Investigating the rollover propensity of a 15 seater mini bus

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Abstract: In the present paper a full vehicle model of the Rural Transport Vehicle (RTV) is developed in MADYMO. The steering, tyre and suspension are modelled using standard modules available in the package. A speed controller was also designed using the package to maintain a constant speed of the RTV in simulations. Validation of the model was against experimental accelerations measured over bumps. The validated model is used to predict rollover characteristics using Slowly Increasing Steer (SIS), J-turn and Road Edge Recovery (RER) manoeuvres. These manoeuvres were conducted for three different loading conditions viz. RTV without passengers, RTV with unrestrained passengers and RTV with restrained passengers.

Keywords: rural transport vehicle; RTV; rollover; slowly increasing steer; SIS; J-turn and road edge recovery; RER.

Reference to this paper should be made as follows: Chawla, A., Mukherjee, S., Nayak, A. and Mohan, D. (2007) 'Investigating the rollover propensity of a 15 seater mini bus', *Int. J. Vehicle Safety*, Vol. 2, Nos. 1/2, pp.1–19.

1 Introduction

In India, a Rural Transport Vehicle (RTV), popularly known as RTV, shown in Figure 1 has been a mode of passenger conveyance system since 1998. Since then several rollovers of RTV have been reported, with frequency disproportional to their share of road occupancy. This necessitated investigation of rollover characteristics of RTV. Forkenbrock and Garrott (2002) and Forkenbrock et al. (2003) had proposed rollover manoeuvres, which we have called the NHTSA manoeuvres, that include effects of controlled suspension and traction. The rollover characteristics of 2001 Chevrolet Blazer, 2001 Toyota 4 Runner, 1999 Mercedes ML320 and 2001 Ford Escape were experimentally measured. Momiyama et al. (1999) has proposed procedures to estimate the dynamics leading to rollover from experiments that do not involve rollovers. Gawade et al. (2003) had developed methodology to predict rollover characteristics of three-wheel scooter taxis for the NHTSA manoeuvres through rigid body simulations implemented in MATLAB. Hardware in the Loop (HIL) analysis to predict the effect of specific components in rollover has been reported by Kim and Park (2004).

Figure 1 The RTV

In this paper the rollover characteristics of the RTV have been predicted through a theoretical model of the RTV developed in MADYMO for the Slowly Increasing Steer (SIS), J-Turn and Road Edge Recovery (RER) manoeuvres. For validating the MADYMO model of the RTV, the vertical acceleration of the RTV passing over a bump was measured. The results of the experiment were compared with those obtained through simulations in MADYMO, for the equivalent operating conditions to validate the heave mode of the vehicle. Takanoa et al. (2003) reported that loading affected the rollover stability. Albertsson et al. (2006) reported that seat belts made a significant change in the injury outcome. To incorporate the effect of loading as well as seatbelts on the rollover outcome, three different loading conditions, RTV without passengers, RTV with unrestrained passengers and RTV with restrained passengers, are used in the rollover simulations.

Hindustan Motors launched an RTV in 1998. The vehicle is popular because of its smaller size and shape and has a capacity for conveyance of 15 people. For the purpose of modelling, some technical specifications for RTV were obtained from the manufacturer's catalogue (listed in Table 1) and remaining data, necessary for modelling, was obtained through manual measurement of physical dimensions and weighing of components. The overall mass of the vehicle was known from the manufacturer, the location of the centre of gravity and moments of inertia were estimated from weighbridge measurements. Stiffness and damping properties of suspension were estimated from experiments.

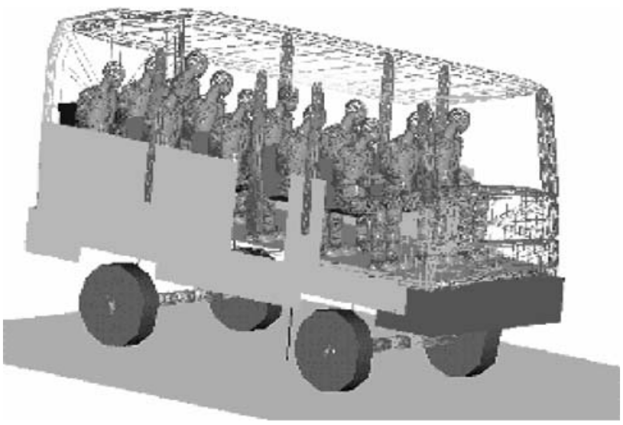
Table 1 Technical specification of the RTV

Engine weight	205 kg
Engine dimension	$710 \times 640 \times 863$ mm^3
Wheel base	240 mm
Wheel track	150 mm
Weight of RTV	1460 kg

2 RTV MADYMO model

A full vehicle model (Figure 2) of the RTV was developed in MADYMO V 5.4. To simulate rollover manoeuvres, special care has to be taken for the steering model, suspension model, tyre model, tyre-road contact, the RTV seat model. The SIS simulations require a constant speed drive. This is implemented by a numerically efficient closed loop controller that maintains the speed even on turns by computing the differential torque at the wheels. The suspension was modelled as spring damper elements and stiffness and damping properties were estimated from experiments. The tyre damping ratio and tyre stiffness were taken as 0.011 and 300 kN/m, respectively based on the work of Hinch et al. (1991) and Lupker et al. (1991).

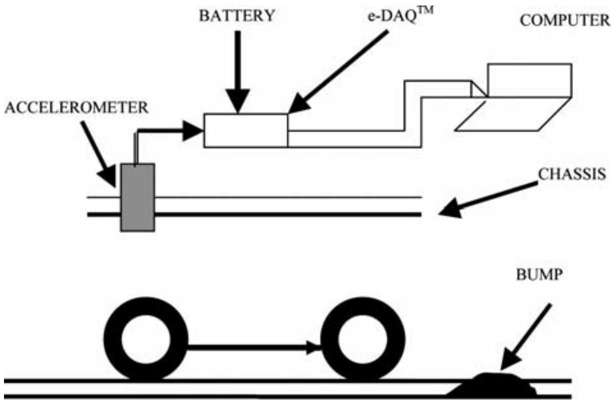
Figure 2 RTV MADYMO model with passengers



3 Validation of RTV MADYMO model

Experiments were conducted to measure the vertical acceleration of the RTV chassis over a bump for different velocities of RTV. The vertical acceleration of the chassis was measured using a Brüel & Kjaer Delta Shear Piezoelectric accelerometer type 4371 and charge amplifier type 2635. The accelerometer was attached to the RTV chassis as shown in Figure 3 and placed at the rear part of the RTV as the maximum acceleration is expected at the rear end.

