Development and Validation of a 12-DOF Vehicle Model for Ride and Handling Analysis for Three-Wheeled Vehicle

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Author’s Profile

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Professional Experience : Head Chassis systems & Vehicle Dynamics EV & ICE Vehicles

- 18 years of rich experience in Chassis systems and Vehicle Dynamics & Control
- Leading Chassis and Vehicle Dynamics team in TVS Motor Company for the Commercial Mobility
- 40 Patents publications in the area of Vehicle Systems Dynamics and Control
- Working with international Collaborative projects with Ricardo UK, Warwick University UK.

1. Introduction

- Three-wheeled vehicles have a higher tendency to tip over during severe maneuvers.

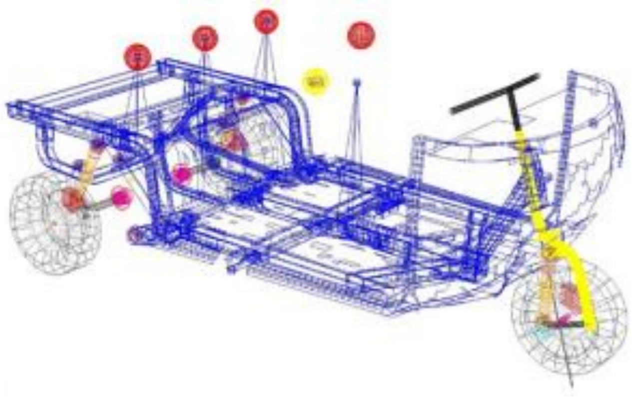
- These vehicles exhibit poor directional stability, making control more challenging.

- There are no standardized handling tests to evaluate stability, ride, and handling

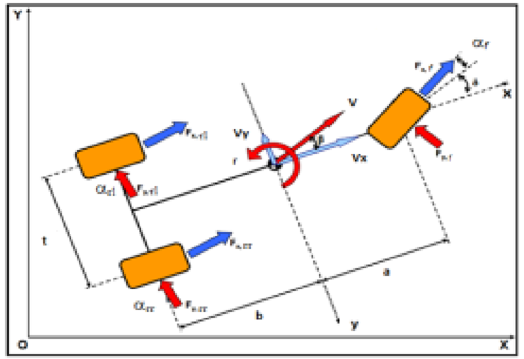
- Instability at high speeds is caused by front-wheel steering with low mechanical trail, high CG height, and low wobble mode frequency (2-4 Hz).

2. Objective

- Develop a mathematical model for the longitudinal, vertical, and lateral dynamics of a three-wheeled vehicle, incorporating tire, steering, and suspension compliances.
- Design a control method for improving vehicle stability with a low-cost controller.
- Develop an MBD model in ADAMS Car and integrate it with the stability controller.
- Build a prototype and validate its performance through simulations.



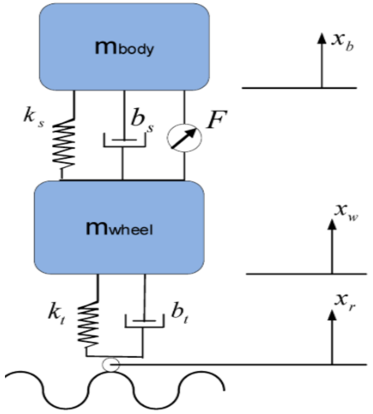
MBD model



Vehicle model

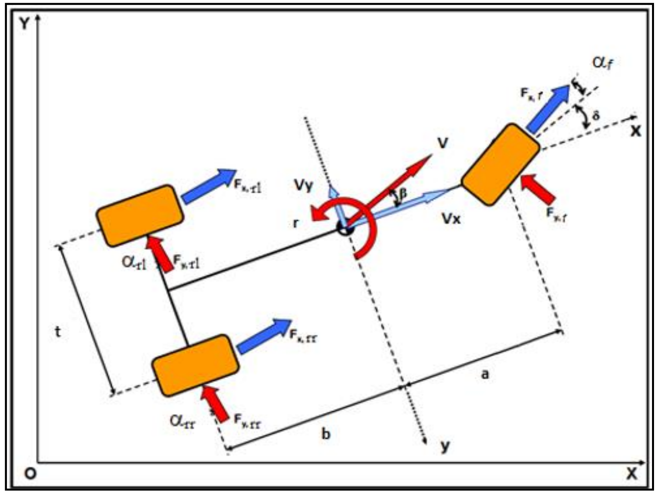
2.1 Scope of Work

- Development of a mathematical model for a three-wheeler vehicle, including tire, roll, and suspension models with non-linear and linear correlations to experimental data.
- Study of the effects of CG location, roll center location, and suspension and tire compliances on rollover dynamics.
- Simulation of the vehicle in ADAMS, integrating updated suspension, steering, and tire compliances.
- Experimental verification of rollover dynamics, handling, and comparison with control systems (both subjective and objective methods).
- Suspension optimization for improved ride and handling using existing models.

