DESIGN AND FABRICATION OF HEAVY VEHICLE ROLLOVER WARNING DEVICE BY IOT BASED MONITORING

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Faculty of Mechanical Technology and Engineering

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Mohammad Ammar Bin Mohammad Rozaimin

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A thesis submitted
in fulfillment of the requirements for the degree of
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ABSTRACT

Heavy vehicle rollovers are a significant concern, contributing to a high number of fatal accidents worldwide. Statistics show that rollover incidents account for a substantial portion of traffic accidents, often resulting in severe injuries and fatalities. This project addresses this critical issue by designing and fabricating a heavy vehicle rollover warning device using an Internet of Things (IoT)-based monitoring system. The primary objectives are to develop a rollover warning system specifically for heavy-duty trucks and to integrate the IoT system for real-time monitoring. The research methodology involves a two-pronged approach. The first component utilizes Software-in-the-Loop (SIL) simulation, employing TruckSim and MATLAB/Simulink to create and optimize a Modified Odenthal Rollover Index (MORI) algorithm for accurately predicting rollover risks. The second component involves Hardware-in-the-Loop (HIL) implementation, where the MORI algorithm is integrated with an ESP32 microcontroller, sensors, and a Blynk app to develop a functional rollover warning device. Real-time monitoring using the Blynk IoT platform ensures that critical safety alerts are promptly communicated to drivers. The results from the SIL simulations demonstrate that the MORI algorithm provides earlier warnings, specifically 1.13 seconds sooner than the original Odenthal rollover index, allowing sufficient time for drivers to implement corrective actions. Additionally, the integration of the MORI algorithm in MATLAB/Simulink with real-time monitoring via the Blynk app showed excellent synchronization, confirming the reliability and practicality of the IoT-based monitoring system. The system consistently achieved identical RSF threshold crossing times in simulation and real-time monitoring, ensuring robust and accurate rollover detection under various loading and speed conditions. This comprehensive approach highlights the potential of combining advanced rollover detection algorithms with IoT technologies to enhance road safety, reduce accidents, and protect lives in the heavy vehicle industry.

ABSTRAK

Keadaan kenderaan berat terbalik merupakan kebimbangan yang ketara, menyumbang kepada jumlah kemalangan maut yang tinggi di seluruh dunia. Statistik menunjukkan bahawa insiden terbalik menyumbang sebahagian besar daripada kemalangan jalan raya, selalunya mengakibatkan kecederaan teruk dan kematian. Projek ini menangani isu kritikal ini dengan mereka bentuk dan fabrikasi peranti amaran terbalik kenderaan berat menggunakan sistem pemantauan berasaskan *Internet of Things (IoT).* Objektif utama adalah untuk membangunkan sistem amaran *rollover* khusus untuk trak tugas berat dan untuk menyepadukan sistem IoT untuk pemantauan masa nyata. Metodologi penyelidikan melibatkan pendekatan serampang dua mata. Komponen pertama menggunakan simulasi *Software-in-the-Loop (SIL),* menggunakan TruckSim dan MATLAB/Simulink untuk mencipta dan mengoptimumkan algoritma Indeks Rollover Odenthal yang Diubahsuai (MORI) untuk meramalkan risiko rollover dengan tepat. Komponen kedua melibatkan pelaksanaan *Hardware-in-the-Loop (HIL),* di mana algoritma MORI disepadukan dengan mikropengawal ESP32, penderia dan aplikasi Blynk untuk membangunkan peranti amaran rollover berfungsi. Pemantauan masa nyata menggunakan platform Blynk IoT memastikan amaran keselamatan kritikal disampaikan dengan segera kepada pemandu. Hasil daripada simulasi SIL menunjukkan bahawa algoritma MORI memberikan amaran lebih awal, khususnya 1.13 saat lebih awal daripada indeks peralihan Odenthal asal, membolehkan masa yang mencukupi untuk pemandu melaksanakan tindakan pembetulan. Selain itu, penyepaduan algoritma MORI dalam MATLAB/Simulink dengan pemantauan masa nyata melalui aplikasi Blynk menunjukkan penyegerakan yang sangat baik, mengesahkan kebolehpercayaan dan kepraktisan sistem pemantauan berasaskan IoT. Sistem ini secara konsisten mencapai masa lintasan ambang RSF yang sama dalam simulasi dan pemantauan masa nyata, memastikan pengesanan rollover yang teguh dan tepat di bawah pelbagai keadaan pemuatan dan kelajuan. Pendekatan komprehensif ini menyerlahkan potensi menggabungkan algoritma pengesanan rollover termaju dengan teknologi IoT untuk meningkatkan keselamatan jalan raya, mengurangkan kemalangan dan melindungi nyawa dalam industri kenderaan berat.

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I am truly thankful to everyone who has been a part of this journey, and I sincerely hope that the outcomes of this research will contribute to the enhancement of heavy vehicle safety and the reduction of catastrophic rollover accidents.

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a	-	Distance from front tire to center
a_y	-	Lateral acceleration
$a_{y,2}$	-	Lateral acceleration of the body only
b	-	Distance from rear tire to center
c	-	Damping coefficient
C_{sf}	-	Front damper coefficient
C_{sr}	-	Rear damper coefficient
$F_{Z,L}$	-	Left vertical tire force
$F_{Z,R}$	-	Right vertical tire force
g	-	Gravitational acceleration
h	-	Height of CoG
h_R	-	Roll center height
I_x	-	Moment of inertia of roll axis
I_{xx}	-	Roll inertia
K	-	Steer gradient
k	-	Spring stiffness
K_{sf}	-	Front spring stiffness
K_{sr}	-	Rear spring stiffness
K_t	-	Tire stiffness
Ka	-	Coefficient of body lateral acceleration
Kr	-	Coefficient of roll angle
L	-	Wheelbase
m	-	Total mass
m_2	-	Body mass
M_s	-	Sprung mass
M_u	-	Unsprung mass
T or t or l_w	-	Track Width
v	-	Velocity
φ	-	Roll angle

$\dot{\phi}$	-	Roll rate
$\ddot{\phi}$	-	roll acceleration
δ	-	Steering angle

LIST OF ABBREVIATIONS

3D	-	3-dimension
ADAS	-	Advanced Driver Assistance Systems
AI	-	artificial intelligence
AIDS	-	acquired immunodeficiency syndrome
ARM	-	Advanced RISC Machine
CDC	-	Centers for Disease Control and Prevention
CoG	-	center of gravity
CPU	-	central processing unit
EMI	-	electromagnetic interference
ESP	-	Espressif System
EWD	-	Early Warning Devices
FMCSA	-	Federal Motor Carrier Safety Administration
HIL	-	Hardware-in-the-Loop
HIV	-	human immunodeficiency virus
HTTP	-	Hypertext Transfer Protocol
IoT	-	Internet of Things
I/O	-	input/output
LED	-	Light-Emitting Diode
LTR	-	Load Transfer Ratio
MIL	-	Model-in-the-Loop
MORI	-	Modified Odenthal Rollover Index
MIROS	-	Malaysian Institute of Road Safety Research

MQTT	-	MQ Telemetry Transport
NHTSA	-	National Highway Traffic Safety Administration.
PSO	-	Particle Swarm Optimization
RAR	-	Rearward Amplification Ratio
RC	-	Remote Control
RI	-	rollover index
RMP		Royal Malaysian Police
RSF	-	Roll Safety Factor
IDE	-	Integrated Development Environment
SUV	-	Sport Utility Vehicle
SPI	-	Serial Peripheral Interface
SRT	-	Static Rollover Threshold
SSF	-	Static Stability Factor
SIL	-	Software-in-the-Loop
SSC	-	step steer cornering
SoC	-	system-on-chip
TTW	-	Time-To-Warn
TTR	-	Time-To-Respond
USB	-	Universal Serial Bus
VIL	-	Vehicle-In-the-Loop

CHAPTER 1

INTRODUCTION

1.1 Background

As technology advances, automobile safety has been prioritized worldwide. The National Centre for Injury Prevention and Control, part of the CDC, reports rising accident rates. They found 1.35 million automobile accident deaths worldwide. In 2022, 42,795 people died in car accidents. At least 3,700 incidents involving automobiles, motorbikes, buses, trucks, and pedestrians were reported. Accidents can also cause permanent disability. Injury and chronic disability would affect 2.35 million people by 2023. Over half of this number are children and adolescents, which is concerning. Accidents kill more than HIV/AIDS. European car accidents kill about 50,000 and injure 150,000.

Malaysia had 6,080 accident deaths in 2023. In that year, deadly automobile accidents killed 17-18 people every day, according to Datuk Lokman Jamaan, the Senior Director of the Enforcement Division of the Road Transport Department. According to the Kosmos Newspaper, the Royal Malaysian Police (RMP) reported 598,635 traffic accidents from January 1 to December 30.

After that, MIROS recorded 34,747 heavy vehicle traffic accidents. MIROS also found that 32.8% and 28.4% of accidents were head-on and rear-end crashes. The average accident rate was 51% during daytime and 49% at nightfall. Poor lighting causes 55.1% of nighttime accidents, reducing driver visibility. Malaysia's transport minister, Anthony Loke, believes overweight lorries may have caused the disaster. Vehicles that are overloaded can lose control or roll over. Studies on rollover events have examined the causes of deadly heavy vehicle accidents.

Lateral car rollovers, where a vehicle slides sideways and hits the curb, are the most common. Due to their weight, size, and center of mass, heavy trucks rollover more often. It's commonly known that traffic accidents involving heavily loaded vehicles transporting products and rollovers can hurt economic growth since they endanger lives and property. Heavy vehicle rollovers in road accidents affect economic growth, individual well-being, and property.

