ROLLOVER CRASHWORTHINESS OF A RURAL TRANSPORT VEHICLE USING MADYMO

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ABSTRACT

In this work a full vehicle model of a rural transport vehicle (RTV) is developed in MADYMO. The steering, tier and suspension are modeled using standard modules available in the package. A speed controller was also incorporated to maintain a constant speed of the vehicle in the simulations. Validation of the model was done against experimental accelerations measured over a bump. The validated model was then used to predict rollover characteristics using Slowly Increasing Steer, J-Turn, and Road Edge Recovery maneuvers. These maneuvers were conducted for three different loading conditions viz. RTV without passengers, RTV with unrestrained passengers, and RTV with restrained passengers, and the safe speeds are compared with those of other vehicles.

Keywords: RTV, Rollover, Slowly Increasing Steer, J-Turn and Road Edge Recovery.

NOTATIONS

F_f, F_r	:	frictional forces between road and front wheel, road and rear wheel
g	:	gravitational constant
H	:	maximum height of bump profile
l_r	:	ascent length of bump profile along X-axis
l_f	:	descent length of bump profile along X-axis
l_x	:	distance travelled along X-axis since commencement of the bump profile.
N_f, N_r	:	normal forces by the road on front wheel and road on rear wheel
P_{fx}, P_r	:	horizontal forces between front wheel and front suspension system, rear wheel and rear suspension system
P_{fz}, P_{rz}	:	vertical forces between front wheel and front suspension system, rear wheel and rear suspension system
T_f, T_r	:	accelerating torque at front wheel and rear wheel
$u_1, \dot{u}_1, \ddot{u}_1$	:	front wheel displacement, velocity and acceleration inputs along vertical axis due to bump profile
$u_2, \dot{u}_2, \ddot{u}_2$	:	rear wheel displacement, velocity and acceleration inputs along verticalaxis due to bump profile
$x, \dot{x}, \ddot{x}$	:	displacement, velocity and acceleration of TWV along longitudinal axis
x_s	:	distances along X-axis where the bump profile commence
x_m	:	distance along X-axis where the peak of bump profile commence

$z, \dot{z}, \ddot{z}$: displacement, velocity and acceleration of TWV body along vertical axis

$z_1, \dot{z}_1, \ddot{z}_1$: displacement, velocity and acceleration of front wheel along vertical axis

$z_2, \dot{z}_2, \ddot{z}_2$: displacement, velocity and acceleration of rear wheel along vertical axis

$\beta, \dot{\beta}, \ddot{\beta}$: pitch angle, pitch velocity and pitch acceleration of TWV body

ω : angular velocity of wheels

INTRODUCTION

In India, an RTV has been a common mode of passenger conveyance system since 1998. Since then numerous cases of rollover of RTV have been reported. This necessitated investigation of rollover characteristics of RTV through experiential as well as theoretical models. Experimental rollovers test are not only destructive in nature, but are also very expensive to conduct. Hence a suitable theoretical model is required to be developed. Forkenbrock [1, 2, 3] had used experimental model for standard rollover maneuvers to predict the rollover characteristics of 2001 Chevrolet Blazer, 2001 Toyota 4 Runner, 1999 Mercedes ML320, and 2001 Ford Escape. Gawade [4] had developed theoretical model in MATLAB, to predict rollover characteristics of three wheel-scooter taxis for standard maneuvers. In this paper the rollover characteristics of RTV has been predicted through theoretical model of RTV developed in MADYMO for standard maneuvers described by Gawade [4], namely the Slowly Increasing Steer, J-Turn, and Road Edge Recovery maneuvers. For validating the RTV MADYMO model, an experiment of RTV passing over a bump was conducted for vertical accelerations and results of the experiment were compared with those obtained through simulations in MADYMO, for the equivalent operating conditions. Three different loading conditions, viz. RTV without passengers, RTV with unrestrained passengers, and RTV with restrained passengers, are used in the rollover simulations

PARAMETERS OF THE RTV

A ‘Rural Transport Vehicle’, popularly known as RTV, was launched in 1998. The vehicle is popular because of its small size and shape and has a capacity for conveyance of 15 people simultaneously. As an illustration, In Delhi, it is a major transportation mode for general public. Some technical specifications for RTV were obtained from the manufacturer’s catalog and some geometric data necessary for modeling (like physical dimensions), is obtained through manual measurement. The overall weight of the vehicle was known from vehicle catalogue whereas the weights of the individual components has been either measured or approximated / calculated for smaller components. Stiffness and damping properties of suspension were measured experimentally. The Technical specifications of RTV, from manufacturer catalog are given in Table 1.