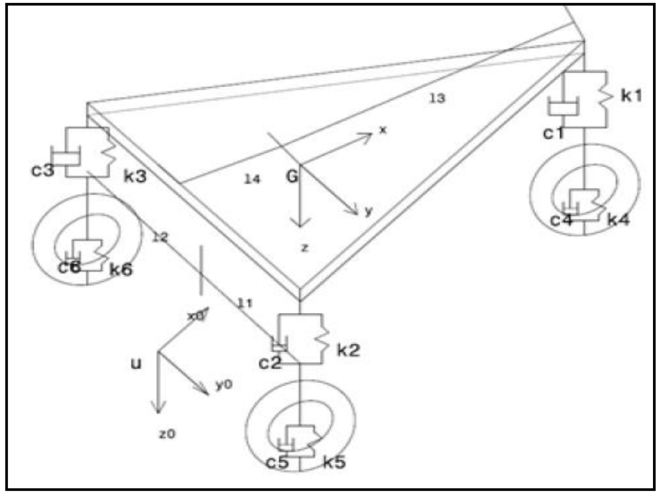


3. Three-Wheeler Vehicle Model

- 12-DOF nonlinear dynamic model for a three-wheeled vehicle is developed.
- The vehicle body has six DOF: translational and rotational motions.
- Each wheel has translational motion and wheel spin.
- Lagrangian mechanics is used to derive the Equations of Motion for ride and handling analysis.
- Below 3- Wheeler vehicle Model will be analytically discussed
    a) Governing Equations
    b) Roll Model
    c) Tire Model



Six DOF Horizontal vehicle model



Six DOF Vertical vehicle model

3.1 Governing Equations

- Governing equations of the Longitudinal, Lateral, and Vertical, Roll, Pitch and Yaw motions can be expressed as

  - Equation of motion for longitudinal motion

$$M_t\left(\dot{v_x} + \dot{\theta} v_z - v_y \dot{\psi}\right) = Fx_{,f} + Fx_{,rl} + Fx_{,rr} \qquad (1)$$

  - *Equation of motion for lateral motion*

$$M_t\left(\dot{v_y} + v_x \dot{\psi} - \dot{\theta} v_z\right) = Fy_{,r} + Fy_{,rl} + Fy_{,rr} \qquad (2)$$

  - Equation of motion for sprung mass vertical motion

$$M_s\left(\dot{v_z} + v_x \dot{\psi} - \dot{\theta} v_z\right) = Fz_{,r} + Fz_{,rl} + Fz_{,rr} \qquad (3)$$

  - Equation of motion for sprung mass roll motion

$$M_x = I_{sxx}\ddot{\phi} - \left(I_{syy} - I_{szz}\right)\dot{\theta}\dot{\psi} = Fz_{,rl} - Fz_{,rr} \qquad (4)$$

  - Equation of motion for sprung mass pitch motion

$$(Fz_{,rl} + Fz_{,rr})b - Fz_{,f}\, a - ((Fx_{,f} + Fx_{,rl} + Fx_{,rr}) \qquad (5)$$

  - Equation of motion for sprung mass yaw motion

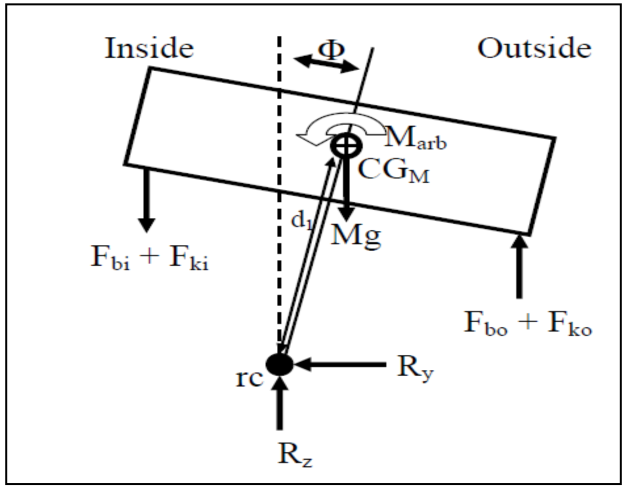
$$(Fx_{,rl} - Fx_{,rr})t/2 - (Fy_{,rl} + Fy_{,rr})b + (Fy_{,f}\, a) \qquad (6)$$

