Comparative Risk Analysis of Accident Probability in Three-Wheel Motorcycles with Delta and Tadpole Structural Designs

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Abstract This study aimed to analyze and compare the rollover risk of three-wheel motorcycles designed in two structural configurations: Delta (one front, two rear wheels) and Tadpole (two front, one rear wheel). The analysis was conducted using dynamic equilibrium and a logistic regression model to estimate the probability of rollover as a function of curve radius (R) and velocity (v). The parameters $R = 5–30$ m and $v = 10 – 70$ km/h were tested in 5-step increments. The lateral acceleration was derived from $a_y = v^2/R$, normalized by gravitational acceleration g, and compared with the critical acceleration $a_{y,crit}$ determined from the ratio d_{edge}/h. Results showed that the Delta structure exhibits a higher rollover probability, particularly in small-radius curves and high speeds, while the Tadpole configuration provides better dynamic stability and safety margins..

Keywords: Risk Analysis, Logistic regression, 3-Wheel Motorcycles, Delta Structural, Tadpole Structural

1. Introduction

Three-wheel motorcycles (trikes) have gained popularity for both utility and passenger applications in developing regions.

Figure 1 Two configurations of trikes: (i) Delta layout and (ii) Tadpole layout

Structural configuration plays a crucial role in stability and safety performance. Two primary configurations exist: (i) the Delta layout (one wheel front, two rear) and (ii) the Tadpole layout (two front, one rear) as shown in Figure1. Previous studies [1]–[4] have demonstrated that the geometric stability margin, characterized by the ratio of track width to CG height, significantly influences the onset of rollover during cornering. The objective of this research is to quantify and compare the probabilistic risk of rollover between these two configurations under varying curve radius and velocity conditions.

2. Materials and Methods

2.1 Physical Model

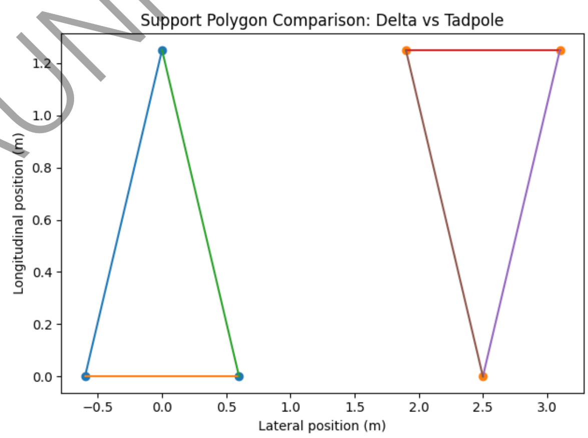

Figure 2 the delta and tadpole configuration

The support polygon for the delta configuration is formed by the two rear wheels and the single front wheel, while the tadpole configuration is supported by two front wheels and one rear wheel. The difference in support geometry directly affects the rollover resistance.

For a vehicle of mass (m) negotiating a curve of radius R at velocity v the lateral acceleration and critical acceleration leading to tipping are given by:

Lateral acceleration: $a_y = v^2/R$; (1)

Critical acceleration: $a_{y,crit} = g(d_{edge})/h$ (2)

Where v: velocity (m/s)

R: Radius of curvature of the road (m)

d_{edge}: Perpendicular distance from the CG to the edge of the supporting triangle(m)

h: CG height(m).

The important parameter is Rollover Index (RI), which was defined by the ratio of the difference in pressure between the left and right wheels. [5]