Table 1 Technical specification of the RTV

Engine weight	205 Kg
Engine dimension	710* 640* 863 mm^3
Wheel base	240 mm
Wheel track	150 mm
Weight of RTV	1460 Kg

RTV MADYMO MODEL

Full vehicle model of RTV was developed. To simulate rollover maneuvers, special care has to be taken for the steering model, suspension model, tire model, tire-road contact, RTV seat model and the differential torque controller. The tier damping ratio and tier Stiffness has been taken 0.011 and 300 KN/m respectively [5, 6].

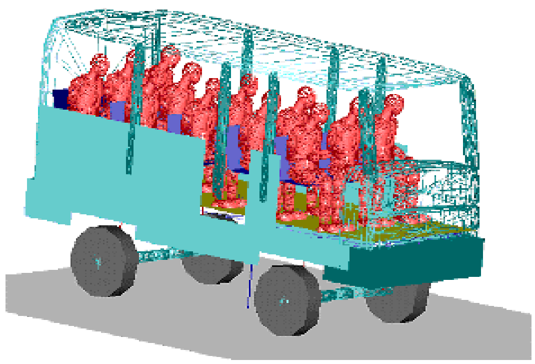

Figure 1 RTV MADYMO Model with passengers

VALIDATION OF RTV MADYMO MODEL

Experiments are conducted to measure the vertical acceleration of RTV chassis over a bump for different velocities of RTV. The vertical acceleration of RTV chassis has been acquired using an accelerometer. Accelerometer was attached with the RTV chassis as shown in Figure 2 and it was placed at the rear part of the RTV because maximum acceleration is expected at the rear part.

