Paper Number

Rollover crash analysis of the RTV using Madymo

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ABSTRACT

A full vehicle model of the RTV is developed in MADYMO including steering, tire and suspension. A torque controller is simulated to maintain set speed of the RTV in simulations. The suspension characteristics were validated using experimental accelerations measured over bumps. The model is used to predict rollover limits using Slowly Increasing Steer, J-Turn, and Road Edge Recovery maneuvers. The rollover limits under three different loading states, RTV without passengers, RTV with unrestrained passengers, and the RTV with restrained passengers have been studied.

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_{rx} 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

A ‘Rural Transport Vehicle’, popularly known as RTV was launched in India in 1998. The vehicle is popular because of its small size and shape, has a capacity for conveyance of 15 people simultaneously and that it runs on the inexpensive CNG. Incidents of rollover of RTV have been reported and there were about 11 reported in Delhi in. This is out of proportion to the vehicle proportion. This paper reports investigations of rollover stability of the RTV based on dynamic maneuvers. Our findings are that the RTV may have low resistance to rollover and hence may not be suitable for deployment in zones having peak speeds in excess of 45 kmph.

The conventional measure of rollover stability has been the static stability ratio. The NHTSA of USA has proposed dynamic rollover maneuvers using which Forkenbrock et.al. (2001)&(2002) had conducted experiments procedures to determine the rollover characteristics of 2001 Chevrolet Blazer, 2001 Toyota 4 Runner, 1999 Mercedes ML320, and 2001 Ford Escape. Subsequently, Gawade et.al (2003) had developed models in MATLAB to predict rollover characteristics of three wheel-scooter taxis for these standard maneuvers.

In this paper the rollover characteristics of RTV in dynamic maneuvers has been predicted using a model of RTV developed in MADYMO. The maneuvers simulated were Slowly Increasing Steer, J-Turn, and Road Edge Recovery maneuvers as reported in Forkenbrock et.al. (2001)&(2002).

The model was built using parameters available in the manufacturers catalog and field measurements. For validating the suspension characteristics of the model, a of the RTV was run over a bump and the resultant vertical accelerations were measured. The bump-pass was simulated in MADYMO, for the equivalent operating conditions.

Unlike earlier reported tests and simulations, three different loading conditions were studied to evaluate the effect of the number of passengers. The three situations considered were the RTV without passengers, RTV with unrestrained passengers, and RTV with restrained passengers. There is variation in rollover stability under these loading considerations.

Parameters of RTV

Some technical specifications for RTV were obtained from the manufacturer's catalog and remaining data, necessary for modeling, is obtained through measurement. Though the overall mass of the vehicle was known, the masses of the various components have been estimated to obtain the same CG location. Stiffness and damping properties of the suspension was determined experimentally by loading them and studying the decay curve in free vibration. The technical specifications of RTV as available from manufacturer catalog are given in Table 1.

Table 1: Technical specification of the RTV

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

RTV MADYMO Model

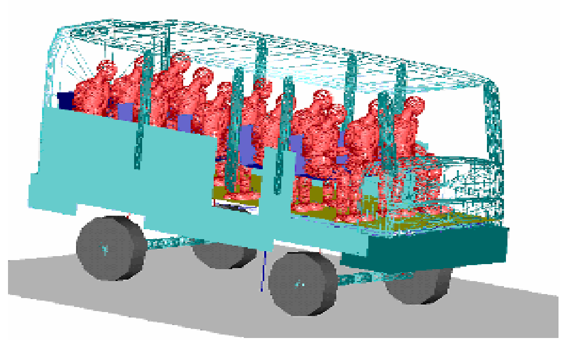

Figure 1:RTV MADYMO Model with passengers

Full vehicle model of RTV was developed. To simulate rollover maneuvers following features were incorporated in the model:

1. Steering mechanics
2. Suspension
3. Tyre model
4. Tyre-road interaction
5. RTV seat modeling
6. Differential torque controller

The tyre damping ratio and tyre stiffness was not determined experimentally but has been taken 0.011 and 300 KN/m respectively, based on the work of Hinch et.al. (1991) and Lupker et.al. (1991)

Validation of RTV MADYMO Model

In dynamic maneuvers, in addition to the geometry, the suspension parameters play a significant role. Experiments were conducted to measure the vertical acceleration of RTV chassis over a bump for varying velocities of RTV to validate the suspension model.

