular displacement (or rotation) time histories. Both angular rate and rotation are important parameters for rollover sensing algorithm development. The aims at developing MADYMO-based are to provide such information through simulations.

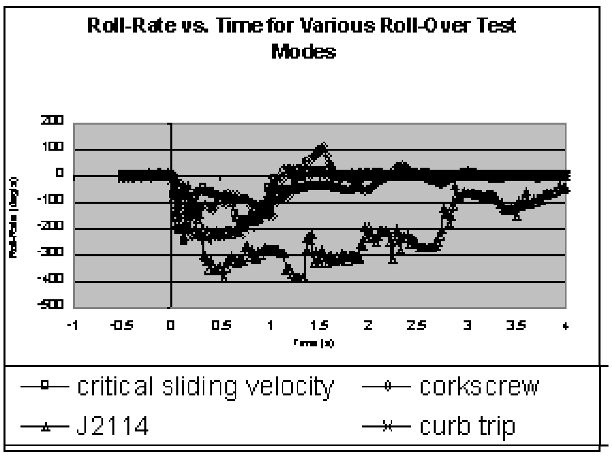

Figure 3 – Typical sample data from rollover tests.

Vehicle parameters that need to be included in the model are: wheel base, track width, roof height, CG height, weight, moments of inertia in roll/pitch/yaw directions, suspension spring rate and damping. The exterior and interior profiles of the vehicle are represented by a series of ellipsoids, including the windshield, seat back, seat cushion, door trim, steering wheel, etc. The contact between the vehicle and the ground is characterized by specifying load-deflection curves for the contact between the vehicle ellipsoid and the plane representing the ground. Contacts between the dummy and vehicle interior components are determined by the contact between ellipsoid-to-ellipsoids, representing the vehicle interior and the dummy segments, respectively. The behavior of tires is modeled using ellipsoids with prescribed stiffness, damping and coefficient of friction. These characteristics are approximations for demonstrating the vehicle/occupant kinematics with very limited representation of vehicle structural energy absorption during the rollover. For occupant restraint system performance, MADYMO provides a finite element capability for not only modeling the belts and/or curtain airbags, etc., but also simulating structural deformation during vehicle contact with the ground. Flexible structural modeling using MADYMO still needs to be evaluated for possible future applications. However, this study focuses on the development of rigid-body-based MADYMO rollover models for simulating four test modes as shown in Figure 1.

MADYMO ROLLOVER MODELING MERHODOLOGY

In MADYMO, the vehicle is modeled as a system consisting of the vehicle body and the suspension sub-systems. Inclusion of the suspension sub-system allows simulation of wheel's bouncing/jouncing effect on the vehicle body in addition to the deformation of the tires during rollover events. The resulting deflection, which is dependent of spring and damping characteristics of the suspension system, has substantial effects on the rollover kinematics. In the suspension sub-system model, a translational joint is used to model the wheel bouncing in the vehicle vertical direction. In addition, a revolute joint is applied to model the spin of the wheel/tire, which is essential in rollover simulation of a vehicle driving forward over a corkscrew ramp.

a) Simulation of SAE J2114 Rollover Test Mode:

A MADYMO-based model for simulating SAE J2114 rollover test procedure consists of the following:

Vehicle and Test Platform Sub-models - This model, as shown in Figure 4, consists of vehicle, test platform and ground sub-models. The ground is modeled as a plane and is the global reference frame from which all the parameters were measured. The vehicle is modeled with two (2) body systems consisting of vehicle and engine masses. The engine is connected to the vehicle CG by a very stiff joint via Cardan restraints. The total mass of the vehicle is about 2000 kgs. Hyper-ellipsoids of the 8th order are used to represent the vehicle parts such as windshield, doors, roof, tires and engine. The coordinates of the vehicle CG and mass moments of inertia about the CG are obtained from actual vehicle test data. The vehicle is initially oriented at an angle of 23 degrees from the horizontal and resting against the flange as described above. The test platform is modeled as one body system. Hyper-ellipsoids are used to represent the inclined platform, and base of the platform.