Use warning system devices to advise drivers in advance so they may take precautions to prevent rollovers. The devices will help drivers quickly apply brakes and change steering angle to stabilize vehicles. Rollover occurrences can also occur when the warning signal is delayed, causing heavy trucks with big loads and high forward inertia to brake insufficiently. The gadgets' warning systems' ability to alert drivers early will be assessed. Rollover occurrences remain the top cause of fatal road accidents, hence rollover warning devices must be prioritized even when other safety measures have improved.

1.2 Problem Statement

Uncontrolled autos roll or swerve. Accident severity impacts how often cars flip over before stopping. In 2015, 12.3% of fatal truck accidents and 9.9% of injury collisions were rollovers. National Highway Traffic Safety Administration says rollovers can hurt heavy vehicle drivers. Rollovers injured 58% of large heavy vehicle drivers 2011–2015. The Malaysian Department of Traffic Transport reported 19,888 heavy vehicle traffic incidents in the first six weeks of 2022, including rollovers. Statistics and percentages are alarming given high injury and fatality rates.

Rollovers are more complicated than other accidents, making cause identification tougher. Most car accidents are caused by driver weariness, drowsiness, health difficulties, road conditions, weather, visibility, and vehicle conditions. Over 56% of heavy vehicle rollovers occur on straight roadways, per NHTSA/FMCSA. It's interesting that 93% of heavy vehicle rollovers occur on dry roadways. Speeding caused 28% of heavy vehicle accidents. Rosenfeld (2016) observed 66% of heavy truck rollovers had 10-year drivers.

Most heavy vehicle rollovers are caused by human mistake, especially safety negligence. Rollovers can happen from misjudging bend degrees, speeding on curves, and abrupt actions. Vehicle type, load location, and caravan torsional rigidity caused rollovers. More tractor-trailers, pickups, vans, and SUVs rollovers. Uneven upper weight distribution raises the vehicle's center of gravity, reducing stability. Rapid acceleration and speed cause rollovers. Driving while texting, eating, or drinking causes 40% of deadly fast-curving highway rollovers.

Research strongly supports vehicle aid technology for rollover alerts, especially for large heavy vehicles. Our system alerts drivers to switch automobiles immediately. This system lets the driver escape the car in an emergency, saving their life. Complex coding and algorithms notify drivers and prevent delays with this rollover safety warning system. The system uses contemporary microcontrollers. The warning system will flashlights and signals to show the rollover threshold after installation. Buzzer or speaker for drivers who miss flashing lights. Make sure the warning light activates the driver. IoT devices warn about car rollovers. Any company may monitor and punish hazardous drivers with this technology. The rollover index is derived utilizing velocity, mass, vehicle stature, partially loaded or unloaded conditions, and design in this sophisticated procedure.

More data will help the auto rollover warning system determine the threshold. New Arduino

IDE, ESP 32, and algorithms will improve data reading. Speed and steering angle may increase warning indicator accuracy and reaction. Real-time technology anticipates heavy truck rollovers.

1.3 Research Objective

The primary objective of this research is to develop, construct, and enhance a rollover warning system specifically for heavy vehicles. The subsequent are the precise goals:

- To develop and manufacture rollover warning systems for heavy-duty trucks.
- To integrate the IoT system with the Rollover Warning Device for the purpose of monitoring.

1.4 Scope of Research

The scope of this research are as follows:

- The modified rollover index is included within the microcontroller.
- A rollover warning device is created using MATLAB/Simulink, TruckSim, and Blynk.
- The IoT system is created as a monitoring system that receives, stores, and analyses data supplied by a microcontroller.
- Develop appropriate application notifications to transfer the gathered sensor data to a centralized monitoring system.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides a concise overview of the current research on early warning systems designed to identify and prevent vehicle rollover incidents. This document encompasses many categories of rollover cautionary systems, the stages of rollover occurrences, and the notion of rollover index. The review does not end here, and instead goes into the details of the process in which the work was put to operation, confirmed and validated through the validation and implementation principles of software and hardware-in-the-loop. Moreover, this describes the use of microcontroller platforms and Internet of Things (IoT) for improving vehicle safety applications.

2.2 Early Warning Device

Rollover Early Warning Devices (EWDs) are intended to detect the initiation of a rollover and deploy countermeasures to prevent or mitigate the event. This includes body attitude detection wire-controlled auxiliary braking (Wang et al., 2023a), the intelligent seat belt early warning system research based on big data analysis (Zhou, 2020), real-time voice warning collision avoidance detection system (Wolf, 2021).

These enable warning mechanisms that use sensors and algorithms to watch vehicle motion and dynamics, engaging in safety interventions: tightening seatbelts, selective braking, alarms, and even airbags. The EWDs are able to avoid crashes from the roll-over situations, reducing the number of fatalities of roll-overs being a critical safety feature of the vehicle, particularly in the SUVs, trucks, and vans due to the early detection of the possible roll-over.

2.2.1 Wire-Controlled Auxiliary Braking

An improved anti-rollover system for cars uses body attitude detection to trigger automatically regulated auxiliary braking. In terms of vehicle dynamics, the system uses sensors to continuously monitor the vehicle's lateral acceleration and roll angle in order to identify situations where there is a high chance of rollover. When a critical situation is detected, the system applies differential braking to the front wheels through an electro-hydraulic brake-by-wire actuation system. This produces a stabilizing moment, which opposes the rollover and assists the driver in maintaining the vehicle in control.

The key advantages of this system are its effectiveness in preventing rollovers, especially for taller vehicles, and relatively simple implementation compared to other active anti-rollover technologies. On the other hand, it adds complexity and cost and depends upon the accuracy of body-attitude detection algorithms for proper reliability. Basically, this system represents a promising approach to enhancing vehicle safety and stability in rollover-prone situations. Figure 2.1 shows the general drawing of the Brake-by-Wire system.

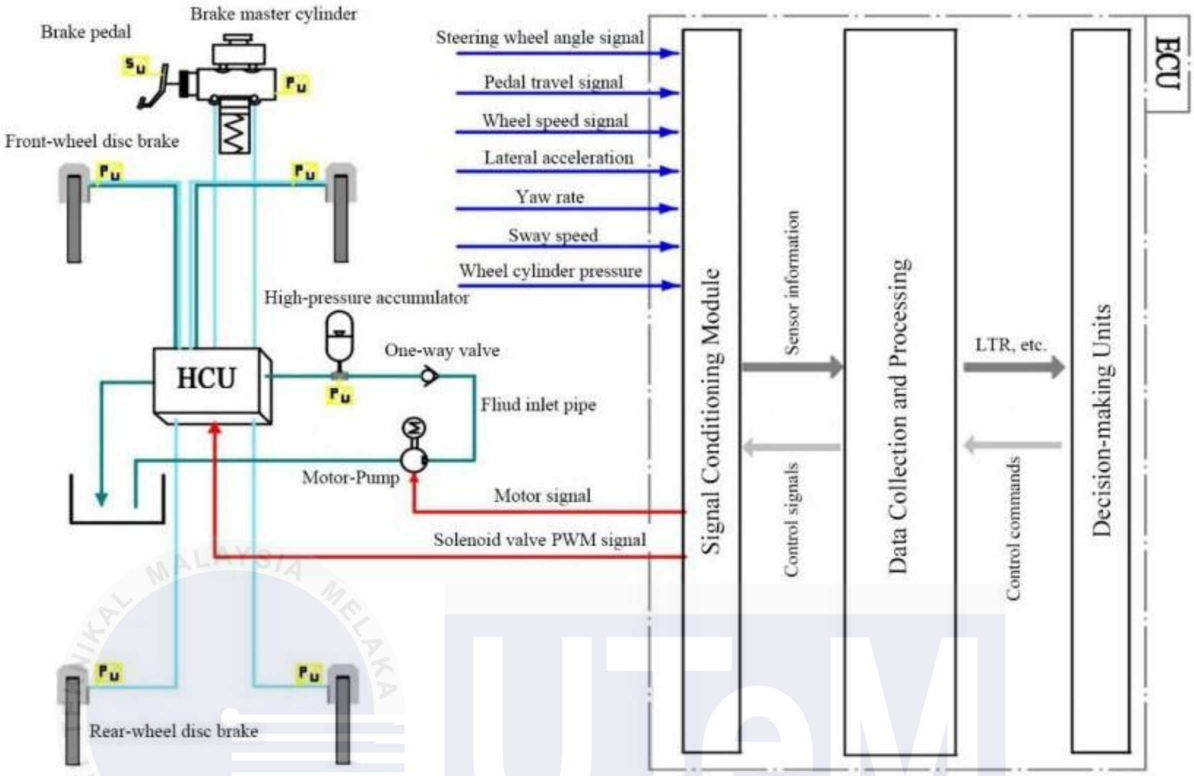

Figure 2. 1: General Drawing of The Brake-By-Wire System (Wang et al., 2023b).

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2.2.2 Intelligent Adjustment System

The early warning seatbelt intelligent adjustment system is an advanced safety system that uses big data analysis technology to enhance protection provided for seatbelts during vehicle collision. The system takes into consideration many sensors that constantly monitor the running conditions of the vehicle, such as vehicle speed, seatbelt use, and information on occupants, and then runs this real-time data using advanced big data analysis techniques.

The system would smartly adjust the pretension and locking mechanisms of the seatbelt in view of actual driving conditions and occupant characteristics to provide higher safety. This increased functionality comes at the cost of added complexity and cost, considering the fact that such a system requires special hardware, software, and algorithms to process and act on the data gathered from sensors. Generally speaking, this early warning seatbelt intelligent adjustment system would represent an innovative approach toward improving vehicle safety by optimizing the performance of the seatbelt system in real-time compared to traditional seatbelt systems.