The vertical acceleration of RTV chassis was acquired using an accelerometer. Attached to the chassis, as shown schematically in **Figure 2** at the rear of the RTV. The location was selected as the maximum acceleration while passing over a bump is expected at the rear.

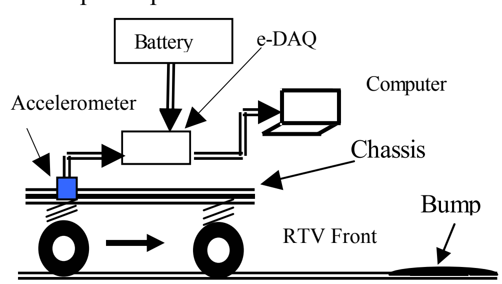

Figure 2 Experimental setup

Acceleration was sampled at the sampling frequency of 1000 HZ through the 'e-DAQ' (data acquisition system). The data was filtered digitally using Butterworth (which order ??) low pass filter at what frequency ?. Experiments were conducted over the bump at various speeds.

A comparison of the experimental and simulation results in time domain is shown in **Figure 3 and Figure 4.**

Vertical accelerations predicted by the MADYMO model of the RTV agrees well with those of experimental results (Can we quantify this matching ??). For the correlation is good 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 has traveled over the bump. In this region, the decay of the vertical acceleration of the chassis, as predicted by the theoretical model, is slower as compared to the experimental results. Data necessary for modeling components other than those listed above, like chassis compliance were not available to us and could be contributing to the discrepancy.

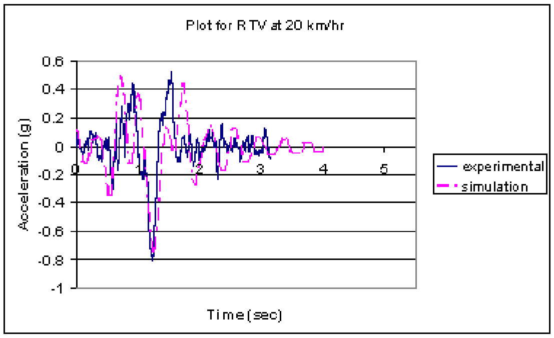

Figure 3: Experimental and simulation results at 20 km/hr

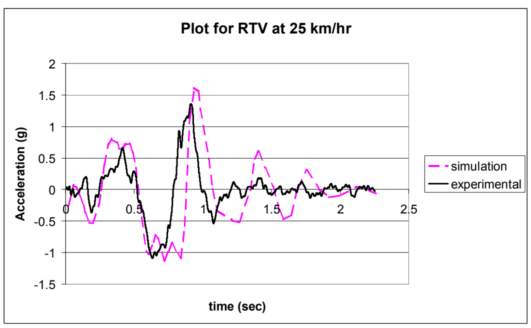

Figure 4: Experimental and simulation results at 25 km/hr

Rollover Maneuvers

The standard NHTSA rollover maneuvers as described in Forkenbrock et.al (2003) were used for the evaluation.

1. Slowly increasing steer maneuver

The Slowly Increasing Steer (SIS) maneuver used to characterize the lateral dynamics of each vehicle; based on the “Constant Speed, Variable Steer” test defined in Forkenbrock et.al (2003) was simulated. In this maneuver, vehicle running at the maximum possible velocity in the normal driving condition (taken as 60 km/hr for RTV) is steered at increasing angles till wheel lift off is indicated. The SIS is used to determine the parameters for the J-Turn and RER maneuvers and in itself is not a good measure of rollover stability.

To execute the SIS maneuver, the vehicle is initially driven in a straight line at a constant speed. Hand wheel (steering) position was linearly increased from zero to 270 degrees at a rate 13.5 degree per second, as shown in [**Figure 5**] (Change time scale to secs??). Hand wheel position was held constant at 270 degrees for two seconds, and then returned back to zero degrees in four seconds. During the maneuver, the lateral acceleration of the RTV is tracked.. The lateral acceleration was plotted with respect to time and the linear segment was identified to be between a 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 estimated as 53.86 degrees (this corresponds to 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.

In field tests, the driver or computerized drive actuates the accelerator pedal in a vehicle to maintain a constant speed. The speed drops quite rapidly when steered if the vehicle is in free roll. So a differential torque controller is modeled to maintain constant speed for the RTV in the slowly increasing steer maneuver.(Need to add a reference to Tushar’s SAE/Canadian paper??) . 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**]. In simulating of SIS maneuver, speed drops by 0.67 m/s, which is an 4.091 % variation, within the acceptable range.