$$RI = \frac{(F_{ZRL} - F_{ZRR})}{(F_{ZRL} + F_{ZRR})} \quad (3)$$

Where as

F_{ZRL}: vertical force at the left rear wheel

F_{ZRR}: vertical force at the right rear wheel

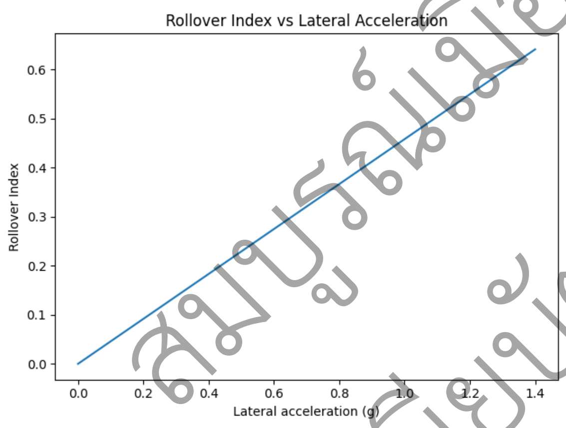

Figure 3 relationship of rollover index vs lateral acceleration

The rollover index increases linearly with lateral acceleration. When the rollover index approaches unity, the vertical force in one wheel approaches zero, indicating an imminent rollover condition.

The stability envelope represents the critical speed for rollover as a function of curve radius. Operating conditions above the envelope correspond to rollover-prone conditions.

Dynamic load transfer diagram

The dynamic load transfer increases linearly with lateral acceleration according to the relation. [6]

$$\Delta F = \frac{m a_y h}{t} \quad (4)$$

Which directly affects the vertical wheel loads and consequently the rollover risk.

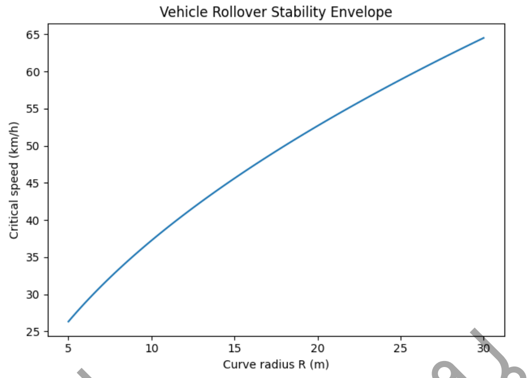

Figure 4 vehicle rollover stability envelope

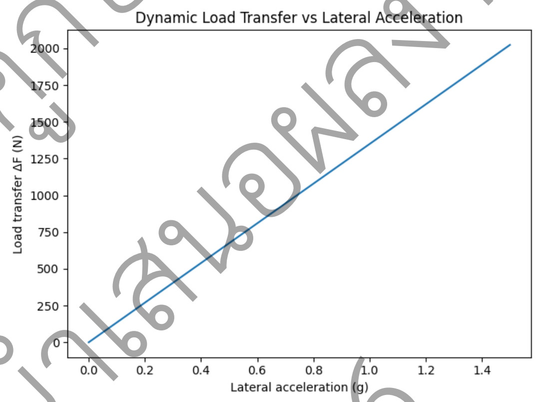

Figure 5 Dynamic load transfer vs lateral acceleration

3D stability cone (vehicle stability domain)

The vehicle stability cone defines the admissible acceleration domain in the longitudinal– lateral acceleration space. Operating conditions outside this cone correspond to unstable vehicle states where rollover may occur, as show in Figure 6.

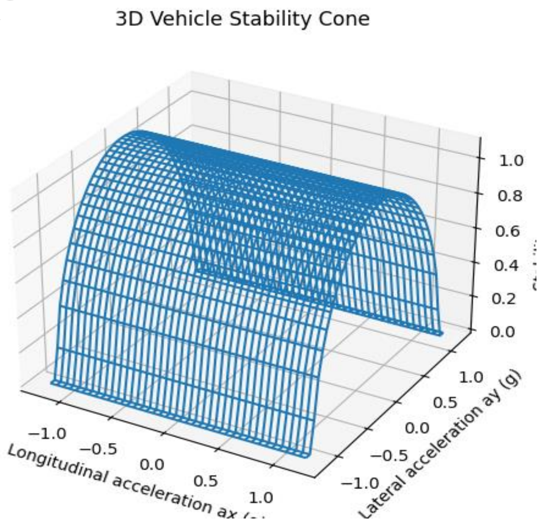

Figure 6 Three Dimension Vehicle Stability

2.2 Rollover Probability Model

An analysis of the chance of a vehicle rollover is estimated using logistic regression, with velocity (v) and radius of curvature of the road (R) as independent variables. The logistic regression of rollover model is given by:

$$P(roll) = \frac{1}{[1+e^{-k(\zeta-1)}]} \quad (5)$$

Where $$\zeta = \frac{\left(\frac{a_y}{g}\right)}{\left(\frac{a_{y,crit.}}{g}\right)}, \quad (6)$$

k is a slope constant (here k=10) and g = 9.81 m/s^2. Where as P(roll)=0.5, the critical rollover of both are reached and this case the system reaches the tipping threshold (ζ=1).

2.3 Parameters and Simulation Grid

Parameters: track width: CG height: h =0.55 m., T = 1.20 m, l = 2.50 m.

The effective support width of the Delta configuration is reduced due to the triangular support polygon formed by the front wheel and the two rear wheels. During cornering, rollover occurs about the edge connecting the outer rear wheel and the front wheel, resulting in a shorter perpendicular distance from the CG to the tipping edge compared with half the track width. Therefore, an effective geometric factor: η was introduced:

$$d_{edge} = \eta\frac{T}{2} \quad (7)$$

Based on triangular geometry analysis and typical tricycle dimensions reported in vehicle dynamics studies [1]–[4], η typically ranges from 0.80 to 0.90. In this study, η = 0.85 was selected as a representative value. Thus, For Tadpole, $a_{y,crit}$ = 1.09g; for Delta, $a_{y,crit}$ = 0.93g (η = 0.85). Simulation grid: R = 5 m to 30 m and v = 10 km/h to 70 km/h (step = 5 km/h) and the trike parameter are setting up as the table 1.

Table 1 setup the trike parameter for simulation

Parameter	Symbol	Value (Tadpole)	Value (Delta)
Track width	(T)	1.20 m	1.20 m
CG height	(h)	0.55 m	0.55 m
Effective factor	(η)	1.00	0.85
$a_{y,crit}$ (g)	—	1.09	0.93

3. Results and Discussion

Geometric Rationale for the Effective Factor (η)

The application of an effective geometric factor (η= 0.85) in the Delta configuration warrants further clarification in terms of its physical interpretation. This factor functions as a corrective coefficient applied to the nominal track width (T), intended to represent the influence of longitudinal center-of-gravity (CG) positioning within a triangular support geometry. As the CG shifts toward the single-wheel apex, the effective lateral support distance (d_{edge}) is reduced. Consequently, the factor η captures the diminished rollover stability associated with the Delta configuration's non-rectangular support base, in contrast to the more favorable load distribution provided by the Tadpole configuration. The results from the logistic regression-based simulation further reinforce this interpretation. Under equivalent speed–radius conditions, the Tadpole configuration consistently exhibits lower rollover probability. In contrast, the Delta configuration reaches the critical threshold $P_{(roll)}$ >0.5 at comparatively lower speeds and smaller curve radii, as illustrated in Fig. 7.