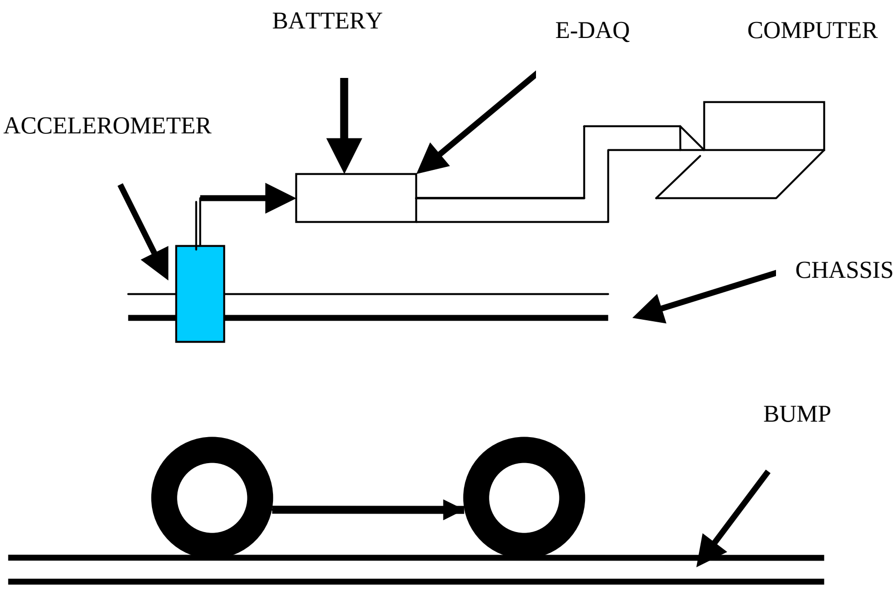

Figure 2 Experimental setup

Acceleration was sampled at the sampling frequency of 1000 HZ with an ‘e-DAQ’ data acquisition system from Somat. The data was filtered digitally using Butterworth low pass filter. Experiments were conducted over the bump at various speeds. RTV MADYMO model was used to simulate equivalent operating conditions in MADYMO. Figure3 and Figure 4 show comparison of the experimental and simulation results in time domain. Vertical accelerations predicted by The RTV MADYMO model agrees well with those of experimental results, for velocities of the RTV, 20km/hr and 25 km/hr, except at the end of the bump where all the wheels of the RTV completed travel over the bump. In this region, the vertical acceleration of the chassis, predicted by the theoretical model, is damped out slowly as compared to that of experimental results. The discrepancy, between the simulation and the experimental results, may be due to the model used for damping, of the joints and materials, is based on the assumed data use in the model of RTV MADYMO. These parameters are difficult to measure and model accurately.

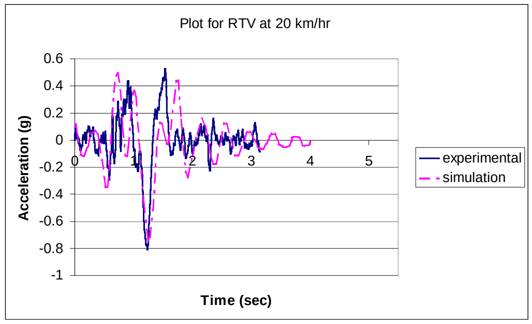

Figure3 Experimental and simulations results at 20 km/hr

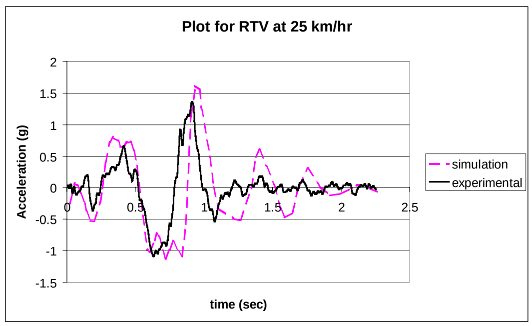

Figure 4 Experimental and simulation results at 25 km/hr

ROLLOVER MANEUVERS

Forkenbrock [2] describes standard rollover maneuvers. These have been simulated for the RTV to assess its rollover propensity.

Slowly increasing steer maneuver

The Slowly Increasing Steer (SIS) maneuver was used to characterize the lateral dynamics of each vehicle, and was based on the "Constant Speed, Variable Steer" test defined in [2]. In this maneuver, vehicle should run at the maximum possible velocity in the normal driving condition (for RTV 60 km/hr). Rollover is predicted for this maneuver, at 60 km/hr of RTV, in the simulation. To begin this maneuver, the vehicle was driven in a straight line at a constant speed. Hand wheel position was linearly increased from zero to 270 degrees at a rate 13.5 degree per second, as shown in Figure 5 Hand wheel position was held constant at 270 degrees for two seconds, and then returned back to zero degrees in four seconds. During the simulation, concerned quantity is lateral acceleration of the RTV. Lateral acceleration data was collected during Slowly Increasing Steer tests. This was plotted with respect to time, and a best-fit line was estimated to accurately describe the data from 0 to 0.4 g as shown in Figure 6. Using the slope of the best-fit line, the steering-wheel position, at middle point of the linear range of lateral acceleration, was predicted as 53.86 degrees (2.15 degree rotation of front wheel). This hand wheel position was used in simulations for maneuvers of J-Turn and RER steering inputs, as described in later sections of this paper. Differential torque controller is modeled to maintain constant speed for the RTV in the slowly increasing steer maneuver. Implementing a differential torque controller was quite effective in the simulations for slowly increasing steer maneuver, to maintain the constant speed for the RTV. The entrance speed of the RTV, in the simulations for SIS maneuver, was 16.67 m/s and the minimum entrance speed of the RTV in the simulation was 16 m/s as shown in Figure 7. In simulating of SIS maneuver, speed drops by 0.67 m/s which is 4.091 % variation of the initial entrance speed. And this variation of the speed of the RTV, is in the acceptable range.