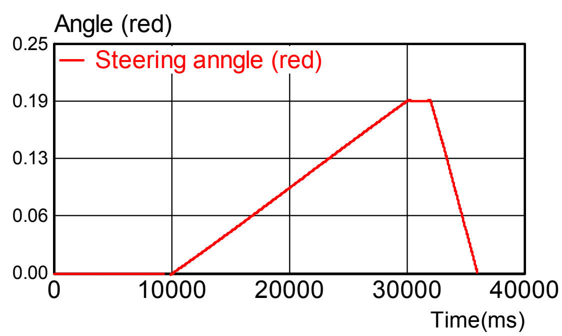

Figure 5: Steering input in the simulation for SIS maneuvers

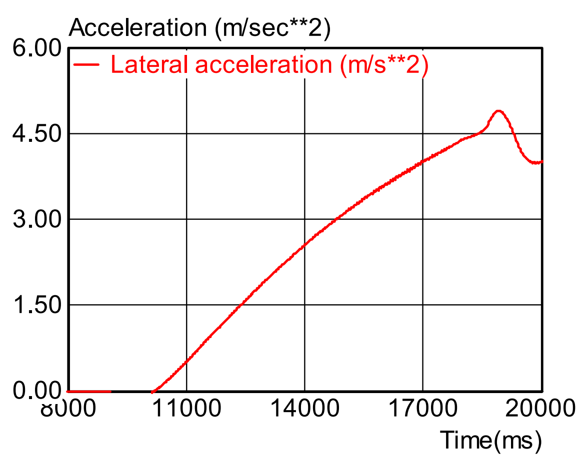

Figure 6: Lateral acceleration of RTV in the simulation for SIS maneuvers

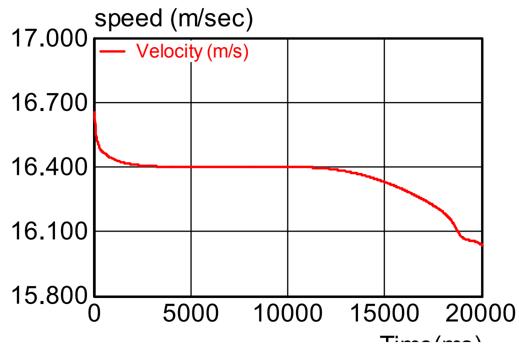

Figure 7:RTV speed variation in the simulation for SIS maneuvers

2. J-Turn Maneuver

The initial steering-wheel magnitudes (A), for simulating the 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 which corresponds to 16.5 degrees rotation of the front wheels. The rate of steering-wheel ramp was 1000 degrees/sec, or 40 degrees/sec at the front wheel (steering ratio for RTV is 25:1). Initial steer was performed in 0.413 seconds. The entrance speeds in the simulations for the J-Turn maneuver was varied until the'two-wheel lift' condition is reached. In the 'two-wheel lift' condition, the inside wheels lift at least by at least two inches from the ground. Also note that this is a free running maneuver, so the torque controller is not activated.

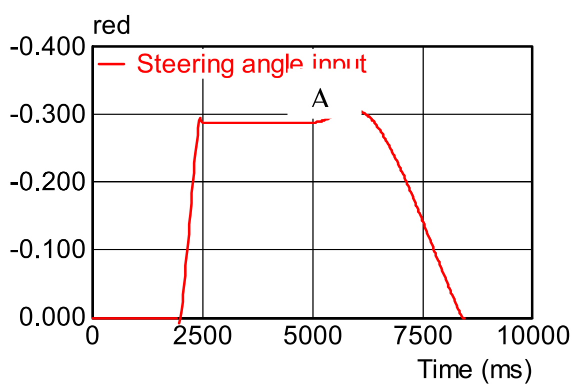

Figure 8: Steering input for J-Turn maneuvers

NHTSA J-Turn maneuver simulations were conducted for three different loading conditions viz. RTV without passengers, RTV with restrained passengers and RTV with unrestrained passengers.

