Journal of Engineering and Technology

ISSN 2180-3811 eISSN 2289-814X https://jet.utem.edu.my/jet/index
DOI: https://doi.org/10.54554/jet.2026.17.1.015

DESIGN AND VALIDATION OF A MODIFIED ODENTHAL INDEX-BASED ROLLOVER WARNING SYSTEM FOR COMMERCIAL VEHICLES

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Article history:
Received Date: 21 August 2025
Revised Date: 18 December 2025
Accepted Date: 30 April 2026

Keywords: Commercial Vehicle,

Abstract— Commercial vehicle accidents, particularly rollovers of lightweight trucks, are frequently reported in the mass media. Rollovers have a significantly higher fatality rate than other types of crashes, posing serious risks to both drivers and passengers. Multiple factors contribute to rollover incidents, resulting in severe injuries and fatalities. This study aims to develop a Rollover Warning Device (RWD) specifically designed for commercial vehicles that exhibit a greater center of gravity height-to-

Odenthal Rollover Index Algorithm, Rollover Warning System

track width ratio. This system collects real-time vehicle motion data and assesses rollover risk through a rollover index (RI) algorithm based on the load transfer ratio (LTR) that is implemented in the rear-wheel drive (RWD) of the vehicle. MATLAB/Simulink is used to optimize the block model parameters and evaluate the rollover index by analyzing step-steering maneuvers at various speeds. To further validate the system, the enhanced Odenthal rollover index approach is integrated into the TruckSim driving simulator and MATLAB/Simulink software. Hardware-in-the-loop (HIL) simulation models the step-steering maneuvers under different speed and load conditions. The experimental results demonstrate that the modified Odenthal rollover index algorithm improves Time-to-Warn (TTW) by 12.5% compared to the original Odenthal index. Additionally, this approach ensures a suitable Time-to-Respond (TTR), allowing drivers to take corrective action effectively. By refining the early warning system, the enhanced Odenthal rollover index algorithm significantly reduces the likelihood of rollover incidents, thereby improving commercial vehicle safety.

I. Introduction

Commercial vehicle rollovers are often caused by human errors, such as speeding on curves, misjudging road geometry, and abrupt maneuvers.

Statistics show that 85% of rollover fatalities involve single-vehicle crashes, with the remaining 15% involving multiple vehicles, often leading to severe injuries or death [1]. Key contributing factors include vehicle size, height, and a high center of gravity (CG), which are common in commercial trucks, vans, and SUVs, hence leading to instability.

Excessive speed plays a major role in rollover incidents, with about 40% of fatal rollovers linked to speeding, particularly on roads with high-speed limits [2]. Distractions like phone use, eating, and miscalculating turns further increase the risk. To mitigate such risks, rollover warning systems are developed to provide early alerts to drivers before a rollover occurs. These systems use algorithms that evaluate rollover potential by incorporating vehicle parameters such as speed, mass, load condition, and vehicle geometry.

Two common metrics for rollover risk are static roll instability and dynamic roll instability. The static indicator is based on the vehicle's track width and CG height, is effective in steady-state scenarios [3]. However, dynamic indicators like roll angle, lateral acceleration, roll rate, and Load Transfer Ratio (LTR) offer better accuracy during real-time driving conditions [4-8].

This study proposes a real-time rollover warning device using a Modified Odenthal Rollover Index (MORI) algorithm that considers driver steering input and vehicle velocity to assess rollover risk. The main objective is to design and fabricate a practical warning device for commercial vehicles that provide timely alerts to enhance road safety.

The rest of this paper is organized as follows: Section 1 provides the research background and literature review related to the rollover warning device, where the gaps, significance, and objectives of the study are determined. Section 2 showed the flow of this study, while Section 3 discussed the results of the proposed rollover index algorithm. Section 4 presented the findings of the study and concluded the paper.

II. Methodology

An early warning system is essential to predict rollover risk in advance and alert the driver before a rollover occurs [9]. This study focuses on the design and development of a rollover warning system, implemented using MATLAB/Simulink. The system simulates the vehicle's dynamic response to external inputs such as steering and speed to evaluate the potential for rollover and trigger a warning signal when necessary.

A. Development of Modified Odenthal Rollover Index (MORI) Algorithm

To improve the predictive accuracy of the original Odenthal, a Modified Odenthal Rollover Index (MORI) is developed by introducing gain parameters K_a and K_r that amplify the effects of lateral acceleration and roll angle, respectively [10]. The MORI algorithm expresses as Equation (1).

$$\boldsymbol{RI_{Modified\ Odenthal} = K_a\left[\frac{2m_2\left(h_{cg2}\right)}{mgT}\right]a_{y,2} + K_r\left[\frac{2m_2h}{mT}\right]\sin\phi} \tag{1}$$

Here, K_a modulates the influence of lateral acceleration, while K_r tunes the contribution of body roll. These gain values are obtained via sensitivity analysis based on a step-steering maneuver performed at 100 km/h in TruckSim, which aims to fine-tune the MORI algorithm for optimal detection and warning responsiveness [11]. The calibration process relies on simulating the rollover index transition where the RI rises above 1 and subsequently returns to its stable state, hence providing

B. Optimization of MORI Model Parameters

In the study conducted by Harun et al. [12], the vehicle model is simulated in the MATLAB/Simulink software, where the parameters K_a and K_r were optimized using Particle Swarm Optimization (PSO) to achieve optimal performance under different load conditions. Table 1 displays the refined values of the K_a and K_r parameters under different load conditions. These parameters were used to conduct studies under different vehicle weight situations.