Figure 3 Experimental set-up



Acceleration was sampled at a sampling frequency of 1000 Hz with the 'e-DAQ™ (from Somat)' (data acquisition system). The data was filtered digitally using a Butterworth low-pass filter. Experiments were conducted over the bump at various speeds. The model was used to simulate equivalent operating conditions in MADYMO. Figures 4 and 5 show comparison of the experimental and simulation results in time domain. Vertical accelerations predicted by the model agreed well with those of experimental results, for RTV velocities of 20 km/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, was damped out slowly as compared to that of experimental results. The discrepancy between the simulation and the experimental results could be due to the parameters used to represent damping of the joints and materials being based on the standard data. These parameters are known to be difficult to measure and model accurately. The validation process is limited by the available experimentation facilities to the heave mode of the vehicle, which is characterised by the suspension parameters and moment of inertia about the transverse axis.

Figure 4 Experimental and simulation results at 20 km/hr

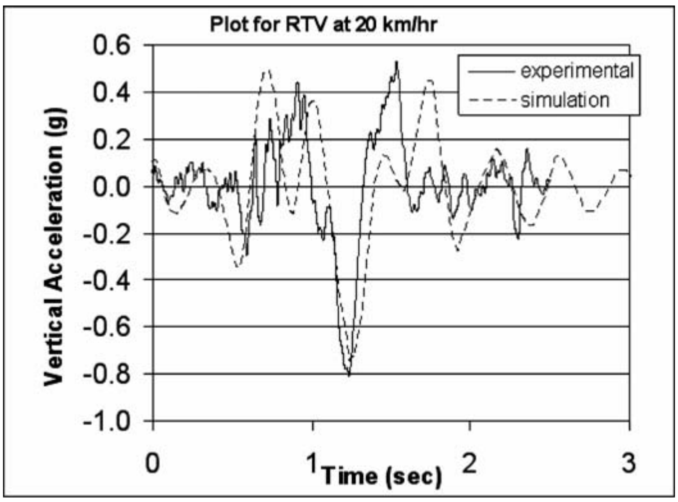
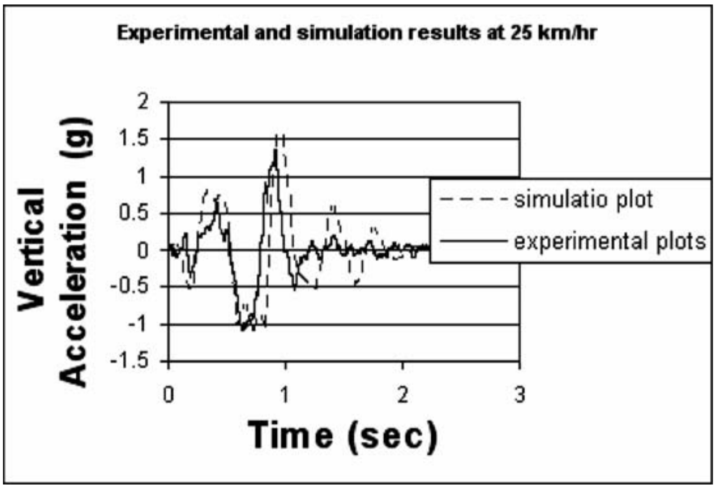


Figure 5 Experimental and simulation results at 25 km/hr



4 Rollover manoeuvres

Forkenbrock et al. (2003) describes the NHTSA standard rollover manoeuvres. These have been simulated for the RTV to assess its rollover propensity.

4.1 Slowly increasing steer manoeuvre

The SIS manoeuvre is used to characterise the lateral dynamics of vehicles, and is a ‘Constant Speed, Variable Steer’ test (Forkenbrock et al., 2003). In this manoeuvre, a vehicle running at the maximum 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 manoeuvres and in itself is not considered a good measure of rollover stability. Hand wheel position was linearly increased from zero to 270° at a rate 13.5° per second, as shown in Figure 6. Hand wheel position was held constant at 270° for 2 sec, and then returned back to zero degrees in 4 sec. During the simulation, the lateral acceleration of the RTV is tracked. This was plotted against time, and a best-fit line was estimated to accurately describe the data from 0 to 0.4 g as shown in Figure 7. 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° (2.15° rotation of front wheel). This hand wheel position was used in simulations for manoeuvres of J-Turn and RER steering inputs, as described in later sections of this paper. In a free roll, the speed of the vehicle drops quite rapidly during the manoeuvre. In actual tests, a driver maintains the speed by pedal control. So a differential torque controller was modelled to maintain the speed for the RTV in the SIS manoeuvre and was quite effective. The entrance speed of the RTV, in the simulations for SIS manoeuvre, was 16.67 m/s and the minimum entrance speed of the RTV in the simulation was 16 m/s as shown in Figure 8. In simulating SIS manoeuvre, the speed drops by 0.67 m/s which amounts to a 4% variation of the initial entrance speed. We consider this variation of the speed of the RTV to be acceptable.