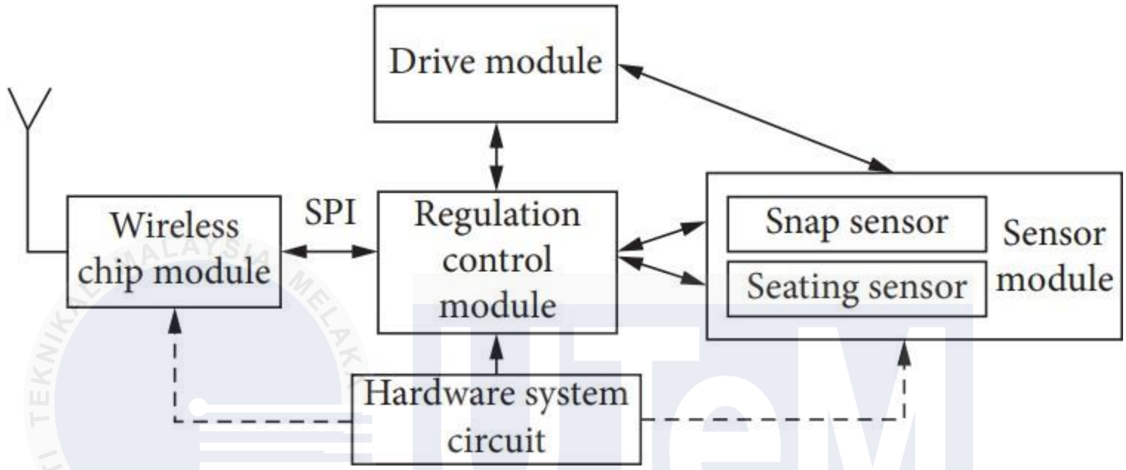

Figure 2. 2 System hardware composition structure diagram (Zhou, 2020).

2.2.3 Real-Time Voice Alarm

The Collision Prevention Warning Detection System with Real-Time Voice Alarms has been an advanced safety feature in enhancing driver awareness and collision prevention. This system is enabled with various sensors, which include cameras, radar, and lidar, to constantly monitor the surroundings of a vehicle in real-time.

Analysing the sensor data, the system can quickly detect possible collision threats, such as other vehicles, pedestrians, or obstacles, and immediately trigger a voice alarm to alert the driver. The voice alarm provides the driver with vital information relating to the direction and proximity of the threat, therefore enabling them to take urgent action to avoid collision. This immediate warning is a key advantage of the system because it gives the driver just the time and context needed to respond appropriately.

However, the effectiveness of such a system will depend on the accuracy and reliability of the sensor data and the threat detection algorithms factors which can be challenging to maintain within complicated or rapidly changing environments. Overall, the Collision Prevention Warning and Detection System with Real-Time Voice Alarms represents a significant advance in vehicle safety technology, enhancing the driver's awareness and potentially averting devastating collisions.

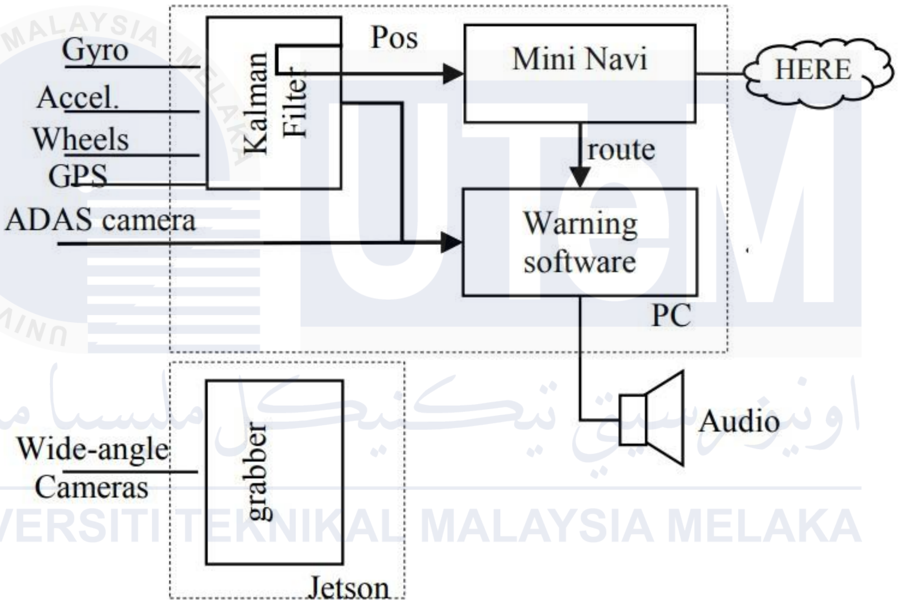

Figure 2. 3 System Overview (Wolf, 2021.)

Early warning devices (EWDs) are critical safety features for detecting and preventing rollover accidents, especially in taller vehicles like SUVs, trucks, and vans. These advanced systems use a variety of sensors to continuously monitor the vehicle's motion and dynamics, looking for indicators of an impending rollover situation. For example, wire-controlled auxiliary braking systems can detect excessive body roll or lateral acceleration and automatically apply differential braking to help stabilize the vehicle. Intelligent seatbelt adjustment systems leverage big data analysis to anticipate rollovers and optimize the seatbelt's pretension and locking mechanisms to provide better occupant protection. Real-time voice alarms can also alert the driver to imminent rollover risks, giving them the crucial seconds needed to take corrective action. By intervening early, before the rollover event has fully developed, these EWDs can play a vital role in preventing accidents and saving lives. As vehicle safety technology continues to advance, these types of early warning and intervention systems are becoming increasingly important safety features, especially for higher-risk vehicle types.

Table 2. 1 Comparison between Early Warning Device Methods

Safety technology	Method	Advantage	Disadvantage	Comment
Wire-controlled auxiliary braking	Body attitude sensing activates front-wheel automatic differential braking to prevent rollover.	Effective in preventing rollovers, especially for taller cars, and easy to install.	Complex, expensive, and requires good body attitude detection algorithms	A viable method for rollover-prone vehicle stability and safety.
intelligent adjustment system:	Adjust seatbelt pretension and locking using real-time sensor data.	Safety is improved by optimizing seatbelt performance based on driving conditions and occupant characteristics.	Special gear, software, and data processing techniques increase complexity and cost.	A unique real-time seatbelt system performance improvement method for vehicle safety.
Real-Time Voice Alarms:	Detects collision dangers using cameras, radar, and lidar and alerts the driver immediately.	Increases driver awareness and offers vital information to avoid collisions.	In complicated situations, sensor data and threat detection algorithms must be accurate and reliable to work.	A crucial automobile safety technology innovation that could prevent deadly incidents.

2.2 Types of Rollover Accident

Rollover is the type of severe traffic accident in which a vehicle may tip over to its sides or roof, resulting in high casualties and damage to property. The types of rollover accidents include eight, and they are differentiated based on various factors. Tripped rollover, which consists of 95% of the single-vehicle rollover, occurs when a vehicle gets tripped by loose gravel or soils or fixed object guard rails. Conversely, untripped rollovers are the consequence of high-speed evasive actions in extreme driving scenarios to cause rollover without external tripping factors (Zhilin Jin, 2019.). Other ways through which rollover may result include forceful steering, ramp-like obstacles, and external disturbances like side-wind or steering excitation. The assessment of rollover accidents is done through the inspection of the physical evidence on the scene, inspection of the vehicle, and assessment of the roll distance, which could be between dolly testing and real-world rollovers and also could differ depending on vehicle types. Eight types of rollover accidents are important in road safety and the development of prevention strategies.

'Trip-over' occurs when the vehicle is stopped suddenly and causes it to be overturned. **'Rollover'** occurs when the vehicle trips over its side, resulting from the factors such as excessive speed, abrupted steering or striking object that cause the vehicles tripping.

A **'Trip over'** occurred when the vehicle motion abruptly stopped, leading the vehicle to roll onto the side or roof.

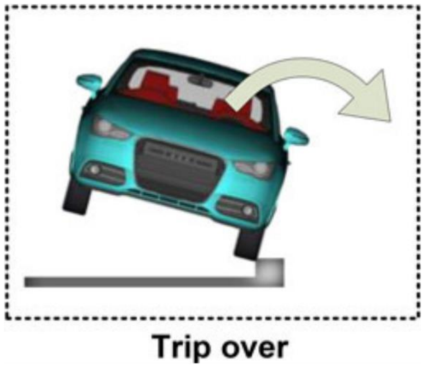

Figure 2. 4 Vehicle illustration when trip-over (Seyedi et al., 2020)

The phenomenon that is known as **'Fall Over'** occurred when the terrain of the vehicle moving slopped downward, leading the changes of center of gravity (CoG) of the vehicle beyond the wheel resulting vehicle to rollover.

Figure 2. 5 Vehicle illustration when fall-over (Seyedi et al., 2020)

A **'Flip Over'** occurred when the vehicle rotated at longitudinal axis due to the presence of obstacles such as ramp-like object on the road surface

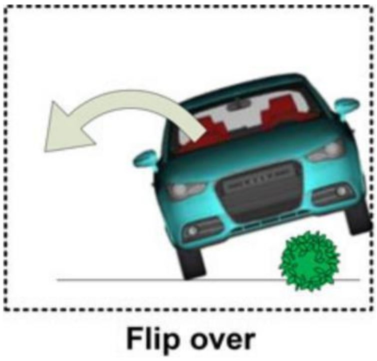

Figure 2. 6 Vehicle illustration when flip-over (Seyedi et al., 2020)

'Bounce over' happens when the vehicle bounces off the stationary object that leads to a rollover.