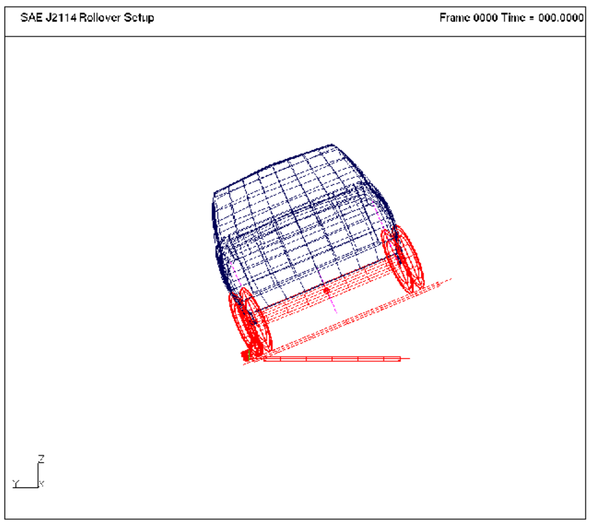

Figure 4 – MADYMO model for SAE J2114 test mode simulation

<u>Initial Conditions & Acceleration Field</u> - The vehicle is prescribed an initial velocity of 30 mph along with the platform in the lateral direction with reference to vehicle. The platform is then stopped in a short distance (less than 3 feet) while maintaining a deceleration rate of at least 20 g's for 40 msec. This is achieved by prescribing an acceleration field on the "platform alone" in the lateral direction opposite to its motion. In the tests conducted in this study, honeycombs are used as a stopping mechanism.

<u>Contact-Interactions</u> - Plane-Ellipsoid sub-model is used for contact interactions for calculating contact forces. Contact is specified between tires of the vehicle and the platform along the flange. Contacts are also specified between all parts of vehicle and ground (e.g., tires/ground, engine/ground, roof/ground and doors/ground). Contact stiffnesses between contacting surfaces have been specified by means of force-deflection characteristics.

Required inputs for generating the SAE J2114 model are a) vehicle geometry in both exterior and interior dimensions, b) vehicle parameters, such as vehicle c.g. location, moments of inertia, track width, wheel base, vehicle weight, etc. c) suspension system and tire parameters such as suspension linkage geometry, spring and damping characteristics, tire dimensions, moment of inertia, tire characteristics, etc., and d) initial conditions: vehicle test velocity, vehicle position, etc.

Figure 5 shows a sequential rollover motion of a vehicle in the SAE J2114 rollover test procedure. Figure 6 presents a comparison of the simulated results in roll rate and lateral acceleration with the test data, exhibiting a favorable agreement in roll-rate time history. Lack of prediction in lateral acceleration is due to many assumptions used in the rigid-body modeling. Some test parameters that affect rollover performance are listed in Table 1, along with MADYMO model limitations.

Figure 5 – Sequential rollover motion of a vehicle in SAE J2114 test procedure

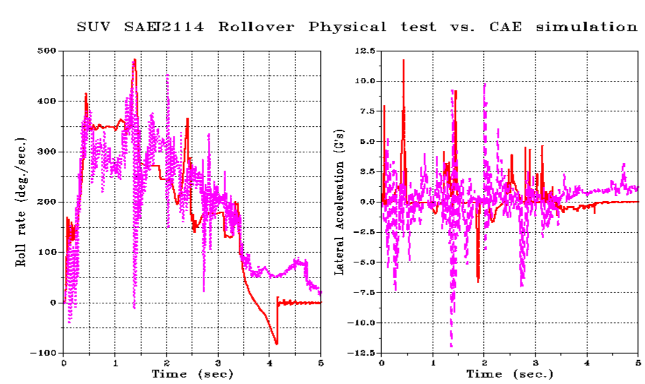

Figure 6 – Comparison s of simulated results with the test data – roll rate and lateral acceleration

b) Simulation of Critical Sliding Velocity (CSV) Mode:

Figure 7 shows the model used for simulating the CSV mode. A system, which models the vehicle carrier, should have the same mass as the actual test fixture. This carrier system is connected to the global system with a translational joint and a specific inclined angle from the test. Flange height should be shorter than the height it represented. Half the height of the flange is used to specify the semi-axial length for the ellipsoid. The travel distance and the deceleration force acting on the vehicle carrier are specified in terms of force-displacement function for this translational joint. Zero force is specified during the free travel of the vehicle carrier. The resistant force is specified to model the deceleration force from the honeycomb, which is used to decelerate the vehicle carrier. The magnitude of the deceleration force is based on the honeycomb used. Both the vehicle and the carrier have zero initial velocity and have a gravitation force of one g in the vertical direction. Major factors affecting the vehicle roll rate in this mode are: flange/tire contact stiffness, flange/tire contact friction, tire/vehicle carrier contact stiffness, stiffness of vehicle suspension system.

Two cases, i.e. no-roll and roll, are simulated. In the no-roll case, the fixture was set at an angle of 11^0, and the comparison of results between the simulation and the test is shown in Figure 8. The simulated result in roll-rate shows a higher peak than the test data. For the roll case, the inclined angle of the test fixture was set at 19^0, and Figure 9 presents both the simulated and test results. Simulated results in both roll-rate and lateral acceleration look good in this case. The simulated result in roll-rate deviates at approximately 0.8 second is mainly due to the setup of the test where the vehicle was restrained with tethers to prevent the test vehicle from being rolled over the test fixture, thus saving the vehicle for repeated use.

Figure 7 – A CSV MADYMO model

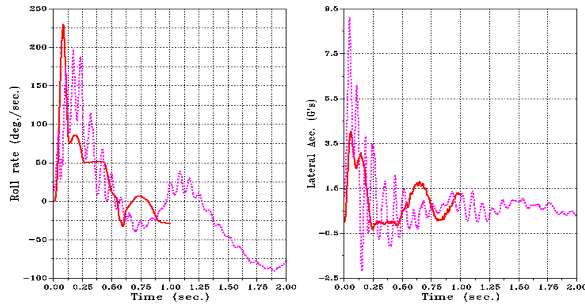

Figure 8 – No-roll case in CSV – simulation vs. test

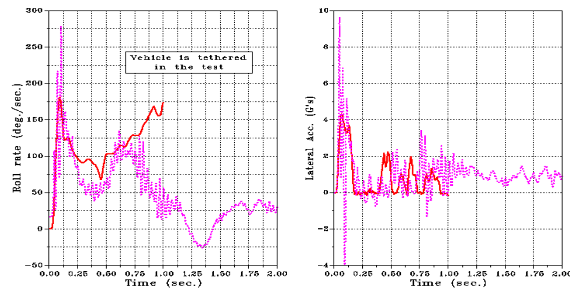

Figure 9 – Roll case in CSV – simulation vs. test

c) Simulation of Side Curb Trip Mode:

A side curb trip MADYMO model is shown in Figure 10. This model uses the same modeling procedure as the one for critical sliding test, except that the translational joint has zero (0) inclined angle with respect to the ground and an initial lateral velocity for the vehicle only is needed. The vehicle carrier is treated as a side flange padded by honeycomb, and no initial velocity is specified on it. The major factors, which affect the vehicle rollover, are: vehicle lateral velocity, flange height, flange/tire contact stiffness, and friction. The roll case of this mode is simulated using an initial lateral velocity of 16 mph. Figure 11 exhibits the simulated results when compared with the test data. The initial peak in roll-rate compares well with that from the test, while the model still predicts higher peaks in lateral acceleration.