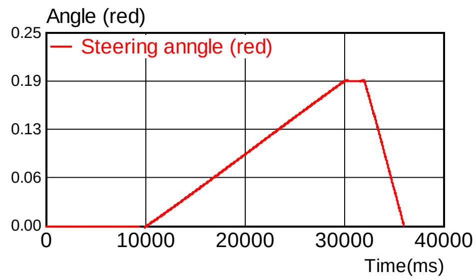

Figure 5 Steering input in the simulation for SIS maneuvers

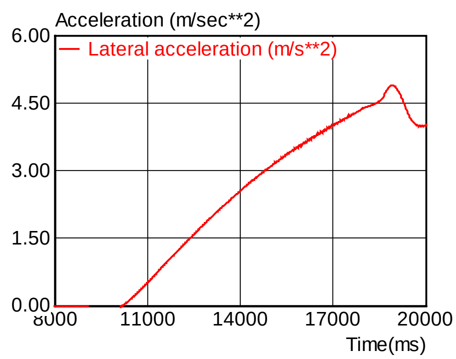

Figure 6 lateral acceleration of RTV in the simulation for sis maneuvers

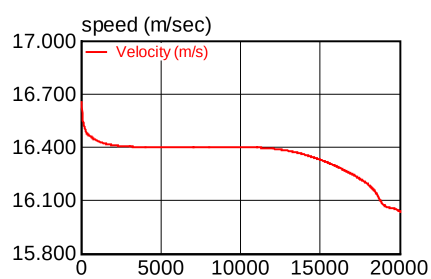

Figure 7 RTV speed variation in the simulation for SIS maneuvers

J-Turn Maneuver

The initial steering-wheel magnitudes (A), for simulating J-TURN Maneuver, were calculated by multiplying the steering-wheel angle that produced an average of 0.2g in the Slowly Increasing Steer maneuver by a scalar of 8.0 and is equal to 16.5 degrees rotation of the front wheels. The rate of steering-wheel ramp was 1000 degrees/sec, which is equal to 40 degrees/sec for front wheel (steering ratio for RTV is 25:1). Initial steer was performed in 0.413 seconds. The nominal entrance speeds in the simulations for J-TURN Maneuver ranges from 5 to 8 m/sec. The Termination condition in the simulation is achieved when 'two-wheel lift' condition is reached. The requirement for 'two-wheel lift' condition is that at least two inches of simultaneous lift of the inside wheels is to be observed during a particular simulation.

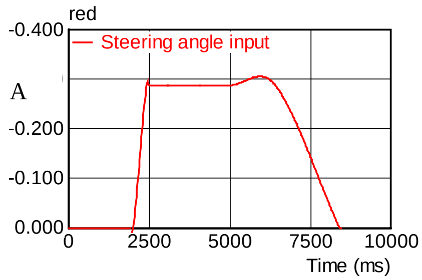

Figure 8 Steering input for J-Turn maneuvers

NHTSA J-TURN maneuver simulations are done for three different loading conditions viz. RTV without passengers, RTV with restrained passengers and RTV with unrestrained passengers.

RTV WITHOUT PASSENGERS

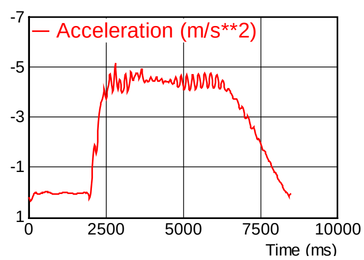

Figure 9 Lateral acceleration of RTV without passengers

The NHTSA J-Turn simulations are performed for different entrance speeds. The termination condition (two-wheel lift) was achieved for the entrance speed of 8 m/s. During downward iteration of vehicle, the maximum entrance speed of the RTV is 7.5 m/s where two-wheel lift was not observed, for RTV without passengers.