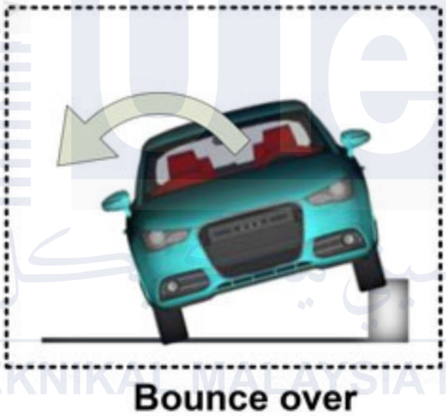

Figure 2. 7 Vehicle illustration when bounce-over (Seyedi et al., 2020)

A **'Turn over'** happens when the vehicle takes a sharp turn or rotation which makes the vehicle unstable due to the excessive centrifugal force.

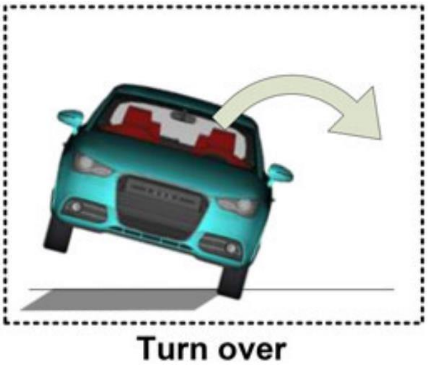

Figure 2. 8 Vehicle illustration when turn-over (Seyedi et al., 2020)

A **'Collision Rollover'** is defined as a phenomenon when the vehicle rollover due to the vehicle colliding with another vehicle.

Figure 2. 9 Vehicle illustration when collision with another vehicle has occurred (Seyedi et al., 2020)

A **'Climb Over'** occurrence arises when the vehicle rides up the guardrail or barrier that makes the vehicle evaluated.

Figure 2. 10 Vehicle illustration when climb-over (Seyedi et al., 2020)

A state of **'End-Over-End'** occurred is where the vehicle rolling to its lateral axis when crashing to an object or obstacles.

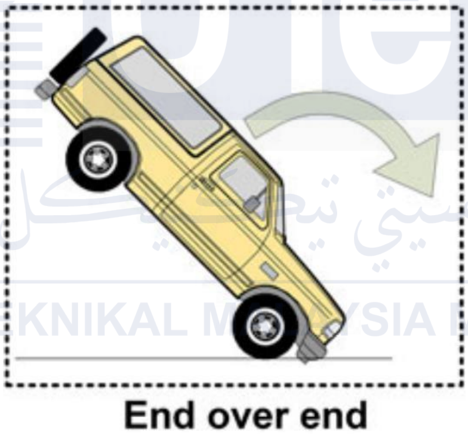

Figure 2. 11 Vehicle illustration when end-over-end (Seyedi et al., 2020)

Among the 8 rollover types, this research will focus on **'Turn Over'.**

2.2.1 Rollover Phase

Rollover crashes can span over a second and involve several strikes, making this event significantly more complex than frontal and side impacts, which typically last less than 200 milliseconds. Figure 2.12 illustrates the sequence of a single vehicle rollover crash. Traffic accidents of all types can be further segregated into three phases: pre-crash, crash, and post-crash. The pre-crash phase can be further segmented into three sub-phases. The longitudinal velocity and the vehicle's longitudinal axis are aligned during the usual driving subphase. The vehicle loses stability, and the yaw rate substantially changes in the following sub-phase. Active rollover safety systems now make an effort to stop the rollover. The car eventually reaches the point where at least two tires come off the road due to the excessive roll rate. This understanding, in detail, of the dynamics of the rollover crash is of paramount importance for developing and accessing safety systems that would reduce the potential damage from such accidents.

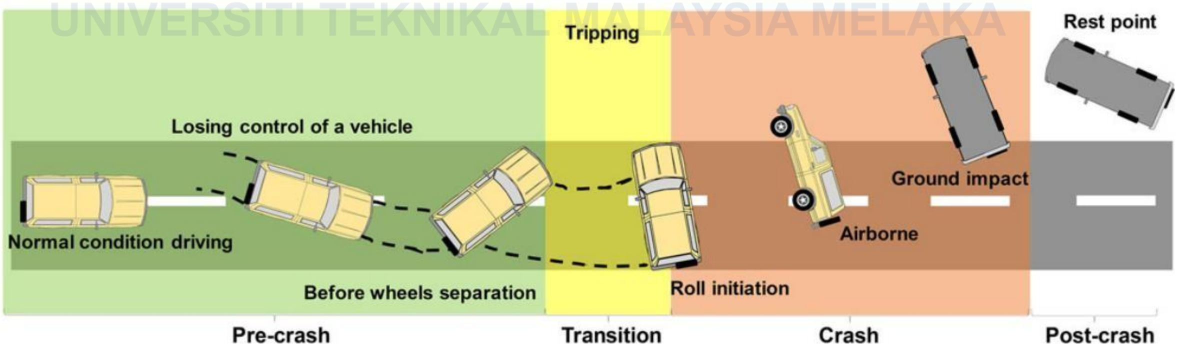

Figure 2. 12 Rollover Crash Phase (Seyedi et al., 2020)

2.3 Rollover Index

A rollover index can have the important function of detecting and predicting the possibility of an imminent rollover event in heavy-duty vehicles, which are highly probable to roll over because of their high centre of gravity and large sizes. Such an index will attempt to describe the dynamic changes in vehicle stability and rollover risk, encompassing aspects such as the lateral load transfer ratio, road bank angle, and vehicle suspension dynamics.

These indices, through various parameters and dynamic models, identify the likelihood of rollover in different driving conditions to implement rollover control systems and effective strategies to prevent accidents. Besides, they guarantee real-time rollover detection, diminish parameter uncertainties, and provide adequate response time for controllers to intervene and avoid rollover incidents (Shin et al., 2021; Zheng et al., 2023)

2.3.1 Static Roll Instability

Two types of static roll instability for vehicles are the Static Rollover Threshold (SRT) and the Static Stability Factor (SSF). The SRT is utilized to assess the maximum lateral inertial force a heavy tank-truck vehicle can withstand before initiating the rollover process, crucial for determining safe speeds during curves(Moreno et al., 2020). On the other hand, the SSF serves as a measure of rollover risk during cornering or evasive maneuvers, dependent on the vehicle's lateral and vertical positioning

A popular metric for evaluating a vehicle's static roll instability and rollover propensity is the Static Rollover Threshold (SRT), which is especially useful for big vehicles like trucks and tractor-trailers. It is the most amount of lateral acceleration that a car can handle in steady-state turning maneuvers or on banked surfaces before going into rollover mode.

The vehicle's center of gravity height and track width are directly correlated with the SRT. Better static roll stability is indicated by a higher SRT, which is a result of a wider track and a lower center of gravity. On the other hand, a lower SRT and a higher centre of gravity lead to a narrower track width, which raises the possibility of rollover at lower lateral acceleration levels.

The SRT is typically expressed in units of gravitational acceleration (g). For heavy heavy vehicles, a general guideline is to maintain an SRT above 0.35-0.40g to ensure adequate static roll stability. However, the acceptable SRT can vary based on vehicle configuration, load conditions, and operational requirements.

According to the traditional analysis, a roll moment occurs when a car turns because the lateral tire forces balance the lateral inertial force. The usual load on the inner tire (Fz2) is zero at the rollover threshold condition. Equation 2.1 can then be used to compute the SRT factor:

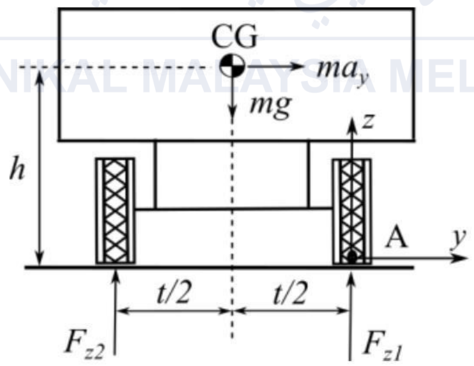

Figure 2. 13 Rigid Vehicle Body (Moreno et al., 2018)

$$SRT = \frac{a_y}{g} = \frac{t/2}{h} \tag{2.1}$$

A critical metric used to evaluate a vehicle's rollover danger, especially when evading or cornering, is the Static Stability Factor (SSF) (Guillermo Moreno Contreras et al., n.d.) .It is measured as the lateral distance between the wheels of the vehicle divided by twice the height of the centre of mass above the ground plane. The SSF can be stated mathematically as:

$$SSF = \frac{T}{2h} \tag{2.2}$$

The SSF serves as a predictor of a vehicle's rollover propensity, especially for heavy vehicles with inherently lower stability characteristics. A higher SSF value indicates a greater resistance to rollover, as it signifies a wider track width relative to the center of mass height, providing enhanced static lateral stability.

In the field of engineering education, laboratory activities centered around the SSF concept play a vital role in helping students comprehend the various vehicle design factors that influence spinouts and rollovers. These activities facilitate an understanding of how parameters such as track width and center of gravity height can significantly impact a vehicle's stability and handling characteristics.

Moreover, the concept of static lateral stability, which is closely related to the SSF, is of paramount importance in the realm of aircraft design. In this context, an equivalent parameter to the SSF is utilized to ensure proper trim conditions and stability during flight maneuvers. Maintaining an appropriate static lateral stability factor is crucial for aircraft to exhibit desirable handling qualities and prevent adverse situations such as wing drops or excessive roll during high-speed turns or turbulence encounters.