RTV Without passengers

The NHTSA J-Turn simulations are performed for increasing entrance speeds starting from 5 m/s in steps of 1 m/s. The termination condition (two-wheel lift) was observed at the entrance speed of 8 m/s. During a downward iteration of the vehicle speed in steps of 0.1 m/s, at the entrance speed of 7.5 m/s two-wheel lift was not observed. This speed is taken as the rollover limit for the RTV without passengers on a J-Turn.

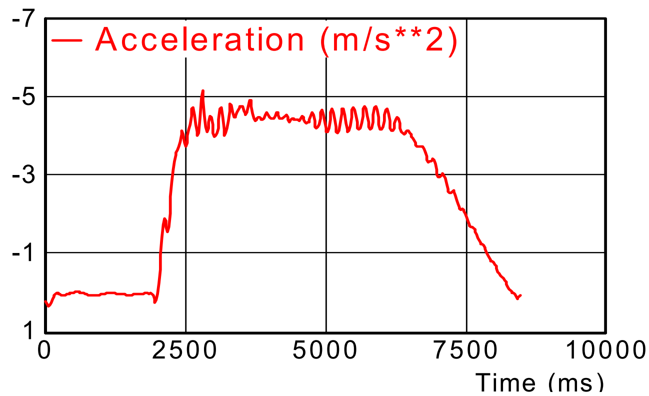

Figure 9 : Lateral acceleration of RTV without passengers

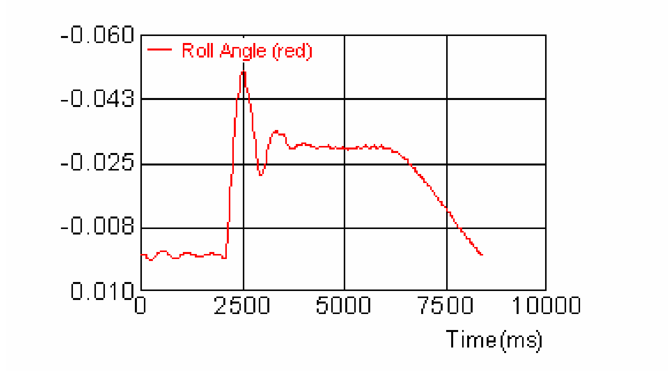

Figure10: Roll angle of RTV without passengers

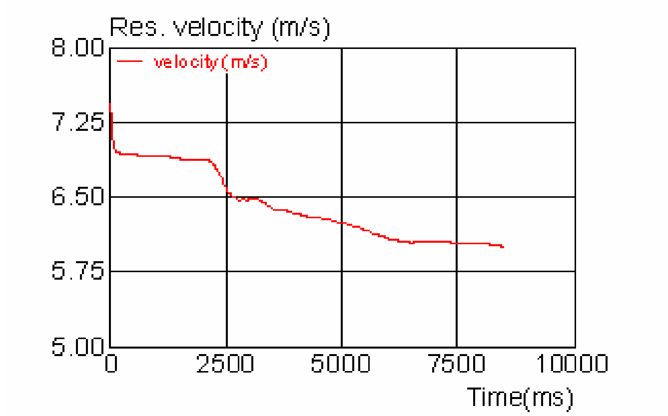

Figure11: Resultant speed of RTV without passengers in the simulations for J-turn maneuvers

RTV With restrained passengers

To simulate the effect of being seat belted, passengers are restrained on to the RTV seat. Since we were interested in studying vehicle rollover and not evaluating the safety of individual passengers, kinematic joint were defined between passenger dummy and the sheet that allowed rotation but disallowed translation between the dummy-pelvis and the seat. The rollover limit of the RTV with restrained passengers is 6.8 m/s , a drop of 0.7 m/s from that estimated for the empty vehicle.

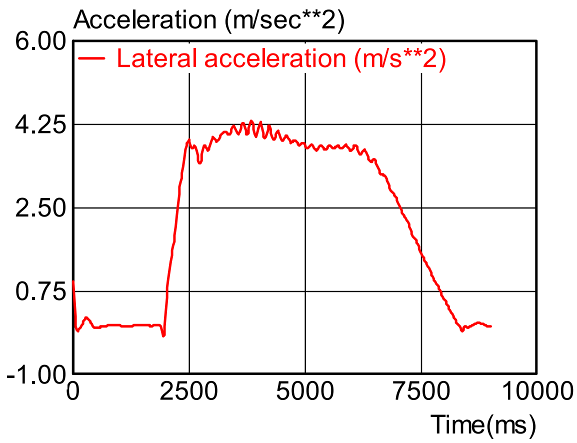

Figure12: Lateral acceleration of RTV with restrained passengers for J-Turn maneuvers