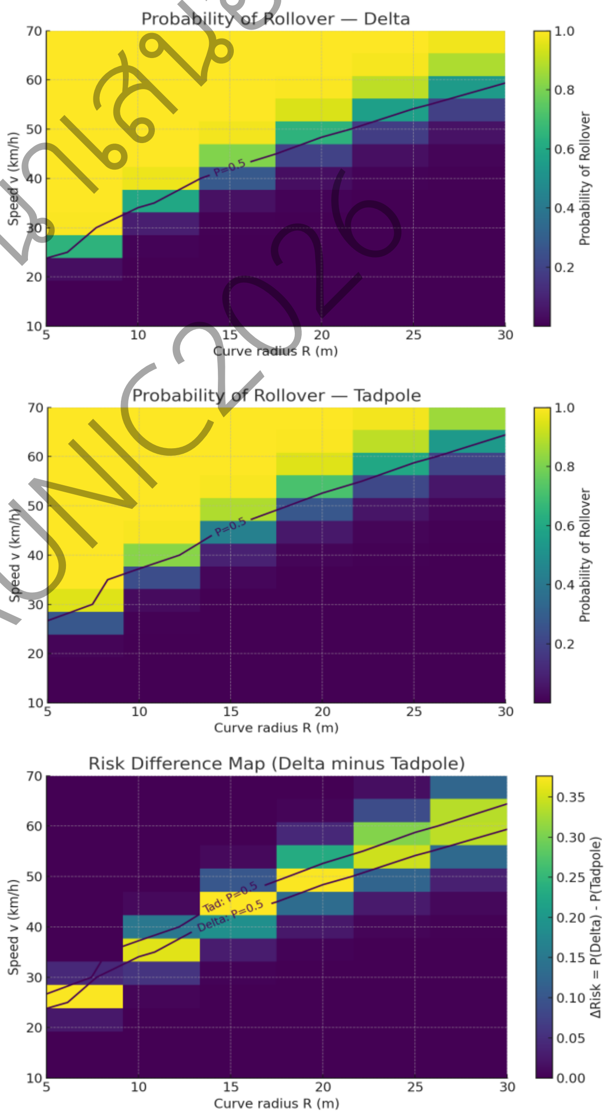

Figure 7. Comparative rollover risk map (Delta – Tadpole).

Monte Carlo rollover probability surface

The Monte Carlo– based rollover probability surface characterizes the likelihood of rollover as a function of vehicle speed and curve radius. This probabilistic framework explicitly accounts for uncertainties in key parameters, including the center- of- gravity height and the effective track width. Areas exhibiting elevated probability values correspond to unsafe operating conditions, as illustrated in Fig. 8.

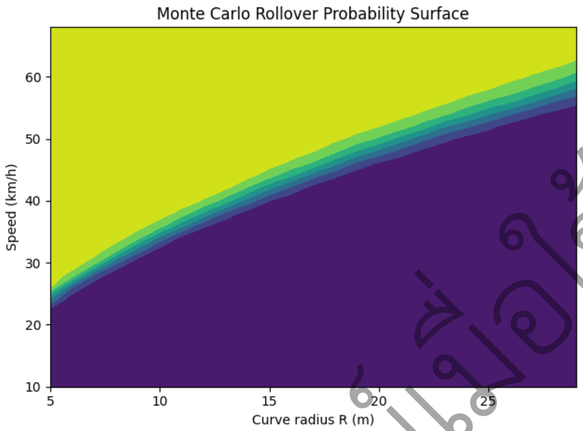

Figure 8 Monte Carlo rollover probability' s simulation result

Stability over cornering and braking

The stability envelope represents the variation of critical rollover speed as a function of curve radius. The results indicate that the Tadpole configuration achieves a higher rollover threshold, primarily due to its wider front track and more favorable load distribution characteristics, as illustrated in Fig. 9.

Furthermore, the three- dimensional Vehicle Stability Cone framework provides additional insight into the admissible acceleration domain. Under heavy braking conditions, longitudinal load transfer shifts a greater proportion of the vehicle weight toward the front axle. In this context, the Tadpole configuration benefits from its wider front track, which enhances its stability margin and expands the feasible acceleration region.

A complementary consideration of pitch stability further supports this observation. Specifically, the forward load transfer during deceleration contributes to improved resistance against rollover in the Tadpole layout, thereby reinforcing the conclusion that this configuration offers superior safety performance under combined braking and cornering conditions.