Table 2. 2 Comparison between Method of Rollover Index (Static Roll Instability)

Method of RI	Concept	Advantage	Disadvantage	Comment
Static Rollover Threshold (SRT)	The maximum lateral acceleration a vehicle can handle before rolling over.	To measure rollover risk for heavy vehicles like trucks and tractor-trailers.	Load circumstances affect vehicle centre of gravity height and track width.	A critical statistic for assessing static roll instability and rollover stability, usually exceeding 0.35-0.40g for heavy vehicles.
Static Stability Factor (SSF)	Measures wheel lateral distance divided by twice centre of mass height above ground.	Predicts rollover tendency, especially for large trucks with reduced stability.	Disregards dynamic elements like suspension and load changes that increase rollover risk.	A fundamental engineering concept to help students grasp vehicle stability and handling. Also used in aircraft design to maintain trim and stability during flight manoeuvres.

2.3.2 Dynamic Roll Instability

Under dynamic conditions, the static rollover threshold (SRT) alone is insufficient to comprehensively assess roll instability in vehicles, especially during transient maneuvers or on varying road surfaces. The greatest lateral acceleration a car may experience in steady-state circumstances before rolling over is known as the SRT. However, this number does not take into consideration the dynamic forces and moments that occur during brief manoeuvres or on uneven terrain. As a result, various methods have been proposed to evaluate dynamic roll instability more effectively.

The Load Transfer Ratio (LTR) and the Rearward Amplification Ratio (RAR) were two of the early methods. The ratio of an articulated vehicle's tractor and trailer units' peak lateral acceleration response is known as the RAR. It is used to evaluate the relative roll performance during high-speed steering manoeuvres, where the dynamic coupling between the tractor and trailer units can significantly influence the overall roll stability(Wu et al., 2023) However, the

RAR is sensitive to the nature and severity of the manoeuvre being performed.

The lateral load transfer between the right and left tyres of each axle, however, is the base of the LTR. It has been suggested as a way to evaluate large trucks' roll stability limitations (Chen et al., 2022) .Nevertheless, real-time LTR measurement can be difficult and expensive, frequently needing extra sensors and hardware, and the precise LTR value that corresponds to the relative rollover state is not well defined.

An alternative measure, the Roll Safety Factor (RSF), has been proposed as a more reliable indicator of relative rollover conditions for heavy vehicle (Vempaty et al., 2020). The RSF is related to the load transfer ratio of all axles except the first, and it reaches a value of ±1 when the vehicle approaches the relative rollover state, regardless of the vehicle configuration. While the RSF is considered the most reliable of the rollover indicators, it is commonly not easy to quantify. In contrast, variables like the axle roll angle, lateral acceleration, and steering factor are more easily measurable but depend on various vehicle design parameters, making them less reliable rollover indicators compared to the RSF.

According to Odenthal**,** one of the well-known techniques for assessing dynamic roll instability is the rollover index (RI) algorithm. This technique is based on a vehicle rollover model that takes into account the roll moments around the centre of gravity of the body and the equilibrium of vertical forces. The definition of the basic Rollover Index (RI) is:

$$RI = \frac{F_{Z,L} - F_{Z,R}}{F_{Z,L} + F_{Z,R}} \tag{2.3}$$

Where FZ, L and FZ, R are the left and right vertical tire forces, respectively. This can be further expressed as:

$$RI_{Odenthal} = \frac{2m_2}{mT}\left[(h_R + hcos\phi)\frac{a_{y,2}}{g} + hsin\phi\right]$$

(2.4)

The variables in this equation are: m_2 (body mass), m (total mass), T (wheel track), h (height from the body's centre of gravity to the roll centre), h_R (roll centre height), g (gravitational acceleration), φ (roll angle), and $a_{y,2}$ (lateral acceleration of the body).

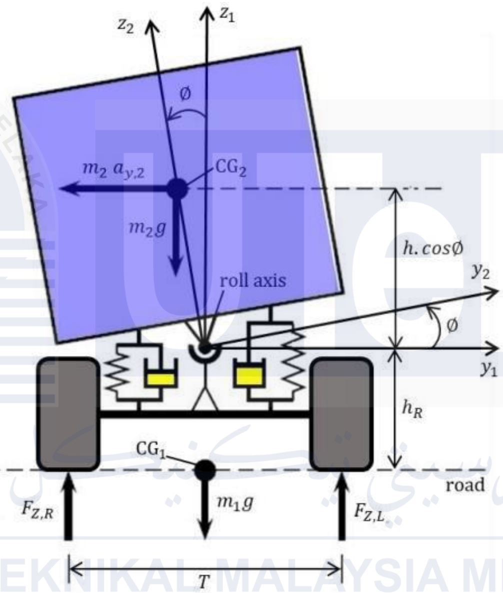

Figure 2. 14 Model rollover of the vehicle (Leng et al., 2023)

The Odenthal RI incorporates various vehicle parameters, such as mass distribution, dimensions, and lateral acceleration, to comprehensively assess dynamic roll instability. It has proven to be a prominent approach for evaluating dynamic roll instability in vehicles, particularly articulated heavy vehicles, where the dynamic coupling between units and varying load conditions can significantly impact roll stability.

Several other researchers have proposed alternative RI formulations based on different modelling approaches and assumptions. Solmaz introduced an RI algorithm using the torque balance equation and load transfer ratio, defined as:

$$RI_{Solmaz} = \frac{2(c\phi + k\phi)}{mgT}$$

(2.5)

where φ is the roll angle, m is the total mass, g is the gravitational acceleration, T is the wheel track, and c and k are the suspension damping and stiffness coefficients. This formulation incorporates the influence of suspension characteristics on roll dynamics.

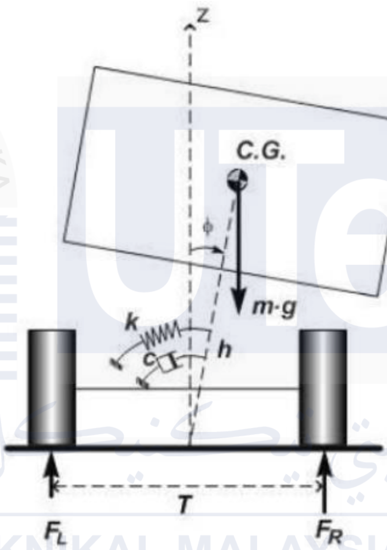

Figure 2. 15 Roll degree of freedom (Ahangarnejad et al., 2020)

Zhao derived an RI based on a 3-degree-of-freedom rollover model, given by:

$$RI_{Zhao} = 2\frac{l_{xx}\ddot{\phi} - mh_0 a_y - mghsin\phi}{mgT}$$

(2.6)

h_0 is the height of the centre of gravity, a_y is the lateral acceleration, T is the wheel track, and other parameters are as previously defined I_x is the moment of inertia about the roll axis. This RI accounts for the roll acceleration and inertial effects.

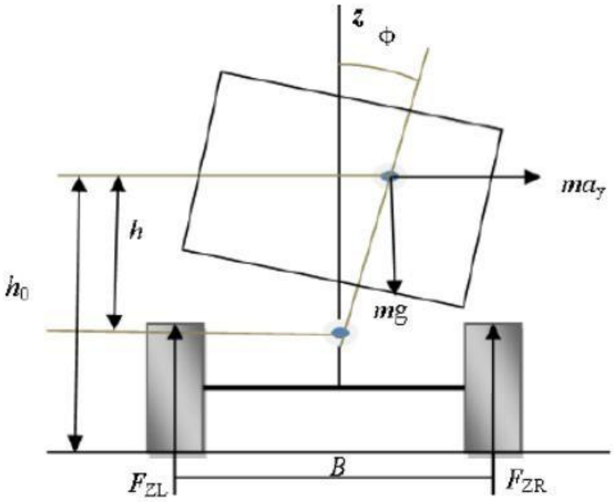

Figure 2. 16 3-DOF rollover model (Arslan & Sever, 2019)

Phanomchoeng and Rajamani proposed an RI incorporating a scaled lateral acceleration and roll angle estimator

$$RI_{Odenthal} = \frac{2m_2 a_y h_R}{mgl_w} + \frac{2m_2 h_R tan\phi}{ml_w}$$

(2.7)

where the other parameters are as previously described, l_w is the wheel track, h_R is the roll centre height, and m_s is the sprung mass. This formulation aims to estimate the RI based on more readily measurable quantities like lateral acceleration and roll angle.

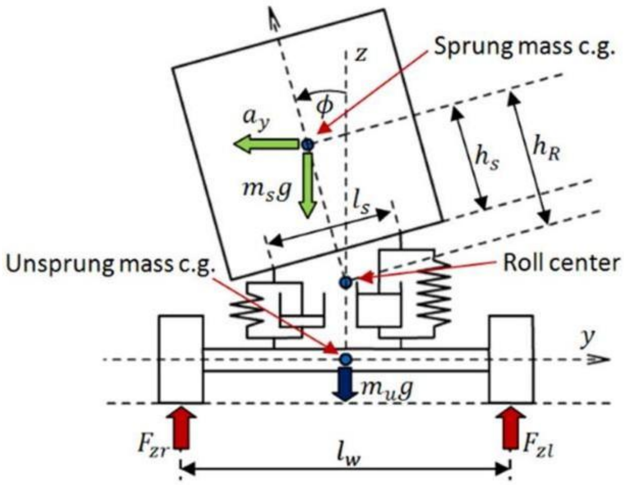

Figure 2. 17 Un-tripped rollover model (Nguyen & Tran, 2023)

While the Odenthal RI has proven particularly prominent for evaluating dynamic roll instability in articulated heavy vehicles due to its comprehensive consideration of various influential factors, the other RI methods offer alternative modelling approaches and assumptions. These contributions have expanded the understanding of dynamic roll instability in different vehicle configurations and operating conditions, providing a more holistic perspective on this critical aspect of vehicle dynamics and safety.