3.2 Roll Model

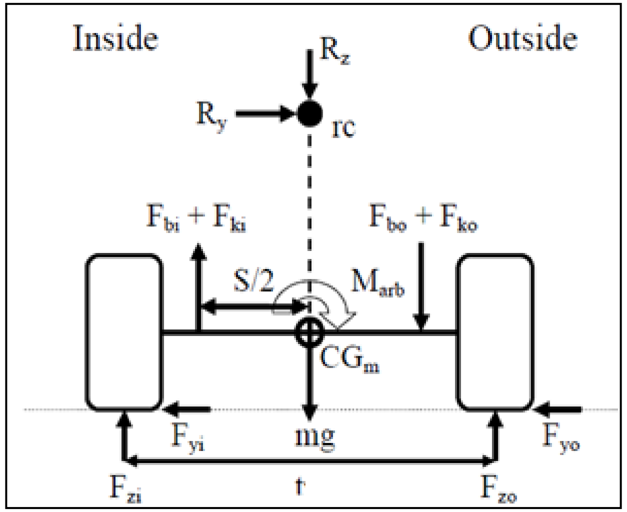
- Roll equations are derived by decomposing the vehicle into sprung and unsprung masses using Newton’s Second Law.
- The linearized model aids in analysing roll behavior, focusing on load transfer, roll stiffness, and suspension for stability.
- Fundamental expression for analyzing roll dynamics in steady-state cornering condition

$$\Phi_{ss} = \frac{M_s d1}{k_{\Phi t} - M_s d1} . a_y$$

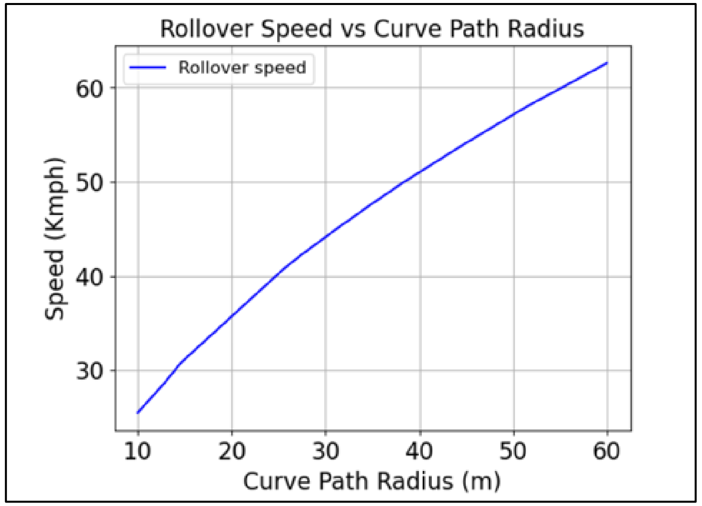
a_y= *Lateral acceleration* , $k_{\Phi t}$= *Total roll stiffness*,M_s= *Total sprung mass*