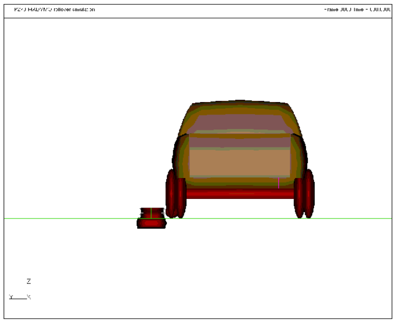

Figure 10 – A Side Curb Trip MADYMO model

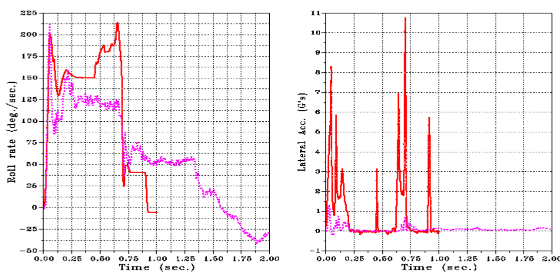

Figure 11 – Comparisons of results of Side Curb Trip – simulation vs. test

d) <u>Simulation of Corkscrew Mode</u>:

A corkscrew ramp MADYMO model is shown in Figure 12. In this model, a finite element tire sub-model is used. The geometric configuration of the corkscrew ramp can be modeled either using ellipsoids, planes associated with the global system or a rigid body associated with a system which is fixed on the ground. Contact between the tires and the ramp must be defined, and a higher friction coefficient for the contact needs to be specified to ensure that the vehicle stays on the ramp. The vehicle forward (or longitudinal) velocity is specified as an initial velocity for the vehicle system. Position the vehicle and make sure the right-hand-side tire ride on the correct position of the ramp. The major factors, which determine the vehicle rollover are: vehicle forward velocity, and the riding position of the vehicle on the ramp. In order to improve the model prediction, a finite element tire sub-model is used instead of ellipsoids. Figs. 13 and 14 show comparisons of roll-rate and lateral acceleration for the no-roll and roll cases, respectively. Results show favorable agreement between the simulation and the test.

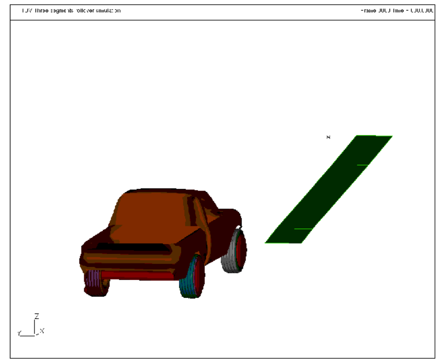

Figure 12 – A Corkscrew ramp MADYMO model

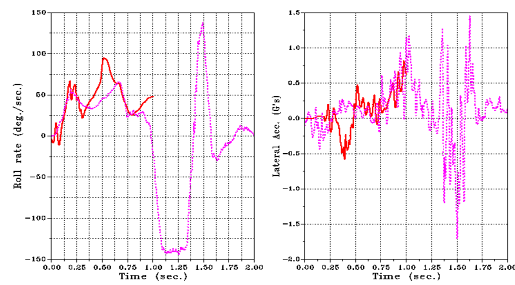

Figure 13 – No-roll case in Corkscrew ramp mode – simulation vs. test

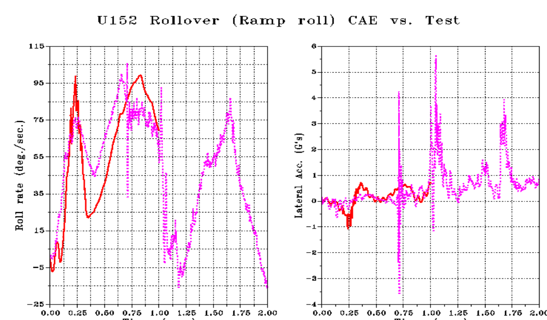

Figure 14 – Roll case in Corkscrew ramp mode – simulation vs. test

FUTURE CAE MODELONG AND TESTING

For future MADYMO-based CAE rollover modeling, efforts should be directed towards:

- Developing algorithms to allow specifying path for vehicle motion;

- Refinement of suspension model for improved side curb impact simulation;
- Developing mechanisms to allow provisions in simulating wheel separation from the axle during impact, if any;
- Using finite element vehicle interior for better contact simulation instead of plane/ellipsoid contact elements
- Developing a suspension model database
- Exploring MADYMO's magic formula for tire modeling
- Exploring MADYMO's finite element capability for structure simulations

In addition, a feasibility study needs to be conducted to develop hybrid modeling methodology by partly using rigid-based technique to obtain vehicle kinematics in rigid-body motion phase, and then using the information from the rigid-body phase data for deformable structural study in calculating stress/strain when the vehicle contacts ground.