Table 2. 3 Comparison between Method of Rollover Index (Dynamic Roll Instability)

Dynamic roll instability	Method	Advantages	Disadvantages	Comment
Load Transfer Ratio (LTR)	Each axle's right and left tyres' lateral load transfer is measured.	Examines roll stability restrictions, notably for large trucks.	Real-time measurement is expensive and complicated, and the key LTR value is unknown.	A pioneering dynamic roll instability assessment method, although implementation issues remain.
Rearward Amplification Ratio (RAR)	Measures the articulated vehicle tractor-trailer peak lateral acceleration response ratio.	Compares high-speed steering roll performance. .	Sensitive to manoeuvre type and severity.	Provides insight into tractor-trailer dynamic coupling, which affects roll stability.
Roll Safety Factor (RSF)	RSF reaches ±1 when the vehicle approaches relative rollover condition.	RSF is reliable for predicting relative rollover conditions across different heavy vehicle configurations.	Direct measurement of RSF is complex.	an alternative measure that correlates well with RSF but is easier to measure is recommended.

Table 2. 4 Comparison between Rollover Index Approach

Rollover Index Formula	Method	Advantage	Disadvantage
Odenthal	considers roll moments around the body's centre of gravity	Suitable for assessing articulated heavy truck roll instability.	May need vehicle details.
Zhou	The 3-degree-of-freedom rollover model accounts for roll acceleration and inertial factors.	Alternative view of roll instability.	May missing vehicle roll dynamics complications.
Phonamchoeng	includes scaled lateral acceleration and roll angle estimator	Practical for limited-data real-world situations.	Model assumptions may reduce accuracy.
Solmaz	Roll instability is assessed using suspension parameters (damping, stiffness).	Roll dynamics as affected by suspension.	May overlook critical factors.

2.4 Implementation and Testing

In developing a comprehensive system that involves both software and hardware, several forms of procedures and experiments are essential. This is to prepare for the parameters and schema calculation and optimization. Simulation experiments can be done nearly upon every component under working condition (Jneid et al., 2023). A simulated experiment is one of the most crucial methods for research and development. This is due to safety issue, causing less injury, fast, repeatability and the method is relatively economical (Jneid et al., 2023). A disadvantage of the experiment is that it requires complicated schema and additional parameters to function. Additionally, learning the exact experimental procedure is difficult which is might involve a lot of drawing and design. Because of the aforementioned, a sophisticated method of concurrent simulation testing using hardware and mathematical simulation was needed.

Therefore, researchers use a sophisticated co-simulation method called Model-in-the-Loop (MIL) simulation. The car sector makes extensive use of this testing system. This is because this method has a high potential to improve the convenience and cost reduction (Rosique et al., 2019). At present MIL technique is one of the most significant validation methods. This is due to its ability to validate both hardware (real) and mathematical models (virtual). MIL comprises several techniques, the most significant of which were Hardware-in-the-Loop (HIL) and Software-in-the-Loop (SIL) simulation (Hafiz Bin Harun, 2021).

2.4.1 Software in The Loop (SIL)

The Software-in-the-Loop (SIL) simulation technique is nothing but the validation of software using simulation. Compared to traditional simulations that are slow and have low fidelity, SIL simulation provides a solution for validating models running for complex large-scale networks that we have today. Besides, it can be used to a project at both the design and the testing stages and can solve the classic simulation issues, namely model realness. SIL utilizes the fidelity of hardware with the low cost and flexibility of the simulator. Easy to use in both design and testing phases, and could lead to significant cost savings by maximizing code reuse and minimising software development coding effort.

In the case of a SIL simulation, this testing doesn't take place on hardware. However, SIL simulation can be executed within a range of different simulated input scenarios during software testing. The primary aim of the evaluation is to test the functionality of the software system in response to a variety of inputs. Thus a system model (in the form of a mathematical model, multibody dynamics model or a 3D virtual model) is then constructed to replicate the interactions, forces and status of the plant. How the real configuration of the plant model looks like the 3D virtual model

Before a system can be used for HIL simulation techniques possible faults occurs the to it are also are taken into account in the SIL Simulation approach. The actuator and actual vehicle used in the simulation analysis are related to HIL mythologies (Rosique et al., 2019). This reduces the risks of major errors, which might damage the real hardware system or hurt personnel performing the testing. SIL is also used to locate any un-desired failure mode that might occur during testing within the controller design.

2.4.2 Hardware in The Loop

A hardware-in-the-loop (HIL) simulation approach replaces the mathematical model. It uses more real hardware system testing. For example, to date, HIL belongs to the currently recognized and established methods used to develop various automotive control systems (Gao et al., 2024). Today, automotive researchers and designers take HIL testing as one of their resource tools (Gao et al., 2024). The intended input is simulated in order to evaluate the device. Additionally, disturbances that could arise in actual settings are tested for.

This will notify the researchers in the event that any errors with the suggested hardware could harm the device or endanger human life. Additionally, the method can maximise the system's robustness while drastically cutting down on the amount of time required to assess it.

Table 2. 5 Comparison between SIL and HIL

Model in Loop	Method	Advantage	Disadvantages	Comment
Software-in-the-Loop (SIL)	Simulation-based software validation combines hardware precision with low cost and flexibility.	Overcomes typical simulation restrictions for design and testing.	Needs thorough modelling and parameter estimation.	Reuses code to tackle model validity simulation difficulties and save money.
Hardware-in-the-Loop (HIL)	Hardware system testing replaces mathematical model.	Used in automotive control system development to analyse inputs and disturbances.	A specific hardware configuration is needed.	Detects hardware faults, improves system robustness, and speeds up testing.

2.5 Microcontroller

These compact, all-in-one computers are exactly microcontrollers, the brains of modern embedded systems. Microcontrollers are capable of running software to make the decisions as what to do when a sensor is tripped or a button is pressed, and this software usually is applied with the toolchain corresponding to that microcontroller, to do basic configuration and other tasks. Microcontrollers are small chips that have a wide variety of uses from simple household appliances to complex industrial automation and Internet of Things applications. Microcontrollers can be programmed with a large variety of options from 8-bit to 32-bit architectures for meeting the demands in any embedded project, thus making it an integral part of the rapid developing electronics and technological world.

2.5.1 Arduino Board

The Arduino (for interactive projects) platform has been significantly established in the development of interactive projects and prototypes. The Arduino board is the hub of the Arduino ecosystem, a development platform based on a microcontroller that provides ease of use combined with the ability to create complex projects. They have many digital and analog input/output (I/O) pins, allowing sensors, actuators and other electronic devices to be easily connected to the board. Arduino is designed [6] to be as user-friendly as possible, in order to be easily accessible to even those with no coding background. It uses a simpler version of C/C++ which makes it easier to pick up the basics of coding than using C/C++ directly. Ubiquuity and Functionality - all the boards have USB, use the most popular communication protocols and support for many existing shields that gives more emulate the ability to expand its functionality for sure. The Arduino platforms are also open source, in both hardware and software, leading to a large and vibrant community of users, developers and contributors, offering a plethora of resources and help for everything from simple blinky lights to complex IoT devices and more robotic systems.

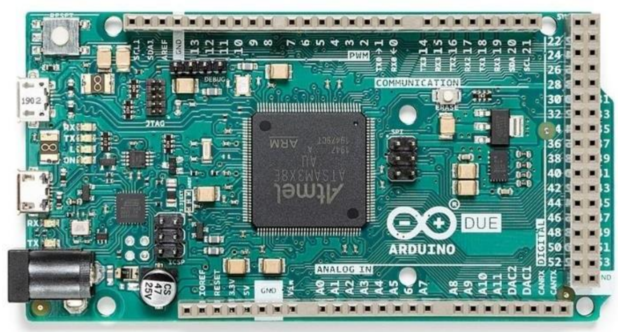

Figure 2. 18 Example of Arduino board (Arduino DUE)

2.5.2 Espressif System (ESP)

The microcontrollers from Espressif Systems (ESP) have had a profound effect on the world of embedded systems and IoT. With integrated Wi-Fi and Bluetooth, these are low cost low power SoCs, perfect for IoT that combines PC and wireless. Being supported with a variety of boards while having an ESP is very cheap and accessible, this platform, where hobbyists, students, small volume projects, not working large sizes, has found a place. ESP microcontrollers are driven by the Xtensa 32-bit LX6 microprocessor making powerful processing resources available to the hardware hackers. The ESP family, which has the ESP8266, ESP32, and ESP32-C3 falls under different categories and can be used in the smart home, industrial automation, etc. The widespread adoption of the ESP platform is also helped in part by its open-source nature and extensive community support.

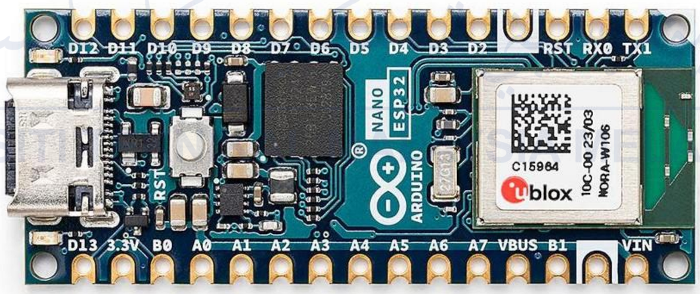

Figure 2. 19 Example of ESP (ESP 32)

2.5.3 Raspberry Pi

A Raspberry Pi is a groundbreaking single-board computer that makes it possible to own a complete computer without having too much cash. Small yet powerful, it boasts ARM-based processors, sufficient I/Os, and has the common OS offering a simple extension of a wide range of compatible operating systems. Due to its affordability, with its microATX-compatible several-purpose and multi-backboard to $5 35 cost, Raspberry Pi has turned into the base of a market that doesn't require clients to be a specialist in PC or hardware. The Raspberry Pi has been a paradigm-shifting and revolutionary device, it has enabled for a plethora uses like education, DIY projects, industrial automation, scientific computing and many more all over the world.