Roll FBD Sprung Mass



Roll FBD Un-Sprung Mass



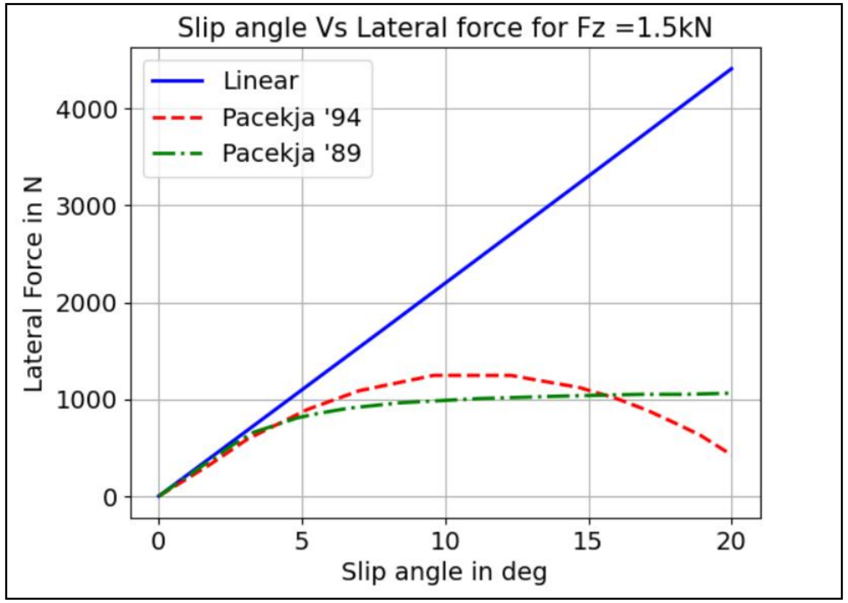
Rollover speed Vs Radius of turn

3.3 Tire Model

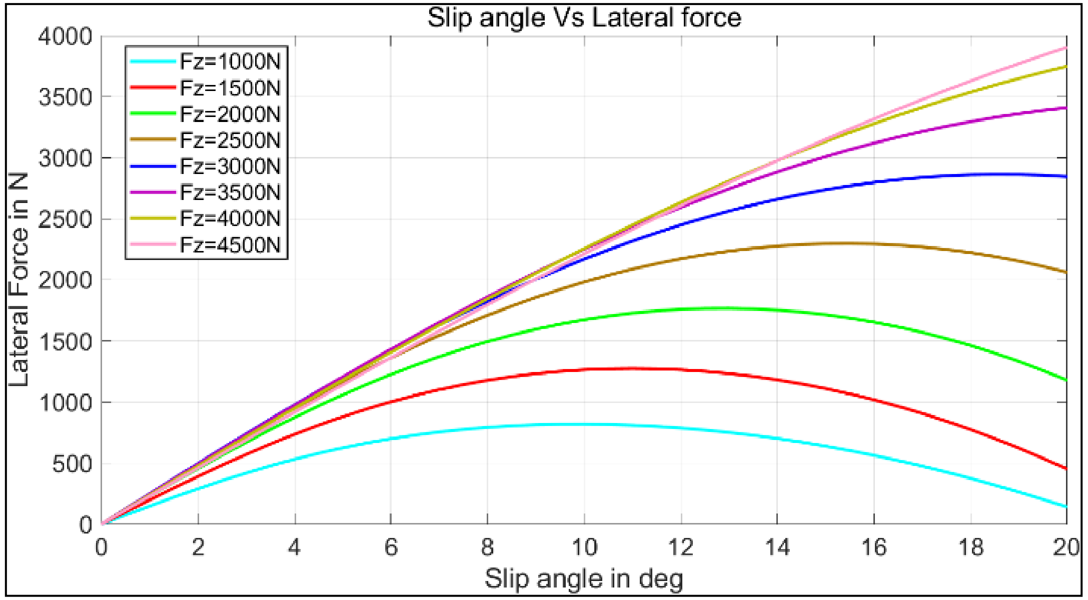
- The Pacejka Magic Formula is used to model tire forces based on experimental data, capturing nonlinear tire behavior through slip angle and slip ratio.

$$y = D \sin\left(C \tan^{-1}\left(Bx - E\left(Bx - \tan^{-1}(Bx)\right)\right)\right)$$

Tire Slip Angle,α , [deg]	2.5º	5 º	7 º
Lateral Force difference between Linear and Non-Linear Tire Pacejka ‘89’ Model	4%	33%	65%
Lateral Force difference between Linear and Non-Linear Tire Pacejka ‘94’ Model	14%	25%	40%



Comparison of Linear vs. Nonlinear Pacejka '89 and '94 Tire Models under a Normal Force of 1.5 kN



Non-Linear Tire Model with Varying Normal Forces

4. Virtual Vehicle Model and simulation

- A flexible three-wheeled MBD model is developed using ADAMS CAR with rear and front frames.