Table 1: The optimized values of K_a and K_r for different load conditions

Load condition	K_a	K_r
Unladen	1.2083	4.0049
Half-laden	1.4934	4.2213
Full-laden	1.8775	4.2327

C. Testing Procedure Using TruckSim Software

A test was conducted using driver hardware in the loop (DHIL) simulation in TruckSim, which allowed real-time assessment of the vehicle's rollover potential [13]. The steering angle and vehicle speed served as input data for the test. A 60° steering maneuver was applied at different speeds ranging from 60 km/h to 120 km/h using MATLAB/Simulink integrated with TruckSim. These speed levels correspond to the low, medium, and high velocity categories from the SAE-932949 standard. The test continued until the rollover index (RI) exceeded 1, indicating tire lift-off.

To evaluate performance under different loading conditions, the truck was tested in three states: full-laden (12,600 kg), half-laden (11,300 kg), and unladen (10,000 kg). An RSF (Reliability Score Factor) of 0.75 was used as the warning threshold, meaning the system would trigger an alert when the RI approached this level.

Figure 1: Setting of truck model in TruckSim software

The truck model setup used in the simulation is shown in Figure 1, and its specifications are detailed in Table 2, which are based on the HINO 300 Series commercial truck [14]. The MORI algorithm and vehicle model were simulated using the Heun solver with a fixed time step of 0.01s, following the simulation procedure by Yussof et al. [15].

Table 2: HINO 300 Series Specifications

Parameter	Value
Sprung mass, M_s	6360 kg
Unsprung mass, M_u	530 kg
Tire stiffness, K_t	900000 N/m
Front spring stiffness, K_{sf}	250000 N/m
Rear spring stiffness, K_{sr}	1083004 N/m
Front damper coefficient, C_{sf}	15000 N/m
Rear damper coefficient, C_{sr}	26000 N/m
Track width, t	2.6 m
Length, l	4765 mm
Height, h	2270 mm
CG to the front axle distance, a	3.012 m
CG to the rear axle distance,b	4.9 m
Roll moment of inertia, I_{xx}	7695.6 kgm^2
Pitch moment of inertia, I_{yy}	30782.4 kgm^2

III. Results and Discussion

Previous studies have identified Odenthal’s Rollover Index (ORI) algorithm as one of the most effective methods for detecting rollover risk. For example, Harun et al. [16] reported that ORI could trigger a rollover warning within 0.51 seconds. However, the algorithm’s performance degrades as vehicle speed increases. According to findings by Shahdah et al. [17], the required driver response time increases by approximately 0.70 seconds for every 10 km/h increment in vehicle speed. This delay is significant and could reduce a driver's chances of taking timely corrective action during critical situations. This study proposed an improved rollover detection method, the Modified Odenthal Rollover Index (MORI) algorithm, which enhances early warning performance by integrating driver steering input and vehicle speed. The following subsection

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presents the evaluation of MORI's performance under unladen vehicle conditions. Results from half-laden and full-laden conditions are summarized later in Table 3.

A. Performance of the MORI Model under Unladen Condition

The MORI algorithm was tested under unloaded conditions using the TruckSim simulator combined with MATLAB/Simulink. The vehicle performed step-steering maneuvers at speeds of 60, 90, and 120 km/h. The unladen condition refers to the lowest test weight (5,000 kg), and a rollover safety factor (RSF) threshold of 0.75 was used as the early warning indicator. At 60 km/h as in Figure 2, both the MORI and Odenthal rollover indices reached a maximum value of 0.56, which remained below the RSF threshold. As a result, no rollover warning was triggered. However, MORI showed a faster Time-to-Warn (TTW) compared to Odenthal, despite the absence of a critical warning condition.