Figure 6 Steering input in the simulation for SIS manoeuvres

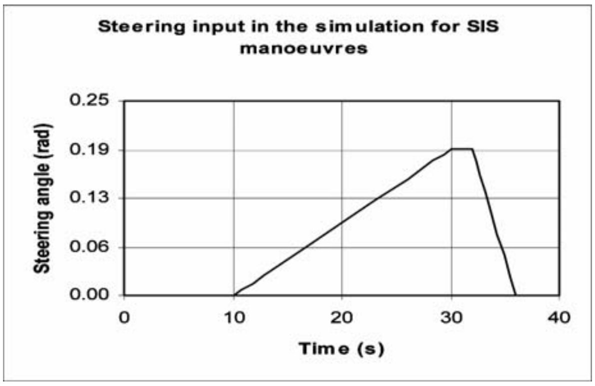


Figure 7 Lateral acceleration of RTV in the simulation for SIS manoeuvres

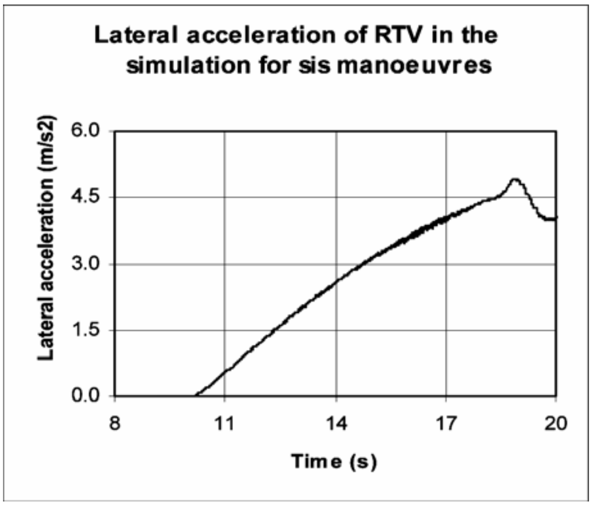
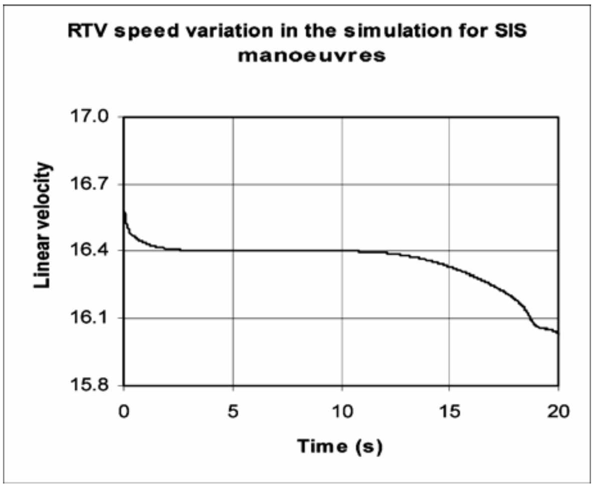


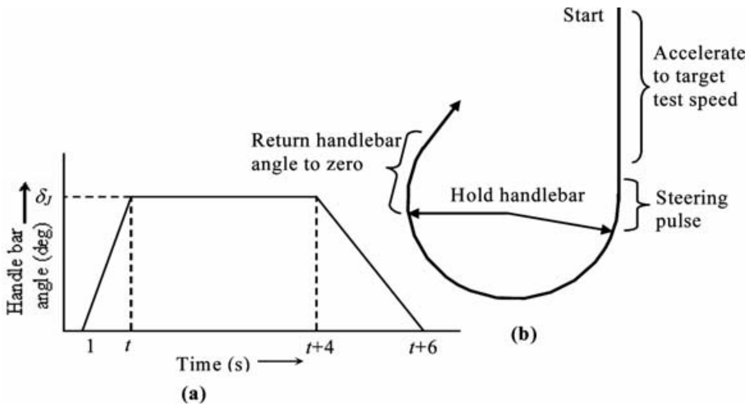
Figure 8 RTV speed variation in the simulation for SIS manoeuvres



4.2 J-Turn manoeuvre

The NHTSA J-Turn manoeuvre entails a sudden and large steering input. Large handlebar angles are chosen to saturate the lateral force response of the tyres of the vehicle. The maximum handlebar angle (δ_J) is held constant for next 4 sec and followed by the handlebar returning to zero, as in Figure 9(a). This manoeuvre models an extreme driver reaction. It mimics what might happen when a driver initiates a severe turn to avoid a road discontinuity or suddenly stalled vehicle. For J-Turn, it is necessary that the steering goes well beyond the limiting lateral acceleration, thus saturating the tyre response. The path traced (Figure 9(b)) resembles the alphabet 'J', giving the test its name.

Figure 9 Schematic of NHTSA J-Turn

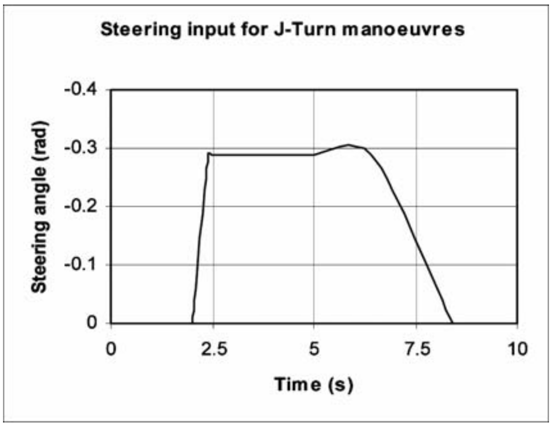


The initial steering-wheel magnitudes for simulating the J-Turn manoeuvre were calculated by multiplying the steering-wheel angle that produced an average of 0.2 *g* lateral acceleration in the SIS manoeuvre by a scalar of 8.0 and is equal to 16.5° of rotation of the front wheels. The rate of steering-wheel ramp was 1000°/s, which is equal to 40°/s for the front wheel (steering ratio for RTV is 25:1). Initial steer was performed in 0.413 s. The steering input curve is shown in Figure 10. The nominal entrance speeds in the simulations for J-Turn manoeuvre was varied from 5 to 8 m/s. 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. This is a free-running simulation and the torque controller is not implemented.