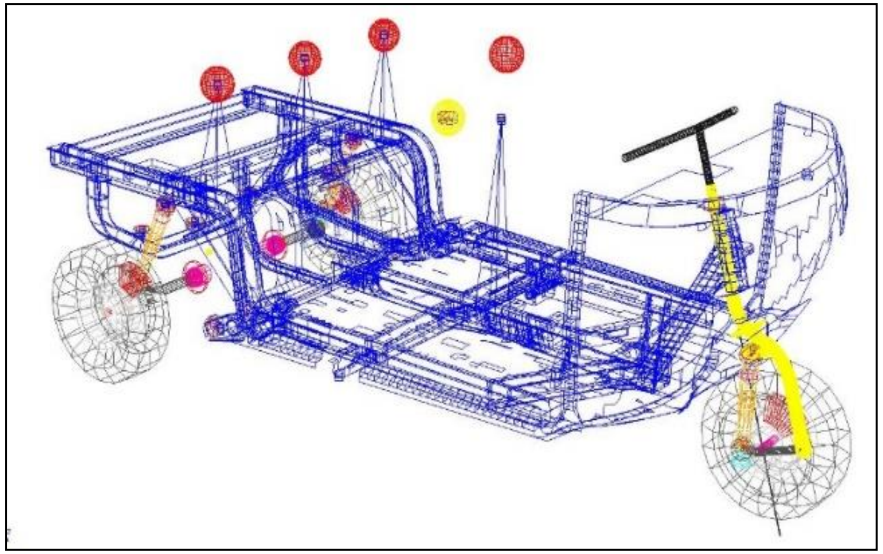
- The frames are connected at the steering axis, allowing relative rotation.

- Key parameters like mass, inertia, and suspension properties are updated with experimental data.

- The Pacejka '94 tire model is used for accurate dynamic tire behavior analysis.

- MBD simulations using ADAMS/Car analyzed handling via open-loop and closed-loop maneuvers to assess vehicle stability and performance.

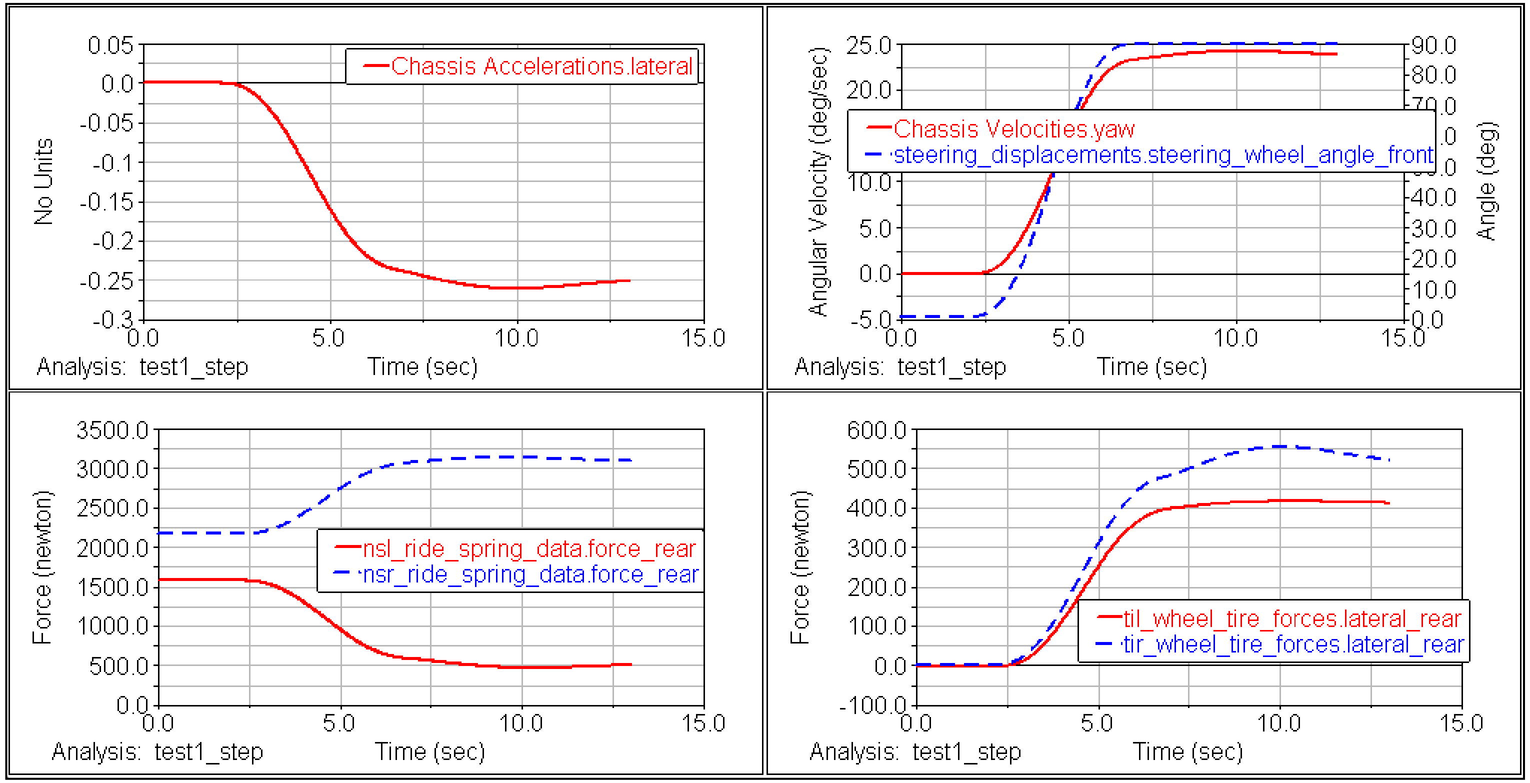
    - **Step Steer Maneuver**
    - **Constant Radius Cornering**