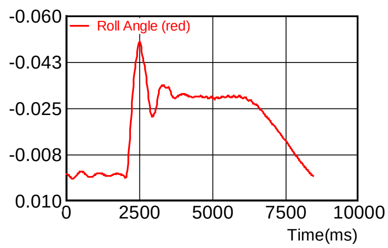

Figure 10 Roll angle of RTV without passengers

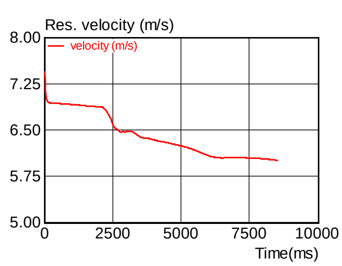

Figure 11 Resultant speed of RTV without passengers in the simulations for J-turn maneuvers

RTV WITH RESTRAINED PASSENGERS

In this model passengers are restrained on the RTV sheet. This condition is obtained by defining spherical kinematics' joint between passenger dummy and the sheet. The NHTSA J-Turn simulations are performed for different entrance speeds. The termination condition (two-wheel lift) was achieved for the entrance speed of 7 m/s. During downward iteration of vehicle, the maximum entrance speed of the RTV is 6.8 m/s where two-wheel lift was not observed, for RTV without passengers.

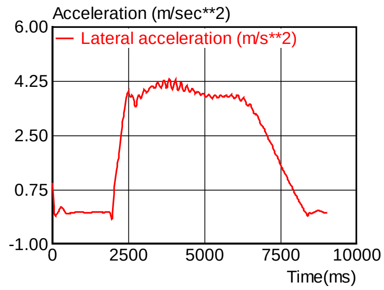

Figure 12 Lateral acceleration of RTV with restrained passengers for J-Turn maneuvers

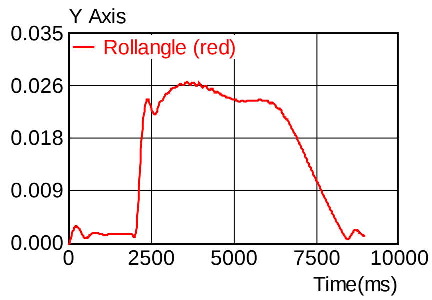

Figure 13 Roll angle of RTV with restrained passengers for J-Turn maneuvers

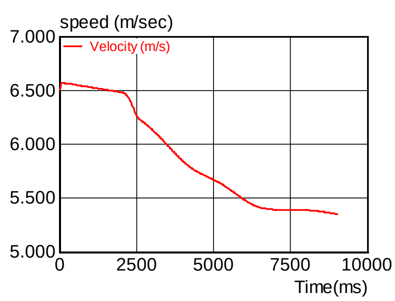

Figure 14 Speed of RTV with restrained passengers in the simulations for J-Turn maneuvers

RTV WITH UNRESTRAINED PASSENGERS

In this model passengers are placed on the RTV sheet by defining contacts between the passenger dummies and the sheet. The loading and unloading properties of the dummies are used for defining the contact between the dummies and the sheet. The NHTSA J-Turn simulations are performed for different entrance speeds. The termination condition (two-wheel lift) was achieved for the entrance speed of 6.5 m/s. During downward iteration of vehicle, the maximum entrance speed of the RTV is 6 m/s where two-wheel lift was not observed, for RTV without passengers.

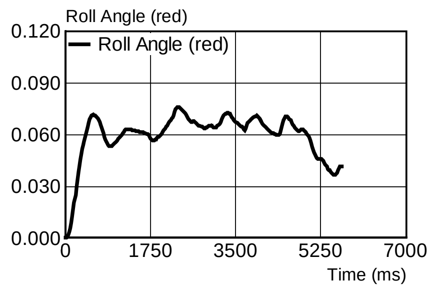

Figure 15 Roll angle of RTV with unrestrained passengers for J-Turn maneuvers

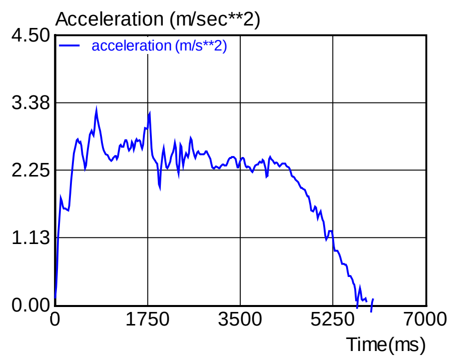

Figure 16 Lateral acceleration of RTV with unrestrained passengers for J-Turn maneuvers