4.3 Road edge recovery manoeuvre

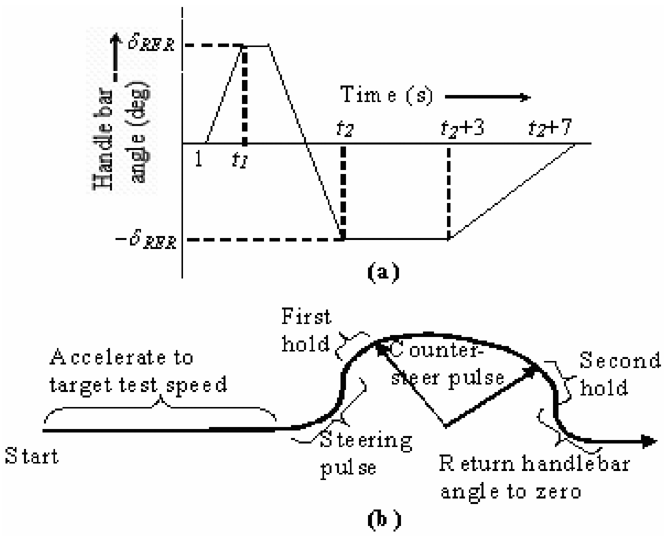
The RER manoeuvre attempts to induce two-wheel lift-off or rollover at a lower lateral acceleration than the NHTSA J-Turn by making a large turn, holding for a short duration at the maximum steering angle and then suddenly reversing the steer. The reversing is initiated when the roll rate approaches zero for the first time, which corresponds to the maximal roll angle of the vehicle. This procedure hence requires one to 'sense' the attitude of the vehicle. During the counter steer, the handle bar is turned to an equal angle in the opposite direction. Following the second turn, the handlebar is held fixed for a short duration and brought back to zero. This manoeuvre models, in an extreme way, what might happen when a driver performs a double lane change or tries to recover from a 'two wheel off the road' position.

Figure 10 Steering input for J-Turn manoeuvres



The RTV is accelerated to achieve the target speed and then the rapid handle bar angle is commanded linearly to reach the maximum angle (δ_{RER}) as shown in Figure 11(a). The handlebar is held constant until the roll angle increases to maximum value then the counter steer is commanded with the same steer rate to reach the maximum angle in opposite direction ($-\delta_{RER}$). Handle bar is held constant for 3 sec and returned to zero in next 4 sec. The path traced by the RTV is predicted in Figure 11(b). During the first steering pulse, the RTV goes off the road. The second steering (counter steer) mimics the driver's action of coming back onto the road and the third steering indicates the re-entry into the initial path before implementing the steering manoeuvre.

Figure 11 Schematic of RER manoeuvre



5 Simulation for RTV

5.1 J-Turn performance of the RTV

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

5.1.1 Without passengers

The NHTSA J-Turn simulations were 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 the vehicle speed, the maximum entrance speed where two-wheel lift was not observed for the RTV without passengers was 7.5 m/s. The lateral acceleration, roll angle and resulting speed of the RTV obtained in this case are shown in Figures 12–14, respectively.

Figure 12 Lateral acceleration of RTV without passengers

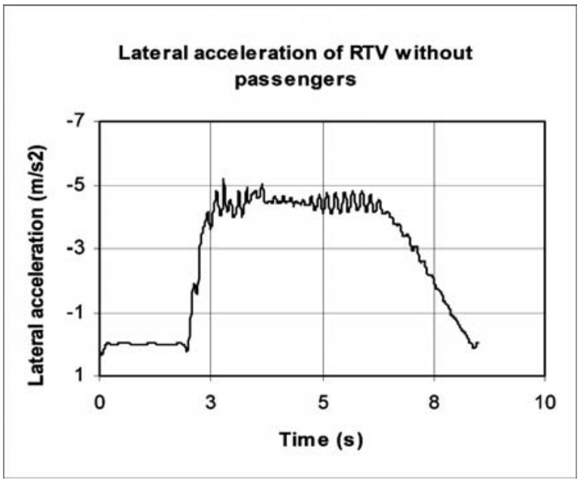


Figure 13 Roll angle of RTV without passengers

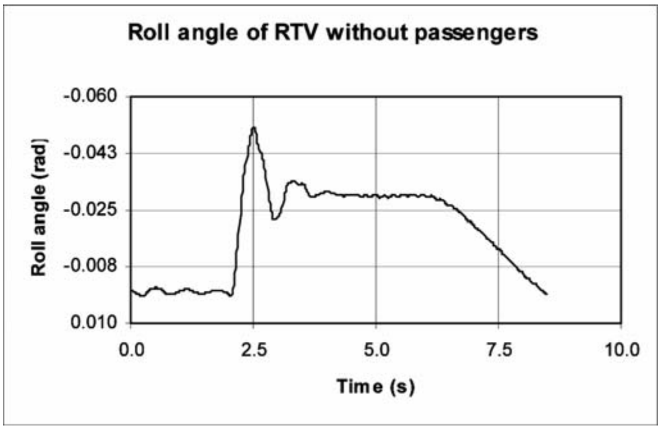
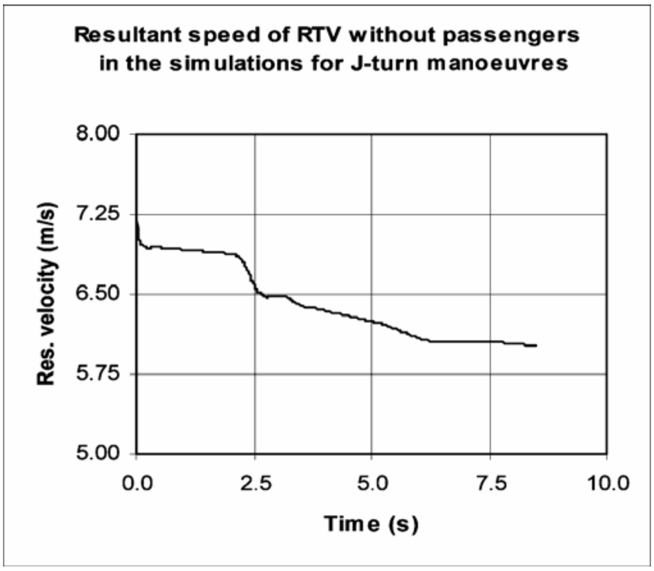


Figure 14 Resultant speed of RTV without passengers in the simulations for J-Turn manoeuvres



5.1.2 Restrained passengers

Lap-belt restraint of passengers has been modelled by constraining translations of the waist of the dummy model with respect to the respective seats. The NHTSA J-Turn simulations were 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 the vehicle speed, the maximum entrance speed of the RTV where two-wheel lift was not observed for RTV without passengers was 6.8 m/s. The lateral acceleration, roll angle and resulting speed of the RTV obtained in this case are shown in Figures 15–17, respectively.