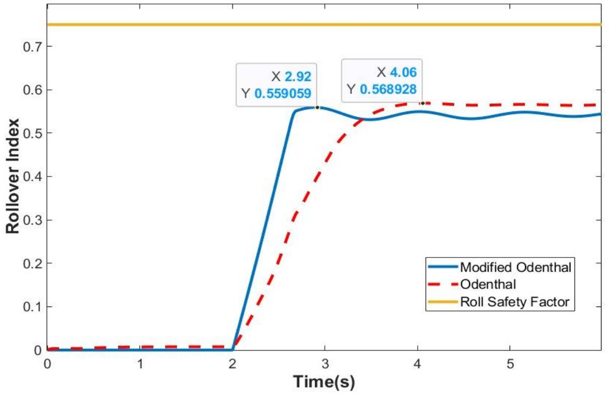

Figure 2: Unladen State with Velocity at 60 km/h

At 90 km/h as in Figure 3, the peak rollover indices increased to 1.24 for MORI and 1.16 for Odenthal, but the response curves still did not cross the RSF line. Again, no warning was issued, but MORI continued to respond faster than Odenthal, demonstrating higher sensitivity. At the highest test speed of 120 km/h as in Figure 4, both indices finally exceeded the RSF threshold, triggering a warning. Odenthal crossed the RSF line at 2.72s with a peak RI of 1.15, while MORI crossed it earlier at 2.38s with a higher peak RI of 1.35. This marks a 12.5% improvement in TTW with MORI compared to Odenthal.

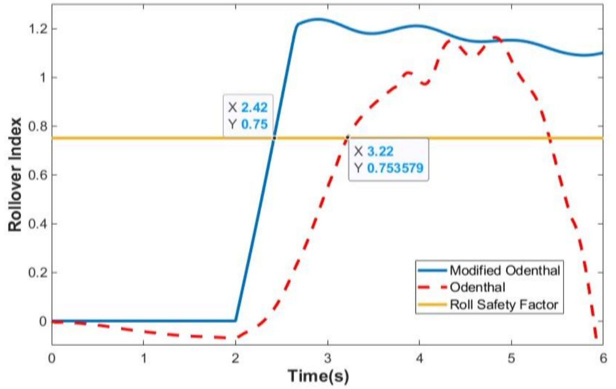

Figure 3: Unladen State with Velocity at 90 km/h

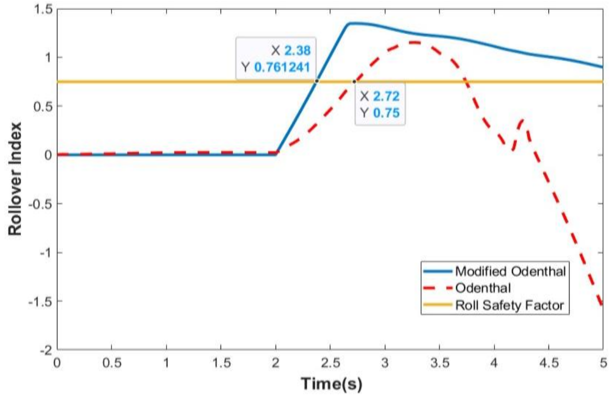

Figure 4: Unladen State with Velocity at 120 km/h

These findings highlight MORI's enhanced responsiveness, especially at high speeds. The algorithm consistently provided earlier warnings, enabling the buzzer and light system to alert the driver before the rollover threshold was reached. This allowed the driver more time to take corrective action, improving safety under unladen and high-speed conditions. While this section presents only the unladen condition in detail, additional simulations under half-laden (11,300 kg) and full-laden (12,600 kg) conditions were also conducted. The results are summarized in Table 3, which compares TTW between the MORI and Odenthal algorithms at each loading level and speed.

Table 3: Percentage of the Time Difference between MORI and ORI at Different Loading Conditions

Loading Condition		RSF Boundary			
Category	Velocity (km/h)	MORI (s)	ORI (s)	Time Difference (s)	Percentage (%)
Unladen	60	-	-	-	-
	90	-	-	-	-
	120	2.38	2.72	0.34	12.5
Half-laden	60	-	-	-	-
	90	2.42	3.08	0.66	21.43
	120	2.28	2.90	0.62	21.38
Full-laden	60	-	-	-	-
	90	2.42	3.22	0.80	24.84
	120	2.28	3.34	1.06	31.74

IV. Conclusion

This study developed a rollover warning system based on the Modified Odenthal Rollover Index (MORI), integrating two key components: driver steering input and vehicle speed into the rollover index algorithm. Unlike conventional methods that rely solely on lateral acceleration, MORI provides a more comprehensive and responsive approach. The system was tested using TruckSim and MATLAB/Simulink, by applying various step-steering maneuvers across different speeds and loading conditions. Results showed that MORI improved reaction speed by 31.74% compared to the original Odenthal model. It also proved effective under high-speed conditions, providing faster Time-to-Warn (TTW) and allowing the driver more Time-to-Respond (TTR) to avoid rollover accidents. MORI achieved a minimum TTW of

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1.06 seconds, giving the driver a critical window to take corrective action. These findings highlight that combining vehicle speed and steering input significantly enhances rollover prediction accuracy and system responsiveness. In conclusion, the MORI-based warning system is a practical and effective solution for improving commercial vehicle safety by delivering timely rollover alerts and enabling preventive driver responses.

V. Acknowledgement

This project is funded by the Ministry of Higher Education Malaysia and Universiti Teknikal Malaysia Melaka (Research Grant Number: PJP/2022/FTKMP/S01888).

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