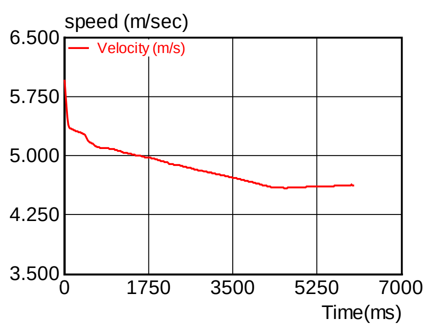

Figure 17 Speed of RTV with unrestrained passengers in the simulations for J-Turn maneuvers

ROAD EDGE RECOVERY (RER) MANEUVER

The parameters to be maintained in the RER maneuver (also known as Fishhook 1b maneuver or the Roll Rate Feedback Fishhook maneuver) are derived from the Fishhook 1 maneuver. Fishhook 1 maneuver is used during NHSTA Phase II. The steering-wheel magnitudes for initial and counter steer were symmetric, and were calculated by multiplying the steering-wheel angle that produced an average of 0.2 g in the SIS maneuver by a scalar of 6.5 and is equal to 30.73 degrees of the front wheel rotation. The rate of steering-wheel ramp was 720 degrees/sec which is equal to 28.8 degrees /sec for front wheel (since the steering ratio for RTV is 25:1). Initial steer was performed in 0.8545 seconds.

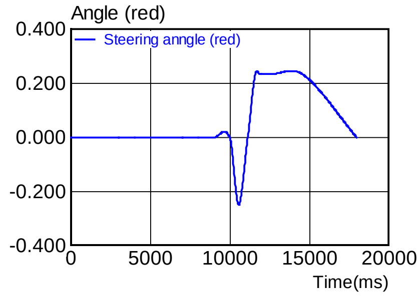

Figure 18 Steering input in simulation for RER maneuver

RER maneuver simulations are done for three different loading conditions viz. RTV without passengers, RTV with restrained passengers and RTV with unrestrained passengers.

RTV WITHOUT PASSENGERS

The RER simulations are performed for different entrance speeds. The termination condition (two-wheel lift) was achieved for the entrance speed of 9 m/s. During downward iteration of vehicle, the maximum entrance speed of the RTV is 8.75 m/s where two-wheel lift was not observed, for RTV without passengers.

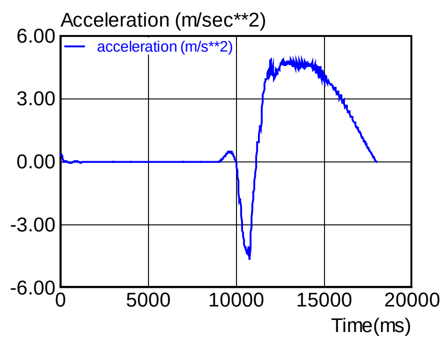

Figure 19 Lateral acceleration of RTV without passengers for RER maneuvers

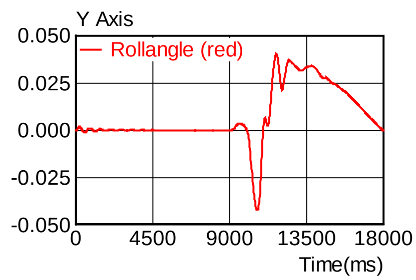

Figure 20 Roll angle of RTV without passengers for RER maneuvers

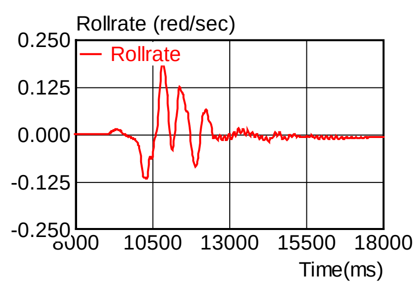

Figure 21 Roll rate of RTV without passengers for RER maneuvers

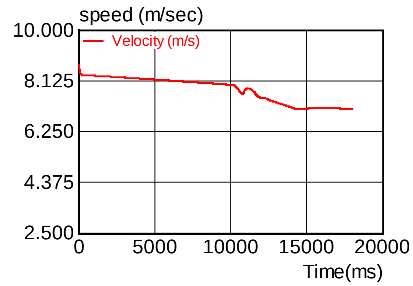

Figure 22 Speed of RTV without passengers in the simulation for RER maneuvers

RER WITH RESTRAINED PASSENGERS

The RER simulations in this case, are performed for different entrance speeds. The termination condition (two-wheel lift) was achieved for the entrance speed of 8 m/s. During downward iteration of vehicle, the maximum entrance speed of the RTV is 7.5 m/s where two-wheel lift was not observed, for RTV with restrained passengers.