Figure 15 Lateral acceleration of RTV with restrained passengers for J-Turn manoeuvres

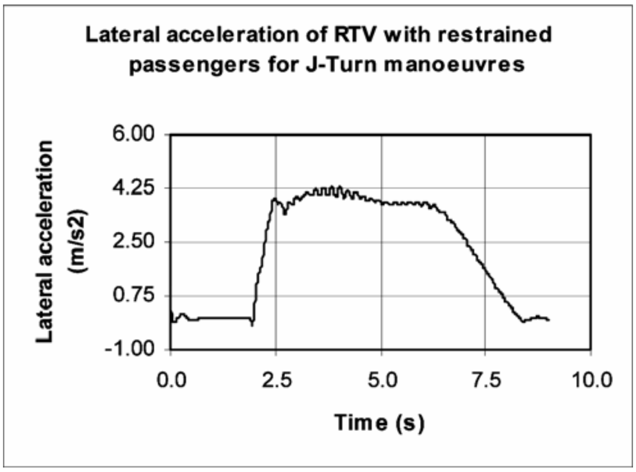


Figure 16 Roll angle of RTV with restrained passengers for J-Turn manoeuvres

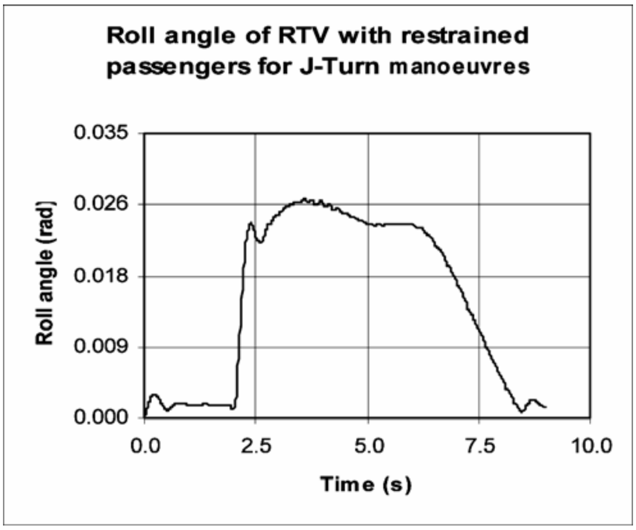
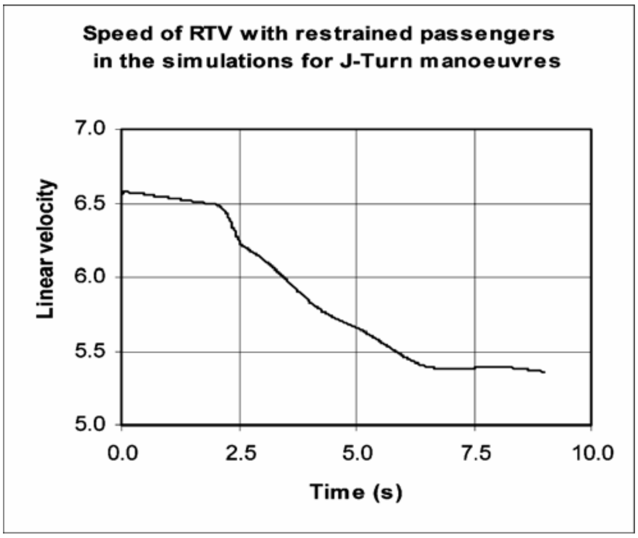


Figure 17 Speed of RTV with restrained passengers in the simulations for J-Turn manoeuvres



5.1.3 Unrestrained passengers

In this model passengers were positioned on the RTV seat with appropriate contact interactions between the dummy and the seat. The NHTSA J-Turn simulations were 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 the vehicle speed, the maximum entrance speed where two-wheel lift was not observed for the RTV without passengers was 6 m/s. The lateral acceleration, roll angle and resulting speed of the RTV obtained in this case are shown in Figures 18–20, respectively.

Figure 18 Roll angle of RTV with unrestrained passengers for J-Turn manoeuvres

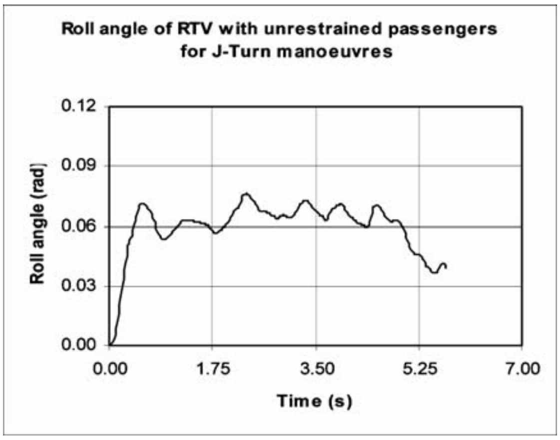


Figure 19 Lateral acceleration of RTV with unrestrained passengers for J-Turn manoeuvres