Figure 2. 20 Example of Raspberry Pi (Raspberry Pi 5 Model B)

Table 2. 6 Comparison between Microcontroller

Types of Microcontroller	advantage	disadvantage	comment
Arduino board	Affordable, accessible, large community, perfect for beginners	May not handle complex tasks due to processing power.	Suitable for low-power prototyping and small designs.
ESP	IoT and wireless applications benefit from integrated Wi-Fi and Bluetooth.	Insufficient on-board peripherals may require additional parts.	Excellent cost-power-connectivity balance for IoT and embedded applications.
Raspberry pi	Powerful, small, inexpensive computing for many applications.	High power consumption, not good for battery-powered projects.	Flexible single-board computer excels in high-processing applications.

2.6 Internet of Things (IoT)

Internet of things (IoT) is a brand new conception wherein items have the capability to speak with each other autonomously over the internet, effectively permitting gadgets to have the functionalities of an application (John et al., 2023). From household appliances to industrial equipment, IoT includes a vast array of interconnected things that can be optimized for remote operation and automation using embedded software applications. This network of sensors, processors and software make huge data collection and analysing possible in turn leading to the automation of everyday tasks across various sectors like smart cities and autonomous vehicles. The end goal of this vision of the world belongs to the already famous acronym in technology: internet of things (IoT) - to create smarter and more efficient systems which include technologies like machine learning (ML) and artificial intelligence (AI) that enable things(objects) to respond immediately to data collected and to human interaction.

2.6.1 Thingspeak

ThingSpeak IoT Analytics Platform ThingSpeak is an open-source platform for over the Internet of Things (IoT) analytics, enables the live data collection, storage, analysis and visualization of its data, and it's from IoT devices and sensors (ThingSpeak - MATLAB & Simulink, 2023.). It includes a cloud environment where users can upload the sensor data and perform tasks for processing, analysis, and visualization. One of the best features of ThingSpeak is that it supports a wide variety of IoT hardware platforms, such as Arduino and Raspberry Pi and it also supports various communication protocols such as HTTP, MQTT, and WebSocket (Anand et al., 2022). Its analytical features, such as MATLAB code execution and visualization tools, allow it to be used for almost any kind of advanced data processing and decision-making functionality IoT projects require.

2.6.2 Blynk App

Blynk IoT Platform Blynk is a popular open-source Internet of Things (IoT) platform that allows users to easily build interfaces for controlling and monitoring IoT devices using their smartphones (Blynk, 2023). The platform is comprised of three main components: a Blynk server, a mobile application that is installed on a smartphone, and libraries for connection to various hardware. Blynk allows users to create digital dashboards with a variety of widgets using a drag-and-drop tool and take control of the app’s operation. Blynk is user-oriented and has become one of the most popular tools for hobbyists, makers, and developers. Since it is compatible with many microcontrollers and sensors, Blynk is used in various development projects. It is an ideal choice for RPM protocols that require regular monitoring and management by their users.

2.7 Summary

The literature review covers early warning systems for vehicle rollovers. It discusses early warning systems (EWDs) that employ sensors and algorithms to monitor vehicle motion and dynamics and deploy seatbelts, brakes, alarms, and airbags to prevent rollovers. The evaluation also covers tripped, untripped, and other rollover methods. Rollover indexes are used to identify and predict rollovers, especially in heavy trucks. Several rollover index formulations have pros and cons. The literature discusses the installation and testing methods used to construct rollover prevention systems, including HIL and SIL simulation.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter focuses on a planned methodology for methodically accomplishing this project. The project development is segmented into three distinct components which is hardware in the loop, software in the loop, and the project's component. The technique is crucial for ensuring the project's success and attaining the targeted output. This chapter provides an overview and explanation of the project's development process, utilising flowcharts and block diagrams to enhance comprehension of the process.

3.2 Methodology

To accomplish the design and production of a heavy truck rollover warning device, various ways will be employed. These methods will be based on IoT technology and vehicle monitoring. The system is built sequentially, beginning with the identification of the problem statement, objectives, and project scope. This is followed by conducting a literature search and then proceeding with the construction of software and hardware. The development process concludes with the collecting of data. This section provides a comprehensive explanation of all the methodologies, equipment, and software utilised in this project. Figure 3.1 depicts the schematic representation of the entire process of project development. To accomplish the activities, the methodology is express the ghant chart in Table 3.1

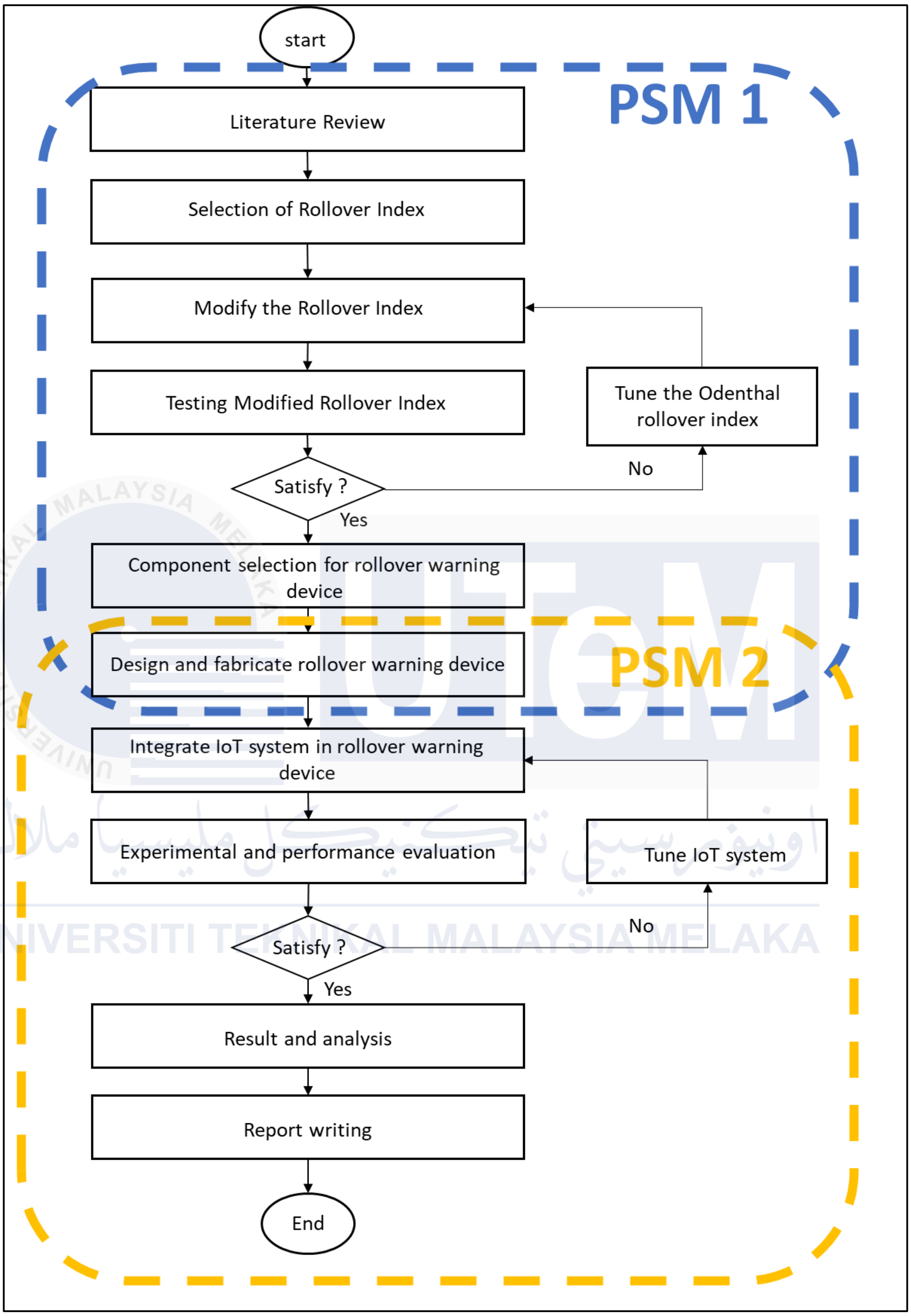

Figure 3. 1 The flowchart of overall project

Table 3. 1 Ghant chart

Project Activity	WEEK 1	WEEK 2	WEEK 3	WEEK 4	WEEK 5	WEEK 6	WEEK 7	WEEK 8	WEEK 9	WEEK 10	WEEK 11	WEEK 12	WEEK 13	WEEK 14	MONTH 1	MONTH 2	MONTH 3
PSM 1																	
Literature Review																	
Selection of rollover index using Software-in-THE-Loop																	
Modify the rollover index																	
Testing modified RI in Software-in-the-Loop																	
Design rollover warning device																	
Component selection for rollover warning device																	
Fabrication of rollover warning device																	
Report writing for PSM 1																	
PSM 2																	
Develop IoT system																	
Integrate IoT system in rollover warning device																	
Experimental and performance evaluation using Hardware-in-the-Loop																	
Report writing for PSM 2																	

3.3 Heavy Truck Model

The heavy truck model used in this study represents a common tractor-semi trailer configuration from Pacejka tractor-semitrailer model, which is widely employed for long-haul goods transportation. This combination of a tractor unit and semi-trailer presents unique challenges in terms of vehicle dynamics and stability that must be accurately modeled and simulated to develop effective rollover detection and warning systems for these large, complex vehicles.

