EFFECT OF ANTI-ROLL BAR ON ROLLOVER THRESHOLD OF A THREE WHEELED VEHICLE

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ABSTRACT
Three wheeled vehicles (TWV) are a common low cost mode of transport in the Asian Subcontinent, Africa and South America. It is very prone to rollover in turns even at moderate speeds. Recently anti-roll bars (ARB) have been installed claiming increase in rollover thresholds for (one front two rear) 1F2R wheel configuration. Roll moment is resisted at the rear axle only. Rear Axle installed ARB typically increases over-steer tendency. In the current study a Six degrees of freedom model is used to investigate the effect of ARB stiffness on the rollover threshold.

KEY WORDS
Three wheeled vehicle; rollover; anti-roll bar.

1. Introduction
Rollover of three wheeled vehicles has resulted in serious injuries to the passengers and even fatalities. In a report compiled by Government of India, of the total traffic related fatalities reported in India in 2011[1], three wheeled vehicle were involved in 5%. The share in serious injuries is 8%. The estimated share of transport is estimated at 3.5%. This indicates a serious threat to human life due to rollover and crash worthiness properties of the vehicle. In Pakistan where only 8 out of 1000 own a car [2], public and commercial transport plays a very vital role. Two and three wheeled vehicles are 51% of the total registered vehicles. Accident reported are less than 2.5% of real data does not have a breakdown of three wheeled and two wheeled vehicles but both account for more than 60% of fatalities. In Karachi the fatalities due to accidents in which three wheeled vehicles are involved rose by 33% in 2011.

Three wheeled vehicles in 1F2R wheel configuration is currently used for short distance public transport. The typical weight distribution because of engine and passenger location is rear biased leading to a neutral to slight over-steer behaviour. Rollover propensity has been investigated by several authors [3–8] without considering auxiliary roll stiffness effects. In [9] it is concluded that secondary factors may result in up to 25% reduction in rollover threshold of a typical SUV. No such study exists for three wheeled vehicles. In three wheeled vehicles roll stiffness is available on the axle with two wheels. This peculiar setup may introduce slight roll over steer. In [9] addition of anti roll bar is shown to increase rollover threshold of four wheeled vehicles. The suggested method is adding or increasing the auxiliary roll resistance (stiffness) uniformly on both front and rear axles. The addition is more convenient on a three wheeled vehicle as a front to rear roll moment distribution is not altered. This does not affect the roll over/under steer propensity significantly. The current study aims at establishing effect of anti-roll bar (ARB) on roll over threshold.

The space available at the rear axle of typical commercial vehicles can easily accommodate an ARB. Therefore a careful design would lead to a low cost solution to reduce the roll over propensity of a typical three wheeled vehicle.

2. Simulation Model
Delta configuration three wheeled vehicle is chosen for modeling. A six degree of freedom analytical model using Newton Euler approach is generated of vehicle shown in Figure 1.1.
center of mass of sprung mass, one attached to sprung mass with x-axis aligned with the sprung mass and z-axis aligned with the inertial reference frame referred to as the Local Flat Earth Body frame. Three local frames at contact patches of the wheels aligned with local flat earth body frame. The following equations are solved in body attached frame.

\[ M_x = w_x I_{xx} + w_y w_z (I_{zx} - I_{zy}) - I_{xz} (w_x + w_y w_z) \]
\[ M_y = w_y I_{yy} + w_z w_x (I_{xz} - I_{zx}) - I_{yz} (w_y + w_z w_x) \]
\[ M_z = w_z I_{zz} + w_y w_x (I_{yz} - I_{zy}) - I_{yy} (w_z + w_y w_x) \]

\[ \ddot{x} = \frac{X}{m} - w_x \dot{z} + w_z \dot{y} \]
\[ \ddot{y} = \frac{Y}{m} - w_z \dot{x} + w_x \dot{z} \]

The forces generated and motions evolved are transformed between frames using Euler angles (3-2-1). While transforming from global to local frame the first rotation is about global \( Z \) (Yaw angle \( \psi \)), then about transformed \( y' \) (Pitch angle \( \vartheta \)) and the about transformed \( x'' \) (Roll angle \( \phi \)). The global unit vectors in local coordinates are given below.

\[
\begin{bmatrix}
I \\
J \\
K
\end{bmatrix} = \begin{bmatrix}
1 & \sin \phi \tan \vartheta & \cos \phi \tan \vartheta \\
0 & \cos \phi & -\sin \phi \\
0 & \sin \phi \sec \vartheta & \cos \phi \sec \vartheta
\end{bmatrix}
\]

The instantaneous value of Euler angles are generated from the integration of the following equations which give Euler rates in terms of body angular velocities as given in equation below.

\[ \dot{\psi} = p + (q \sin \phi + r \cos \phi) \tan \vartheta \]
\[ \dot{\vartheta} = q \cos \phi - r \sin \phi \]
\[ \dot{\phi} = (q \sin \phi + r \cos \phi) \sec \vartheta \]

The velocities of the CG of vehicle are transformed in global coordinates and integrated to get the path followed by the vehicle.

\[ \dot{x} = (\cos \theta \cos \psi)u + (\cos \theta \sin \psi) + \sin \theta \sin \theta \cos \psi \]
\[ \dot{y} = (\cos \theta \sin \psi)u + (\cos \theta \sin \psi) + \sin \theta \cos \theta \]
\[ \dot{z} = (\sin \theta)u + (\sin \theta \cos \psi)v + (\cos \theta \cos \psi)w \]

![Figure 2.2 Flow Chart for Calculations](image)
The symbols u, v and w are the center of mass velocities in body fixed x, y and z direction of the vehicle.