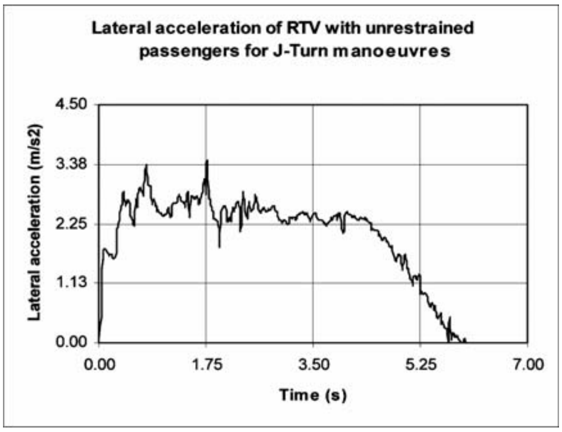
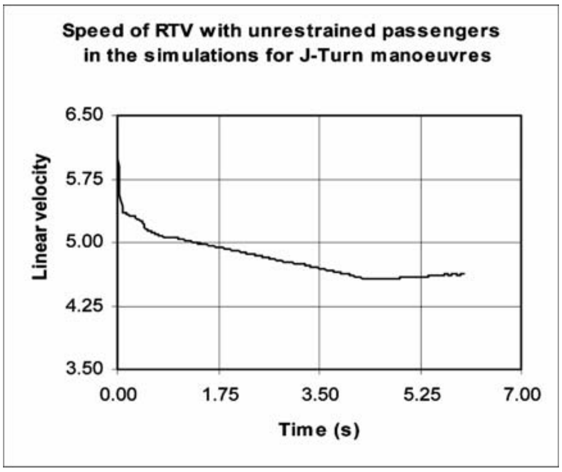


Figure 20 Speed of RTV with unrestrained passengers in the simulations for J-Turn manoeuvres

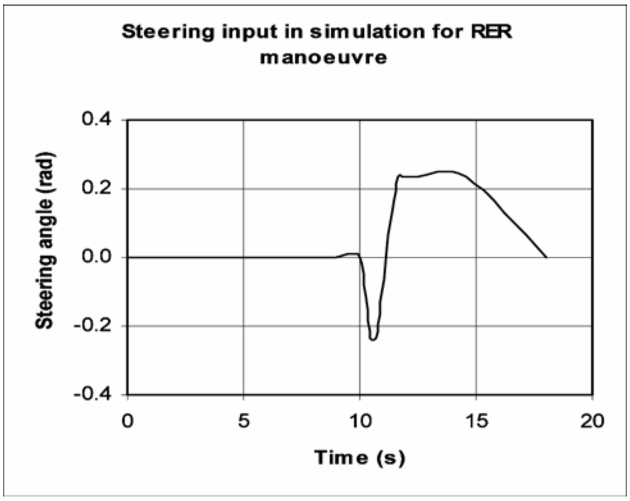


5.2 RER performance of RTV

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 manoeuvre by a scalar of 6.5 and is equal to 30.73° of the front wheel rotation. The rate of steering-wheel ramp was 720°/sec which is equal to 28.8°/sec for front wheel (since the steering ratio for RTV is 25:1). Initial steer was performed in 0.8545 sec. The steering input curve is shown in Figure 21.

RER manoeuvre 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.

Figure 21 Steering input in simulation for RER manoeuvre



5.2.1 Without passengers

The RER simulations were performed for different entrance speeds. The termination condition (two-wheel lift) was observed at the entrance speed of 9 m/s. During downward iteration of the vehicle speed, the maximum entrance speed of the RTV where two-wheel lift was not observed for RTV without passengers was 8.75 m/s. The lateral acceleration, roll angle, roll rate and resulting speed of the RTV obtained in this case are shown in Figures 22–25, respectively.

5.2.2 Restrained passengers

The RER simulations in this case, were performed for different entrance speeds, initially in steps of 1 m/s. The termination condition (two-wheel lift) was achieved for the entrance speed of 8 m/s. During downward iteration of the vehicle speed, the maximum entrance speed of the RTV where two-wheel lift was not observed for RTV with restrained passengers was 7.5 m/s. The lateral acceleration, roll angle, roll rate and resulting speed of the RTV obtained in this case are shown in Figures 26–29, respectively.