Three-Wheeler MBD Model using ADAMS Software

4.1 Step Steer Maneuver – MBD Simulation

- The Step Steer Maneuver applies a sudden steering input to analyse the vehicle's transient response, focusing on yaw rate, lateral acceleration, and roll stability.
- ADAMS/Car increases the steering input from an initial to a final value over a specified time during the Step Steer analysis.



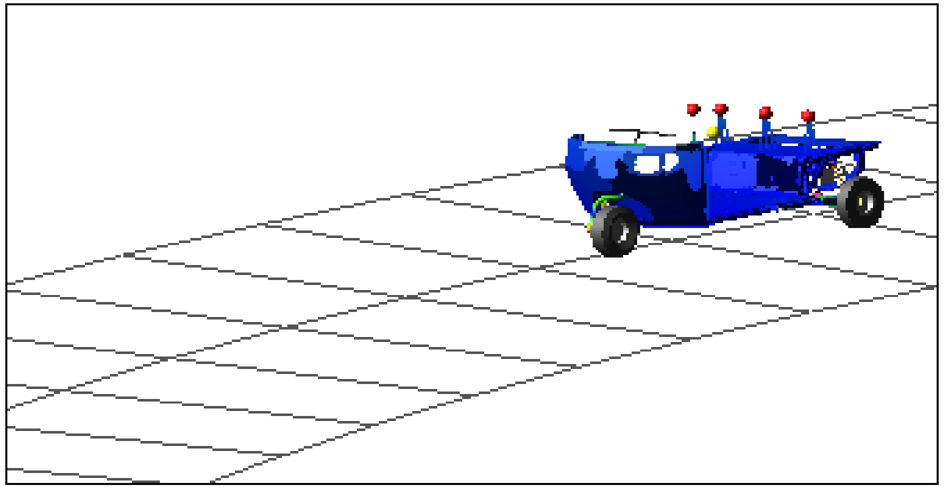
Vehicle lateral acceleration, yaw rate, steering angle input, rear (left/right) spring forces, tire lateral forces

4.2 Constant Radius Cornering simulation

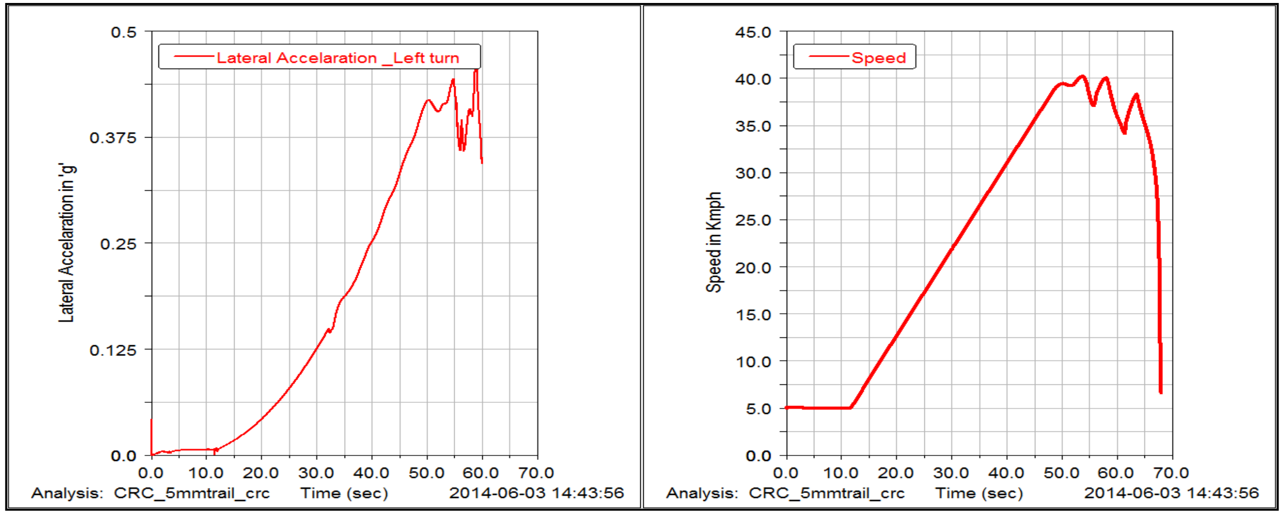
- Constant-radius cornering analysis assesses lateral grip, understeer, and roll behavior, determining the velocity at which roll-over instability occurs.