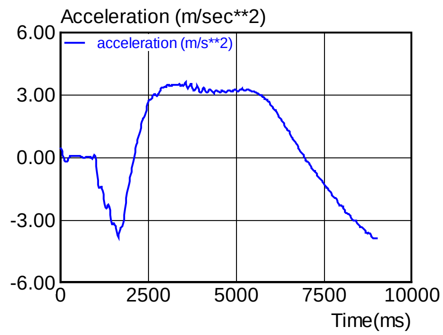

Figure 23 Lateral acceleration of RTV with restrained passengers for RER maneuvers

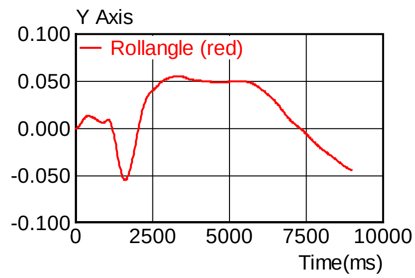

Figure 24 Roll angle of RTV with restrained passengers for RER maneuvers

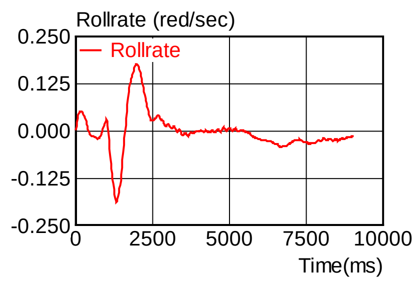

Figure 25 Roll rate of RTV with restrained passengers for RER maneuvers

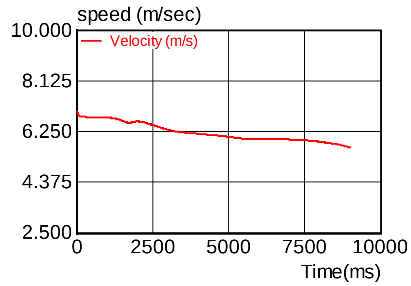

Figure 26 Speed of RTV with restrained passengers for RER maneuvers

RER WITH UNRESTRAINED PASSENGERS

The RER maneuver, in this case, have been simulated with different entrance speeds, the termination condition (two-wheel lift) was achieved at 7.5 m/s. During downward iteration of vehicle, maximum entrance speed of the RTV is achieved at 7 m/s where two-wheel lift was not observed for RTV with unrestrained passengers.

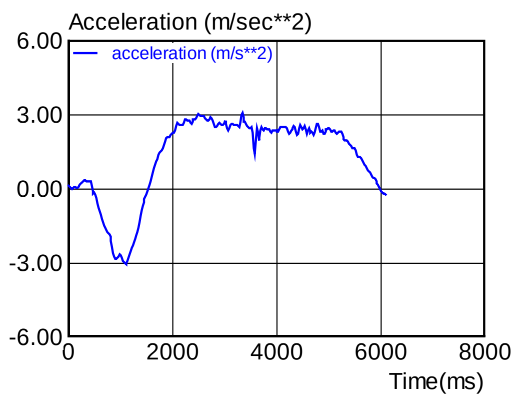

Figure 27 Lateral acceleration of RTV with unrestrained passengers for RER maneuvers