Figure 22 Lateral acceleration of RTV without passengers for RER manoeuvres

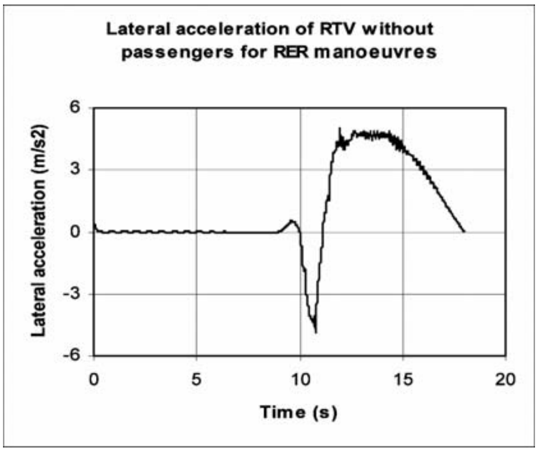


Figure 23 Roll angle of RTV without passengers for RER manoeuvres

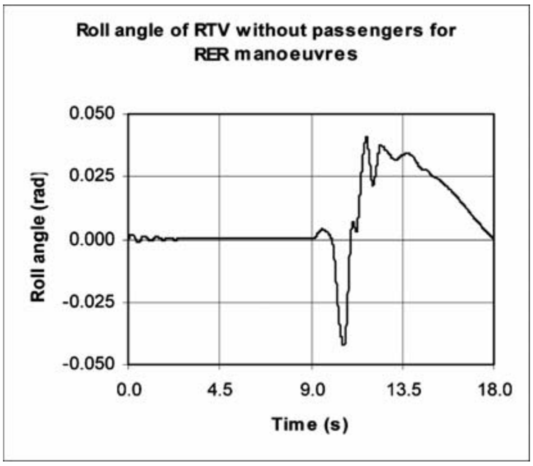


Figure 24 Roll rate of RTV without passengers for RER manoeuvres

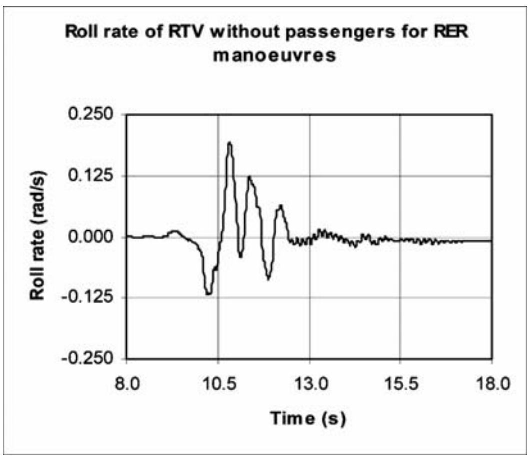


Figure 25 Speed of RTV without passengers in the simulation for RER manoeuvres

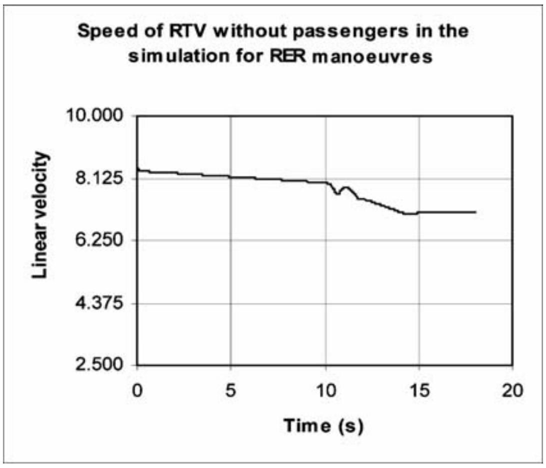


Figure 26 Lateral acceleration of RTV with restrained passengers for RER manoeuvres

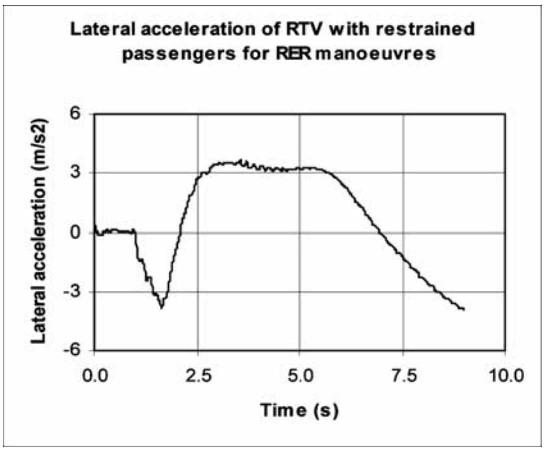


Figure 27 Roll angle of RTV with restrained passengers for RER manoeuvres

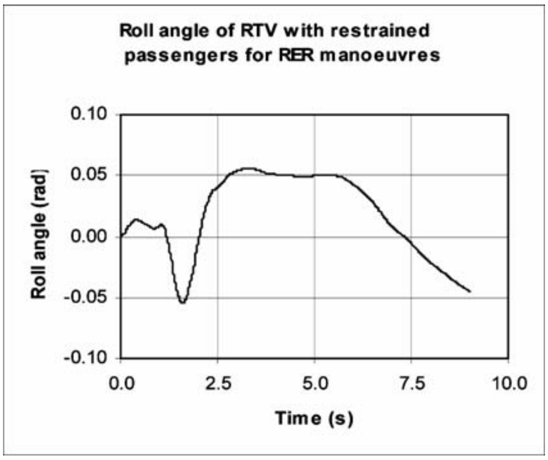


Figure 28 Roll rate of RTV with restrained passengers for RER manoeuvres

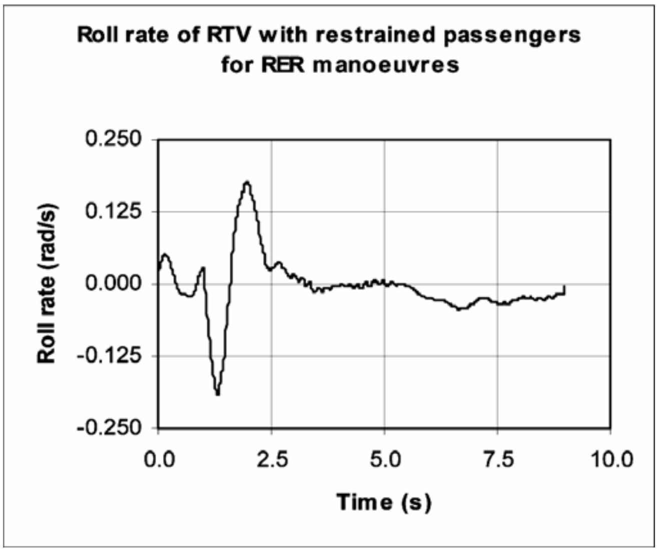
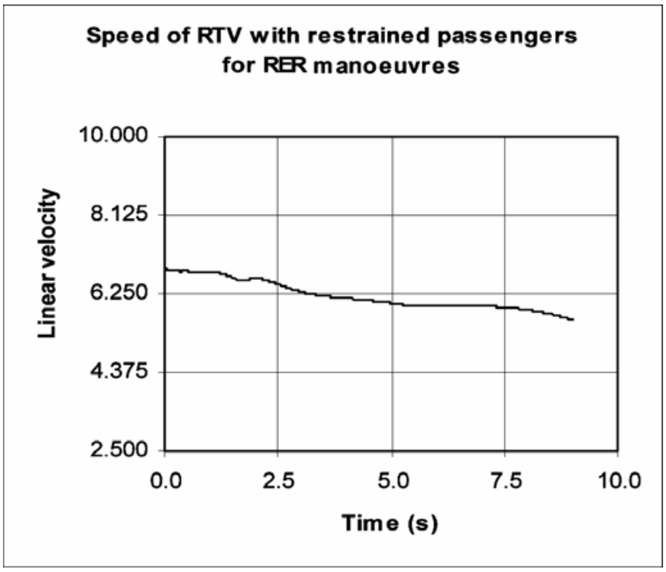


Figure 29 Speed of RTV with restrained passengers for RER manoeuvres



5.2.3 Unrestrained passengers

The RER manoeuvre, in this case, was simulated with entrance speeds at intervals of 0.5 m/s. The termination condition (two-wheel lift) was achieved at 7.5 m/s. During downward iteration of the vehicle speeds at intervals of 0.1 m/s, the entrance speed of the RTV without two-wheel lift was achieved at 7 m/s. The lateral acceleration, roll angle, roll rate and resulting speed of the RTV obtained in this case are shown in Figures 30–33, respectively.