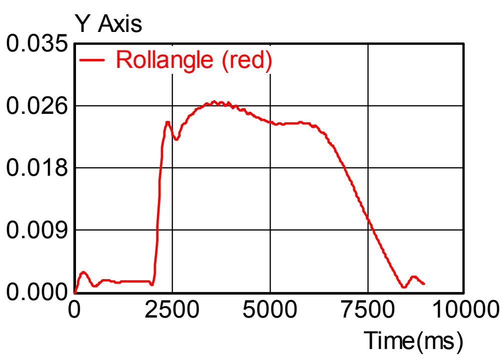

Figure 13: Roll angle of RTV with restrained passengers for J-Turn maneuvers

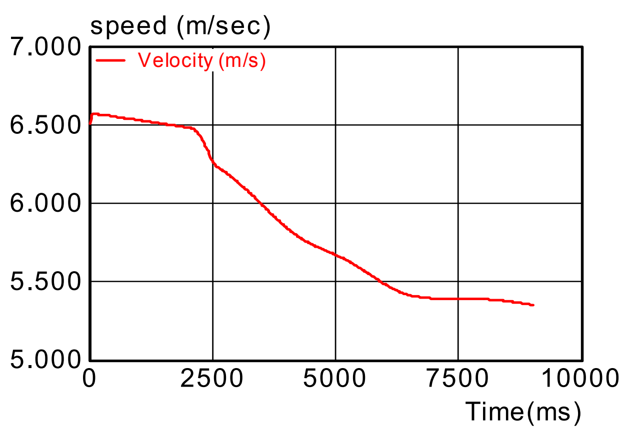

Figure 14: Speed of RTV with restrained passengers in the simulations for J-Turn maneuvers

RTV with unrestrained passengers

For this simulation, a contact interface was defined between the passenger dummies and the RTV body. The contact interface allows separation between the dummy and seat, but does not allow penetration. The NHTSA J-Turn rollover limit was predicted to be 6 m/s for RTV with unrestrained passengers.

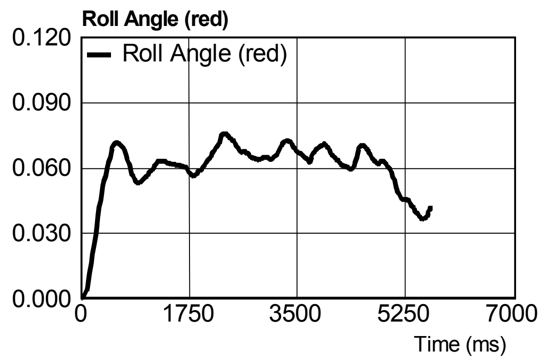

Figure 15: Roll angle of RTV with unrestrained passengers for J-Turn maneuvers

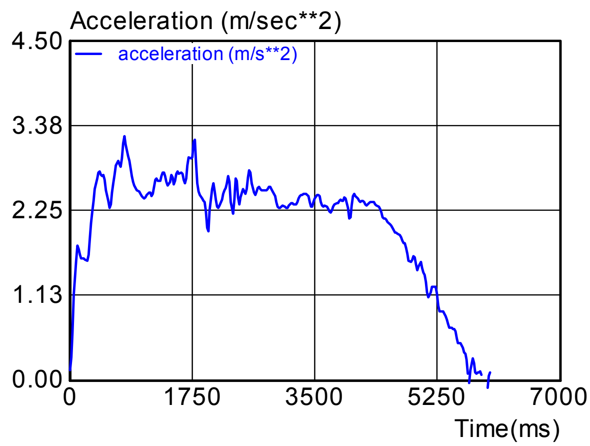

Figure 16: Lateral acceleration of RTV with unrestrained passengers for J-Turn maneuvers