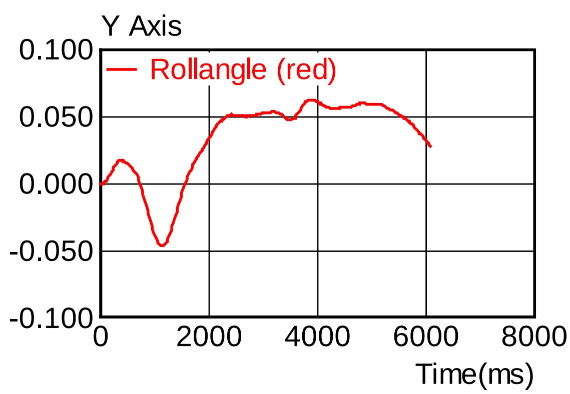

Figure 28 Roll angle of RTV with unrestrained passengers for RER maneuvers

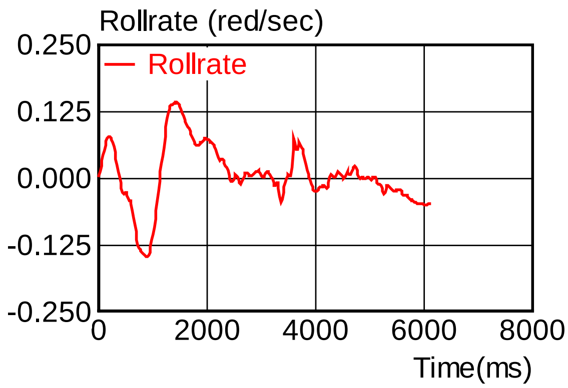

Figure 29 Roll rate of RTV with unrestrained passengers for RER maneuvers

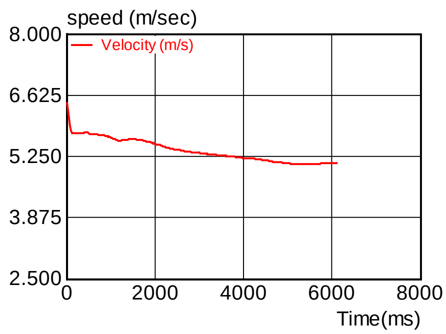

Figure 30 Speed of RTV with unrestrained passengers for RER maneuvers

COMPARISON OF MANEUVERS

J-Turn and RER maneuvers were simulated for the modeled RTV with three different loading conditions. A comparison of both maneuver simulations is presented in Table 2. From the comparison, it is evident that in each of the maneuver maximum possible entrance speed is maximum in RTV without passenger's condition and minimum in RTV with unrestrained passengers. It was expected because center of gravity locations in first loading condition i.e. RTV without passengers is lower than second loading condition i.e. RTV with unrestrained passengers. Comparing the two loading conditions RTV with restrained passengers and RTV with unrestrained passengers respectively reveals that maximum possible entrance speed is higher for RTV with restrained passengers loading condition. This is because of sideways outward movement of passengers during steering of RTV causes outward movement of center of gravity. NHTSA has conducted experiments for standard rollover maneuvers on existing vehicles. Published results are compared with the present RTV simulation results. The comparison is presented in the

Table 3. Results show that entrance speed for RTV is minimum when compared to other vehicles. So it can be concluded that roll over resistance of RTV is very low as compared to other tested vehicles.

Table 2 Results summary of rollover simulations

Loading condition	Maximum possible entrance speed (m/sec) for J-Turn	Maximum possible entrance speed (m/sec) for RER
RTV without passengers	7.5	8.75
RTV with restrained passengers	6.5	7.5
RTV with unrestrained passengers	6	7

Table 3 Maximum possible entrance speed (m/sec) for rollover maneuvers

Vehicle	J-Turn	RER
2001 Chevrolet Blazer	17.29 m/s	16.09 m/s
2001 Toyota 4 Runner	20.5 m/s	17.06 m/s
1999 Mercedes ML320	20.04 m/s	….
2001 Ford Escape	…	21.51 m/s
RTV	7.5 m/s	8.75 m/s

CONCLUSIONS

Model of RTV has been developed in MADYMO and validated for case of RTV passing over a bump. Results of validation, given in article 'Validation of RTV MADYMO Model', for two different velocities 20 Km/hr and 25km/hr, reveal that developed model almost predicts actual behavior of RTV. Validated model, then, is used for predicting rollover characteristics of RTV. The comparisons of results show that rollover characteristics of RTV are not safe as compared to those of other vehicles. Hence the rollover analysis indicates the strong need to improve the design of RTV, for better rollover characteristics.

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