- The vehicle increases speed on a skid pad to build lateral acceleration.

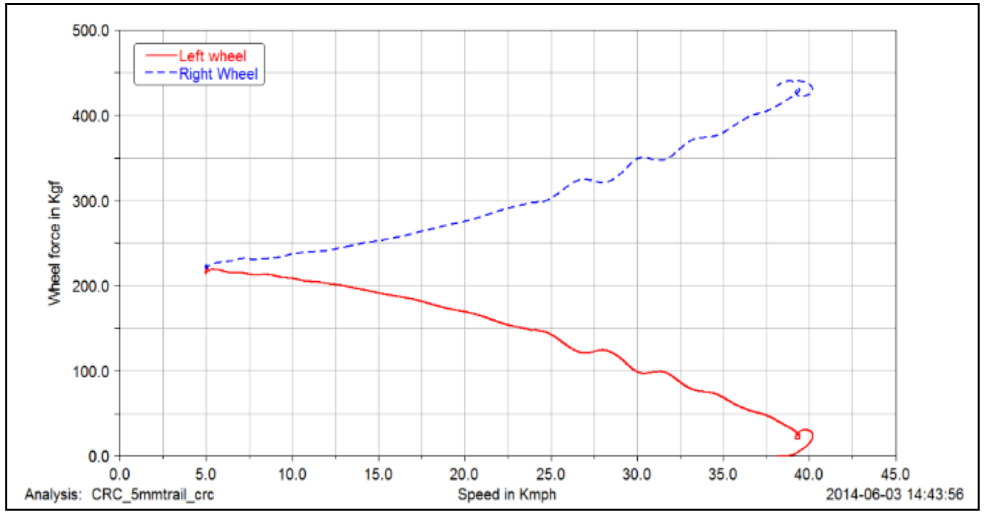
- The vehicle starts to roll at around 38 km/h for a 30m radius, as shown in Graph



CRC – MBD Simulation in ADAMS Software



Vehicle CG longitudinal velocity, lateral acceleration (g)

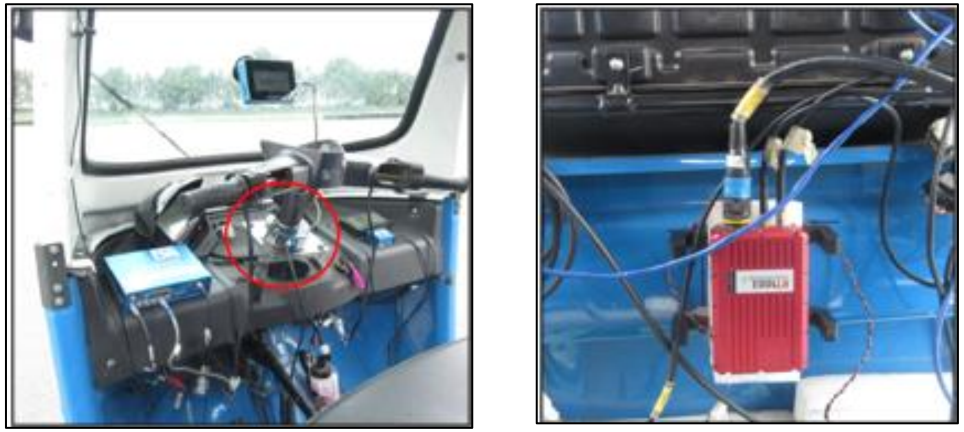


Rear Tire (left and right) normal forces

5. Experimental Setup

- **Test Track and Maneuver:** The vehicle was tested on a 30-meter radius circular track to measure lateral acceleration, roll angle, and yaw velocity.
- **Speed Variation**: Speed was increased in steps, with increments of 0.05 g in lateral acceleration up to 28 km/h, and fixed increments of 2 km/h beyond that, until wheel lift-off occurred.
- **Instrumentation:** The RT1003 IMU and Steering Sensor system captured yaw, pitch, roll rates, and accelerations for precise analysis of vehicle dynamics.
- **Data Collection:** Real-time data on vehicle stability and performance were collected to assess the critical speed and vehicle limits.