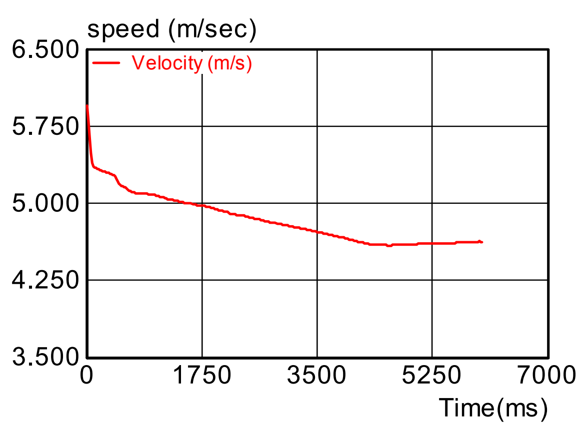

Figure 17: Speed of RTV with unrestrained passengers in the simulations for J-Turn maneuvers

3. Road Edge Recovery (RER) maneuver

The steering-wheel magnitudes for initial and counter steer were symmetric, and were calculated by multiplying the steering-wheel angle in the center of the linear range in the SIS maneuver by a scalar of 6.5 and is equal to 30.73 degrees of the steering wheel rotation. The rate of steering-wheel ramp was 720 degrees/sec which is equal to 28.8 degrees /sec for front wheel Initial steer was performed in 0.8545 seconds.

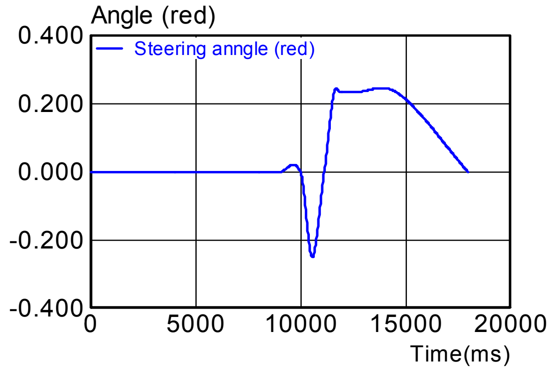

Figure 18:steering input in simulation for RER maneuver

RER maneuver simulations were conducted for the same loading conditions used for the J-turn; RTV without passengers, RTV with restrained passengers and RTV with unrestrained passengers.

RTV Without passengers

The rollover stability for the RER maneuver is predicted to be 8.75 m/s for the RTV without passengers.