To support the above modeling effort, testing is needed to provide data, which characterize (1) tire properties in lateral direction, (2) dummy joint properties in lateral direction and rotation about AP (Anterior-Posterior) direction, and (3) force-deflection pertaining to dummy/vehicle interior interactions.

CONCLUSIONS

Rollover models of varying degrees of complexity based on rigid-body assumptions are reviewed. The analytical studies and model simulations are becoming useful method for determining the influence of vehicle parameters on vehicle response. In this paper, MADYMO-based models for simulating vehicle kinematics in SAE J2114, side curb trip, critical sliding velocity and corkscrew ramp are developed. Simulated results are compared with test data, exhibiting good agreement between them. The rigid-body based MADYMO models are easier to run to provide trend analysis and design direction for rollover restraint system development. However, it should be noted that the rollover modeling techniques described herein do not include the ability to reconstruct a rollover event. Development of rollover models is a continuous improvement process, which requires experimental data for validation and refinement. In the future, this technology will continue to grow with possible use of finite element analysis for rollover modeling to study vehicle structural deformation and occupant kinematics interacting with the restraint system and vehicle interior.

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Table 1. Rollover modes and CAE model summary.

Test Mode	**Test parameters that affect performance**	**MADYMO Model Limitations**
SAE J2114 (23-degree)	▪ Road conditions: dry/wet; concrete/ asphalt; evenness; surface roughness ▪ Friction ▪ Deceleration pulse of dolly: G's & duration ▪ Stopping mechanism: hydraulic/ pneumatic/honeycomb ▪ Vehicle initial ground contact ▪ "Curb" height: (currently 4") ▪ Platform inclination: (currently 23-degree) ▪ Dolly height and tire pressures ▪ Platform orientation (0 vs. 45-deg.) ▪ Test Vehicle wheel rim types; tire size ▪ Test vehicle tire pressures	▪ Engineering judgment with assumed parameters (friction, etc) ▪ Numbers of rigid body system used. ▪ Rigid vs. deformable ▪ Currently tire modeling technology is unavailable ▪ Allowable interactions ▪ Multi-directional friction capability
Critical Sliding Velocity	▪ Test fixture ▪ Sliding surface condition and friction ▪ Lubricant material used to reduce friction ▪ Sliding angle (C.G. may be shifted) ▪ Sliding distance ▪ Release mechanism ▪ Pre-to-run time (tire/lubricant reaction)	▪ Only consider the following vehicle parameters (i.e. C.G. height, track width, moments of inertia) are needed. ▪ Need wheel/curb interaction data
Side Curb Trip	▪ Curb height ▪ Curb stiffness ▪ Tire pressure ▪ Tire & rim types ▪ Velocity ▪ Tire/curb interaction ▪ Test method: vehicle on cart vs. vehicle slides on ground	▪ Suspension model is good for up-and-down motion ▪ Wheels are rigidly attached to axle. Cannot simulate wheel breakage ▪ Lack of information on wheel/curb contact characteristics
Corkscrew	▪ Ramp shapes: height, length continuous vs. segmental ▪ Ramp surface: flat vs. spiral ▪ Wheel/ramp friction ▪ Ramp top edge/vehicle interaction ▪ Vehicle travel path: straight vs. curve ▪ Tire pressure ▪ Velocity ▪ Steering wheel: lock vs. unlock	▪ Need good suspension model for accurate timing for roll ▪ Limited capability in simulating interaction between ramp top edge and suspension ▪ Lack of multi-directional friction capability ▪ Can simulate locked steering wheel case only