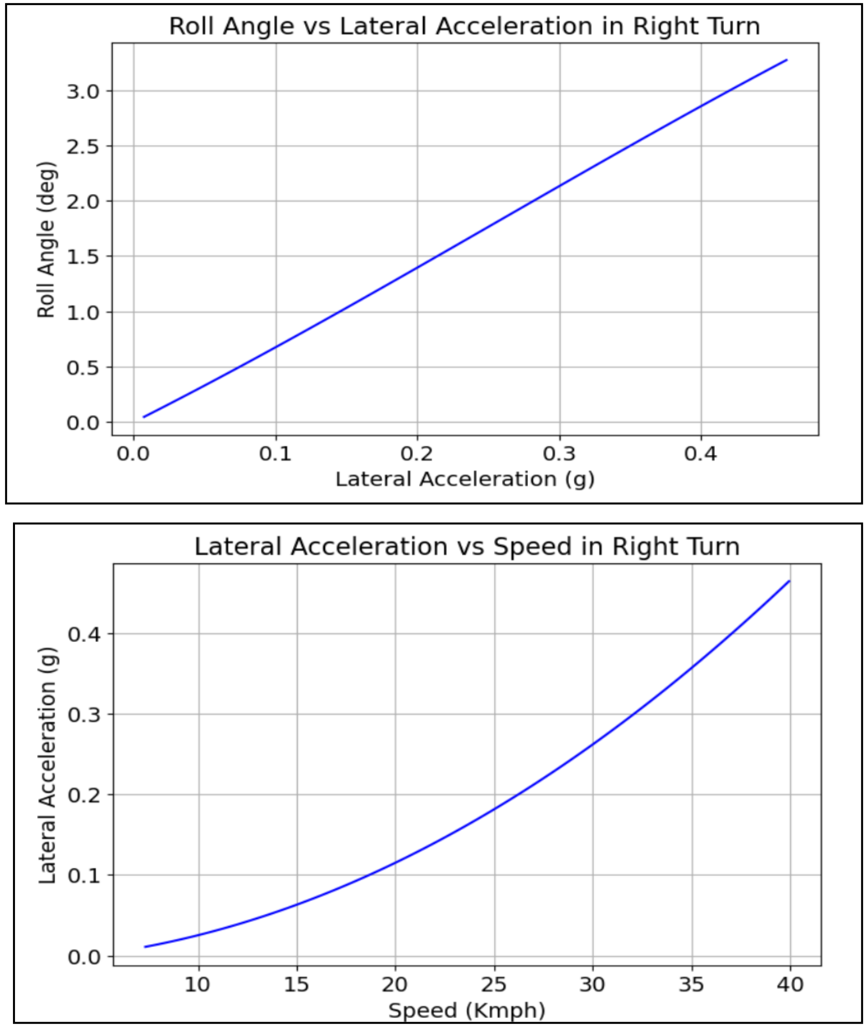
Constant Radius Cornering at Test rack



RT1003 IMU and Steering sensor for Vehicle dynamics Parameter Measurement

5.1 Validation of Results

- Speeds were incremented systematically to observe lateral acceleration and stability limits.
- Wheel lift-off occurred at approximately 40.38 km/h, indicating the point of critical instability.
- The experimental data were compared to simulations to validate the accuracy of predictions regarding vehicle instability.
- The findings helped improve vehicle safety analysis and refine suspension and stability control systems.



Lateral accelerations, Speed and Roll angle

6. Conclusion

- The study developed a 12-DOF vehicle model to analyze ride and handling dynamics, incorporating both linear and nonlinear tire models.
- Validation was achieved through MBD simulations and experimental tests, focusing on key handling metrics like yaw rate, lateral acceleration, and roll stability.
- The simulations showed roll instability at 38 km/h, which closely matched the experimental observation of wheel lift-off at 40.38 km/h.
- The findings highlight the significance of using high-fidelity tire models and conducting real-world testing to improve vehicle stability and enhance safety systems.

7. Future Work

- Future research will examine various road conditions and friction levels to assess their impact on vehicle dynamics.
- Studies will also focus on different vehicle configurations, like three-wheelers, to understand real-world dynamic behavior.
- The model will be improved with higher DOF and structural compliances, along with roll stability detection and control.
- Advanced analyses using WFT data from RLDA will enhance the evaluation of vehicle dynamics, ride quality, and handling.

8. References

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