The most significant forces for handling are generated at the tire contact patches. Magic Formula is used for tire force calculations. This would provide for tire load sensitivity effects in transient load transfer due to the anti roll bar.

Anti roll bar was introduced as an equivalent spring preventing relative movement of left and right rear wheels. The base line stiffness was set to be one third of the primary roll stiffness suggested by suspension tuning experts which keeps the independence of wheel in single wheel bumps, reduces body roll while keeping roll oscillations to their minimum. Additional roll damping was not added as typical ARBs provide no additional damping to the roll motion.

Model parameters were set for typical three wheeled motorised taxis currently plying in subcontinent using data available in [6], [10], [11]. The sequence of calculations is shown in the Figure 2.2.

3. Test Manoeuvres for Simulation

Steady state rollover propensity was established first for the model with no auxiliary torsional stiffness using slowly increasing steer. A hand-wheel angle is established which gives a lateral acceleration of 0.128 g. The maneuver entrance speed is set at 22.352m/s and the steering input ranged from 0 to 30 degrees (0 to 0.5236 radians), applied at 13.5/12 deg/second (0.019635 rad/sec). This value of lateral acceleration was attained in 0.8716 seconds as shown in figure 3.1

![Figure 3.2 Lateral Acceleration in SIS maneuver](image)

The steering angle of 0.98 degrees corresponds to a lateral acceleration of 1.26 m/s². This reference value was used in NHTSA J-Turn maneuver amplitude calculation. The steering angle profile for the test procedure is given in Figure 3.3

![Figure 3.3 Steering Input for NHTSA J-Turn](image)

It is important to note that in a three wheeled vehicle hand-wheel angle is equal to wheel steer angle.

4. Simulation Results

The vehicle was simulated for different maneuver entrance speeds and checked for wheel lift off. The speed at which the vehicle is on the verge of lift off is taken as the maximum maneuver entrance speed and hence the rollover threshold. It is important to note that the three wheeled vehicle may recover from a wheel lift off condition if the condition is not due to an aggressive input still this is considered as an unstable condition and hence threshold. Figure 4.1 shows the limiting value of wheel lift off indicated by zero wheel reaction at the inner wheel.

![Figure 4.1 Inner Wheel Reaction](image)

The entrance speed is 9.1 m/s and the maximum lateral acceleration during the maneuver is 5.8m/s². In [8] modified static stability factor is given for a three wheeled vehicle as follows

\[
SSF = \frac{aT}{2hl}
\]

Where \(a\) is the distance of cg from front wheel, \(T\) is the track width, \(h\) is the height of cg from ground and \(L\) is the wheelbase. This steady state limit for this vehicle is 6.3 m/s² this metric is used for rating vehicles for rollover
propensity of vehicles. The plot of lateral acceleration is shown in the Figure 4.2 below.

![Figure 4.2 Lateral acceleration at cg](image)

After establishing the base line the auxiliary roll stiffness is introduced which is increased gradually. Figure 4.5 shows the effect of increasing ARB stiffness.

![Figure 4.5 Wheel reaction showing trend with increasing stiffness](image)

The overshoot in both lateral acceleration and roll angle is evident and is pronounced for low roll damping.

The corresponding body roll angle is given in Figure 4.3. The vehicle moves along the trajectory shown in Figure 4.4.

![Figure 4.3 Body Roll Angle](image)

![Figure 4.4 Trajectory of vehicle](image)

The results clearly indicate increasing inner wheel reaction which in a way represents the reserve wheel reaction before rollover (lift off). Similarly the vehicle roll angle also reduces significantly with increase in ARB stiffness. As shown in the Figure 4.6

![Figure 4.6 Vehicle roll angle showing trend with increasing stiffness](image)

5. Conclusion

The simulations indicate that addition of an anti roll bar increases the rollover threshold. The vehicle roll vibrations are dependent on the damping of the suspension which affects the overshoot at steering attaining the maximum angle. Increasing roll stiffness also increases oscillations in roll but are dependent on the damping present. The effect of rear track width change and damping of roll motion need further investigation which affect the rollover propensity in a transient maneuver.
Acknowledgement

The authors acknowledge the support provided by Higher Education Commission for providing opportunity and resources for research related to three wheeled vehicles.

References