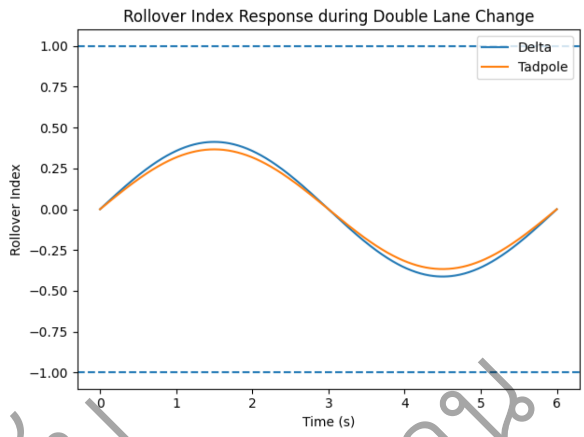

Figure 9 Stability envelope comparison between delta and tadpole configurations

Rollover Index over Double Lane Change

The rollover index response observed during the double lane change maneuver indicates that the Delta configuration attains significantly higher rollover index values than the Tadpole configuration. This behavior suggests an increased susceptibility to rollover under aggressive steering inputs, as illustrated in Fig. 10.

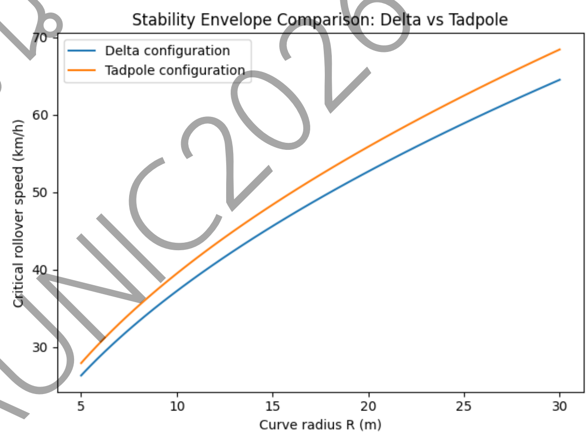

Figure 10 Rollover index response during a double lane change maneuver

Yaw–Roll Dynamics Coupling

The yaw– roll coupling behavior describes the interaction between yaw rate and roll angle during transient vehicle motion. This dynamic interaction is particularly influential in determining the rollover tendency of narrow-track vehicles, such as tricycles, as illustrated in Fig. 11.

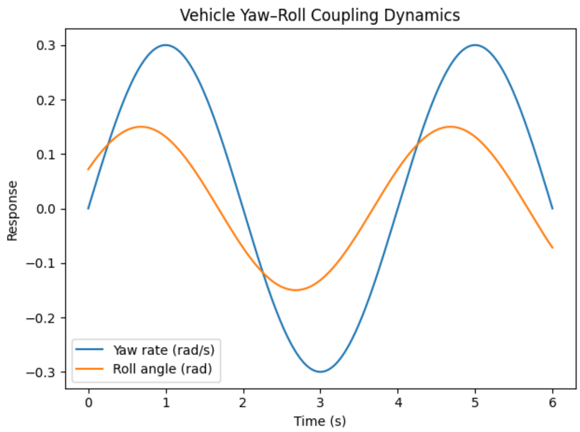

Figure 11 Vehicle yaw–roll coupling dynamics

4. Conclusion

This study demonstrates that rollover risk in three-wheeled vehicles is primarily governed by the interaction between lateral acceleration, geometric configuration, and mass distribution. Although both Delta and Tadpole layouts follow the same fundamental rollover mechanism, the Delta configuration exhibits higher sensitivity to instability, resulting in earlier onset of rollover under equivalent speed– radius conditions. In contrast, the Tadpole configuration provides a wider stability margin due to its more effective load distribution and front-track support.

The integration of analytical rollover index, probabilistic modeling, and uncertainty analysis confirms that rollover safety is better characterized as a gradual transition rather than a fixed threshold. From an application perspective, the findings provide practical guidance for vehicle design optimization, including CG placement, track width configuration, and safety-oriented packaging. Furthermore, the proposed framework can be applied to real-time safety assessment, driver warning systems, and the development of rollover mitigation control strategies for lightweight and urban mobility vehicles..

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