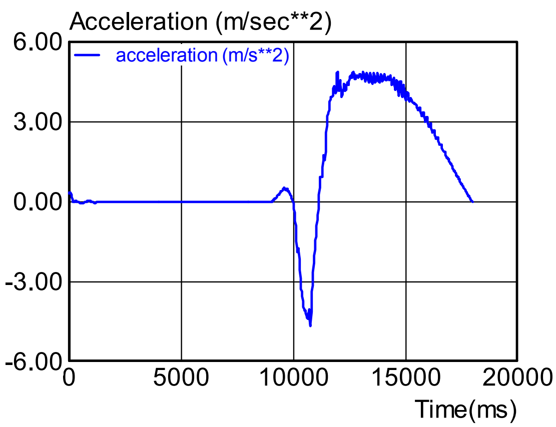

Figure 19: Lateral acceleration of RTV without passengers for RER maneuvers

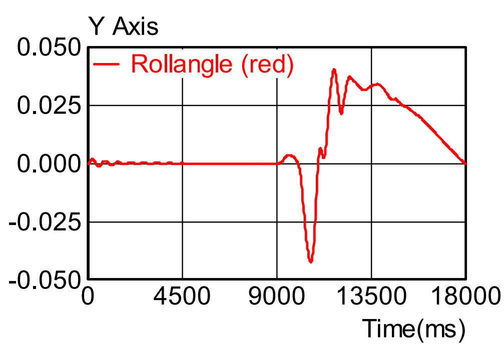

Figure 20: Roll angle of RTV without passengers for RER maneuvers

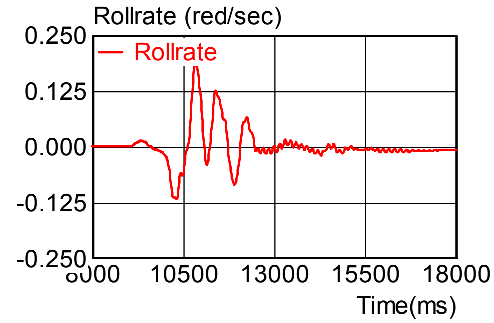

Figure 21: Roll rate of RTV without passengers for RER maneuvers

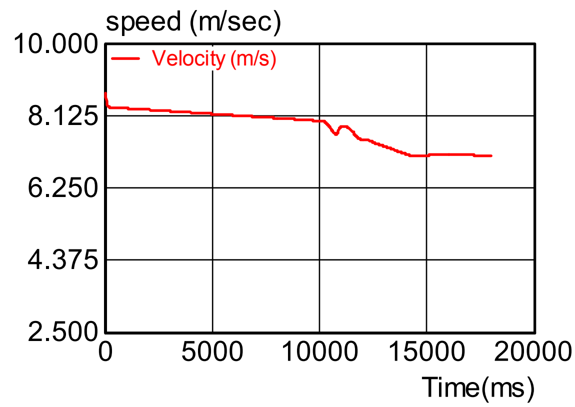

Figure 22: Speed of RTV without passengers in the simulation for RER maneuvers

RER with restrained passengers

The rollover stability for the RER maneuver is predicted to be 7.5 m/s for the for RTV with restrained passengers.

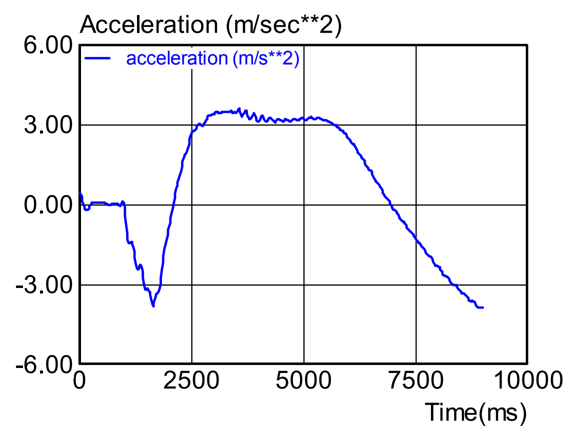

Figure 23: Lateral acceleration of RTV with restrained passengers for RER maneuvers

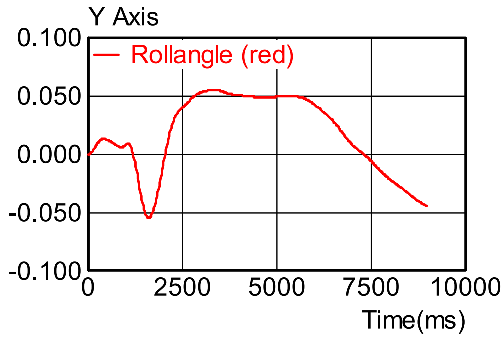

Figure 24: Roll angle of RTV with restrained passengers for RER maneuvers

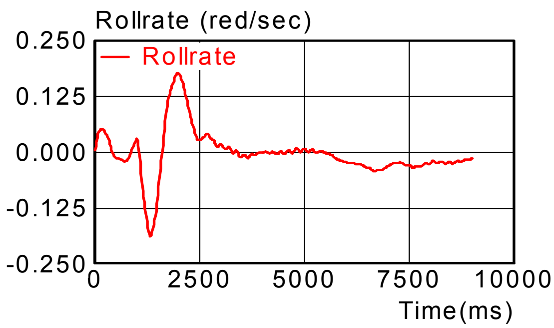

Figure 25: Roll rate of RTV with restrained passengers for RER maneuvers

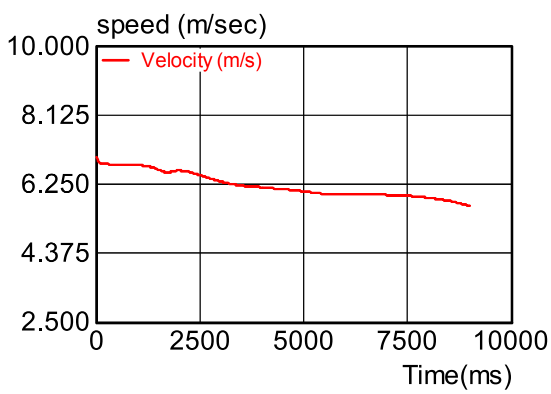

Figure 26: Speed of RTV with restrained passengers for RER maneuvers

RER with unrestrained passengers

The rollover stability for the RER maneuver is predicted to be 7 m/s for the RTV with unrestrained passengers.