Figure 30 Lateral acceleration of RTV with unrestrained passengers for RER manoeuvres

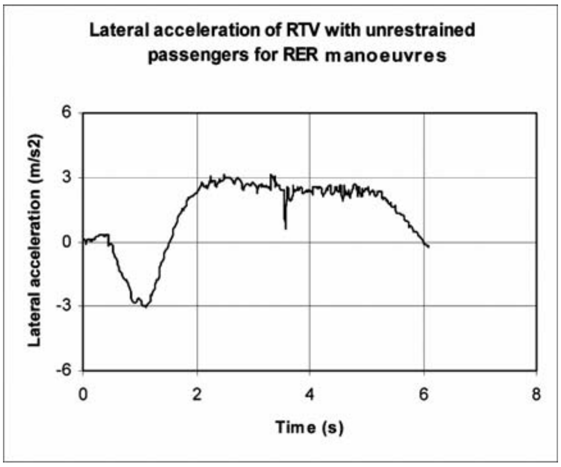


Figure 31 Roll angle of RTV with unrestrained passengers for RER manoeuvres

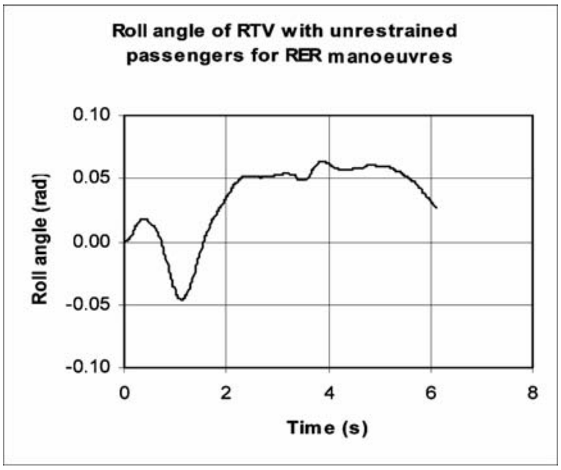


Figure 32 Roll rate of RTV with unrestrained passengers for RER manoeuvres

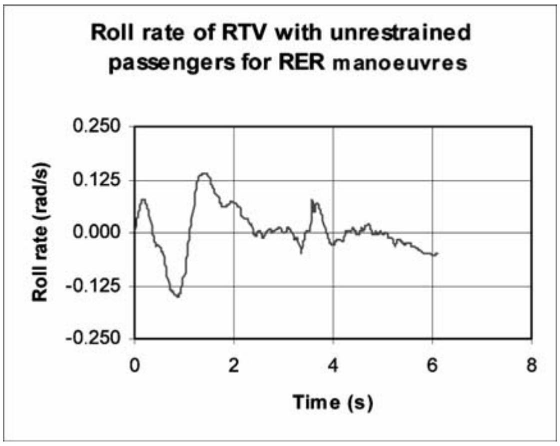
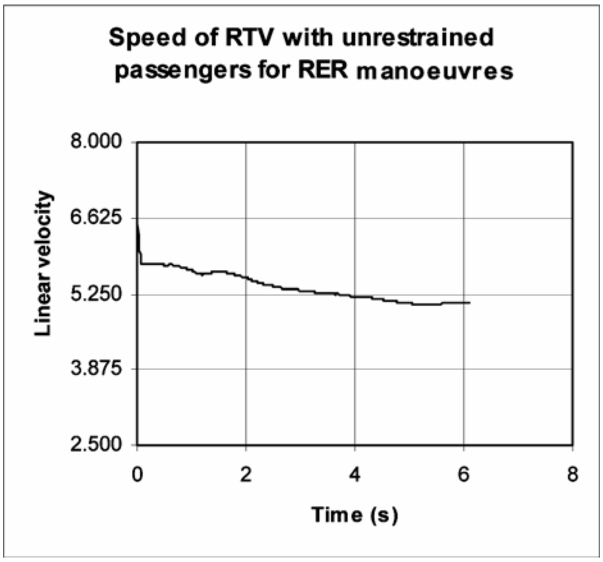


Figure 33 Speed of RTV with unrestrained passengers for RER manoeuvres



6 Summary of manoeuvres

J-Turn and RER manoeuvres were simulated for the modelled RTV with three different loading conditions. A comparison of both manoeuvre simulations is presented in Table 2. The comparison shows that the maximum possible entrance speed without two-wheel lift is maximum in the RTV without passengers and minimum in the RTV with unrestrained passengers in both manoeuvres. The RER limits are higher than the J-turn limits. Comparing the two loading conditions RTV with restrained passengers and RTV with unrestrained passengers shows that maximum possible entrance speed is higher for the loading condition in which the RTV has restrained passengers. The sideways outward movement of passengers during steering of RTV causes outward movement of centre of gravity. So belting would not only reduce injury probability once a rollover has occurred, but also reduces the rollover likelihood of the RTV.

The NHTSA has conducted experiments for the same rollover manoeuvres on production vehicles. Published results are compared with the RTV simulation results in Table 3. It is indicated that the entrance speed for RTV without two-wheel lift is lower than that in other production vehicles.

Table 2 Results summary of rollover simulations

Loading condition	*Maximum possible entrance speed (m/s) for J-Turn*	*Maximum possible entrance speed (m/s) 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 manoeuvres

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

7 Conclusions

A model of the RTV has been developed in MADYMO and validated for the case of the RTV passing over a bump. The experimental results from two different velocities 20 km/hr and 25 km/hr confirm the fidelity of the model. The validated model is then used for predicting rollover characteristics of the RTV using dynamic manoeuvres. Comparison with published results show that rollover limits of the RTV are lower than those of other production vehicles. This indicates the need to improve the design of the RTV, for better rollover resistance to operate in an urban environment.

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