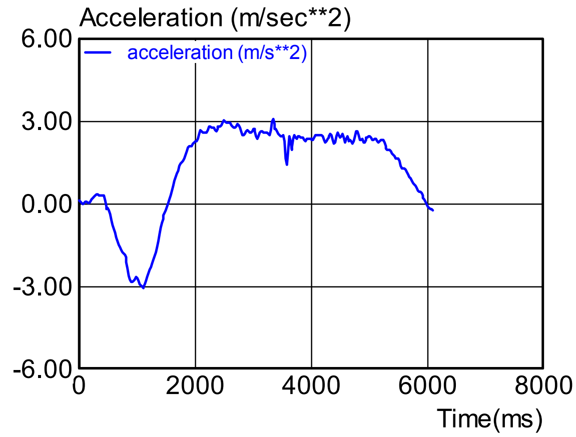

Figure 27: Lateral acceleration of RTV with unrestrained passengers for RER maneuvers

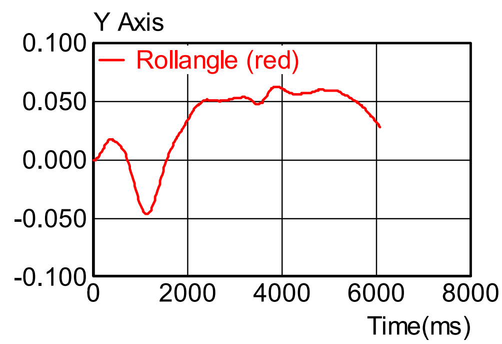

Figure 28: Roll angle of RTV with unrestrained passengers for RER maneuvers

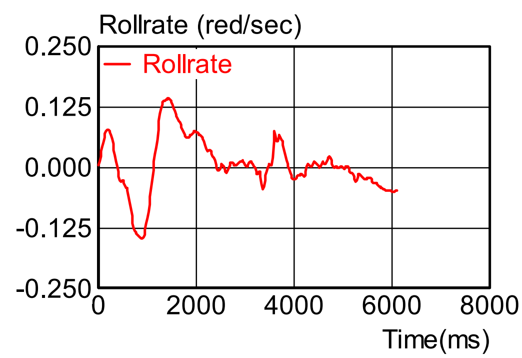

Figure 29: Roll rate of RTV with unrestrained passengers for RER maneuvers

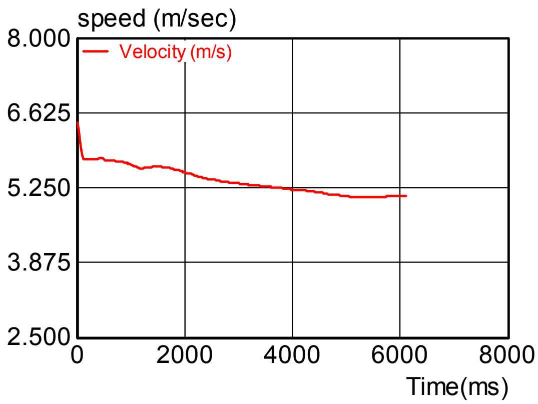

Figure 7: Speed of RTV with unrestrained passengers for RER maneuvers

Comparison of Maneuvers

J-Turn and RER maneuvers were simulated for the modeled RTV with three different loading conditions. A comparison of the predicted stability during both maneuvers is presented in

Table 2] From the table, it is evident that for either maneuver, the stable entrance speed is maximum in RTV without passenger and minimum in RTV with unrestrained passengers. This is to be expected as the center of gravity shifts upwards on addition of the passengers. The stable entrance speed is higher for RTV with restrained passengers than the unrestrained. The sideways outward movement of passengers during steering of RTV moves the CG outwards, closer to the line of support, thus reducing the stability.
NHTSA has conducted experiments for standard rollover maneuvers on existing vehicles. Simulation results for the Bajaj Three wheel vehicle with passenger is also available [Gawade etal, 2004]. Published results are compared with the present RTV simulation results. The comparison is presented in
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 even without passengers 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

Conclusion

Model of RTV has been developed in MADYMO and the suspension characteristics validated by measuring the acceleration of the RTV passing over a bump. The modelis used for predicting rollover characteristics of RTV in dynamic maneuvers. The comparisons of results show that rollover stability of the RTV is predicted to be inferior to conventional vehicles for which there is measured data. The rollover stability seems to seems to be almost at par with the three wheeled vehicles on the Indian roads. Considering that the RTV is capable of greater running speeds, it would seem that the RTV is prone to rolling over in urban roads that sustain higher speeds..

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