The tractor model in Figure 3.2 represents the lead vehicle that would tow the semi-trailer. The tractor's sprung mass, axles, tires, and hitch connection are depicted, allowing the researchers to calculate the vertical forces on the tractor's tires as well as the hitch forces acting between the tractor and semi-trailer. Figure 3.3 represent the semitrailer model also from Pacejka.

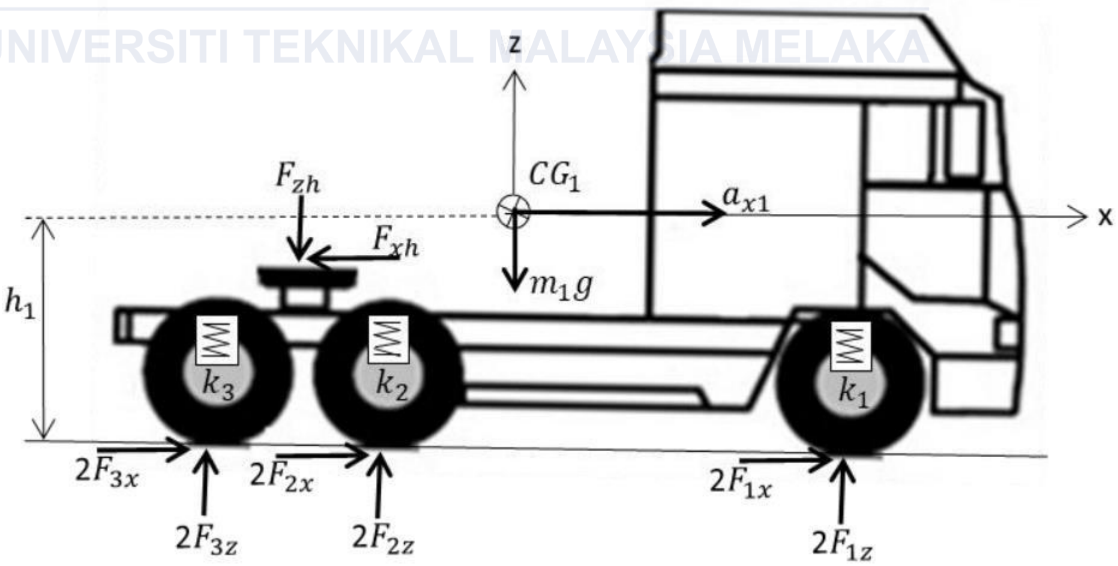

Figure 3. 2 Tractor model

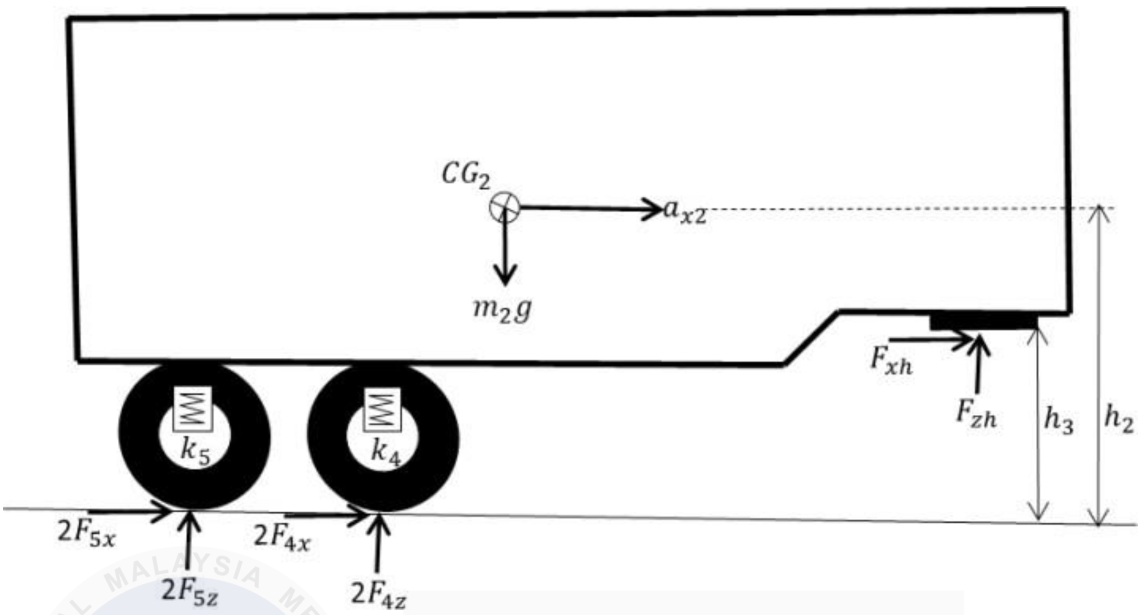

Figure 3. 3 Semitrailer model

3.4 Software in The Loop

Software-in-the-Loop (SIL) technique is use in this study due to an essential method for creating resilient embedded systems. SIL also allows for thorough software validation, seamless integration testing, and ongoing quality assurance by including real parameters and emulating hardware. This leads to the development of high-performance applications. SIL enables developers to assess system performance, optimise code, and assure seamless integration, even in contexts with limited resources. Figure 3.4 depicts the algorithm implemented in the SIL.

Figure 3. 4 Input from Algorithms in Software in the Loop

3.4.1 TruckSim

The TruckSim driving simulator for the first software that this study use, plays a vital role in this research endeavour. This tool is utilised for simulating vehicle dynamics, generating input data, and assessing the performance of the rollover prediction algorithm. It allows for testing and refining the algorithm in a virtual environment before implementing it in hardware. In this study, the TruckSim simulator supplies input data, such as truck speed and steering angle to the rollover index calculation method in MATLAB/Simulink. The programme's output is then utilised to analyse rollover predictions and evaluate the performance of the algorithms. Figure 3.5 show the Trucksim model for heavy truck in this study.

Figure 3. 5 Trucksim model example

3.4.1.1 Setup the Heavy Truck Model

The researchers first set up the heavy truck model in the TruckSim driving simulator, defining the key parameters such as the mass, tire stiffness, moments of inertia and others parameter as shown in Table 3.2, to accurately represent the characteristics of the heavy vehicle being studied.

Table 3. 2 Simulation parameters of truck model

Tractor Parameter		Semitrailer Parameter	
m_{1T}	= 2818 kg	m_{1S}	= 1362 kg
m_{2T}	= 18769 kg	m_{2S}	= 14365 kg
I_{xxT}	= 6967.79 kgm^2	I_{xxT}	= 424700.9 kgm^2
h_T	= 0.656 m	h_S	= 1.3284 m
h_{RT}	= 0.474 m	h_{RS}	= 0.7366
T_T	= 2.032 m	T_S	= 1.651 m
a_T	= 1.385 m	a_S	= 5.5 m
b_T	= 1.016 m	b_S	= 1.016 m
c_T	= 17500 Ns/m	c_T	= 17500 Ns/m
k_T	= 1240103 N/m	k_T	= 1240103 N/m

3.4.1.2 Step Steer Cornering Test

This study involves doing a step steer cornering simulation using the TruckSim programme at speeds 80 km/h and 100 km/h with 60-degree steering input. The simulation model included a tractor with three axles and a semi-trailer with two axles, coupled together and carrying a shipping container. Figure 3.6 depicts the large truck used in TruckSim to illustrate the step steer cornering test.

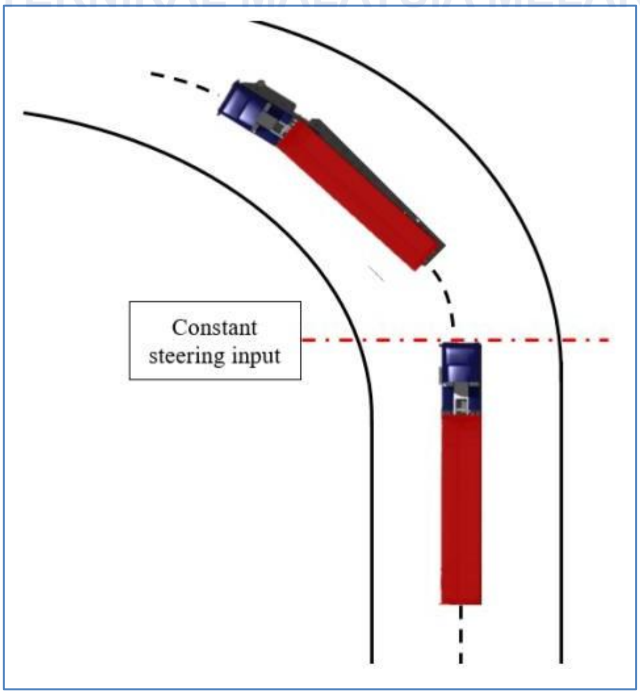

Figure 3. 6 Step steer cornering test track in Trucksim

3.4.2 MATLAB

MATLAB is utilised in this project to facilitate the creation, enhancement, and simulation of the rollover warning system for large vehicles. The study employs MATLAB/Simulink to execute and evaluate the rollover index algorithm, fine-tune its parameters, and simulate different driving scenarios to verify the enhanced Odenthal rollover index methodology. The combination of MATLAB and Simulink offers a strong framework for improving the safety of heavy vehicles by accurately forecasting and alerting against possible rollover incidents.

Figure 3. 7 MATLAB version R2024a

3.4.2.1 Rollover Index Selection

This section examines the reaction of the heavy truck rollover index. This study introduces two criteria for measuring rollover index response, namely Time-To-Warn (TTW) and Time-To-Respond (TTR). TTW refers to the time generated by RI in order to promptly alert the driver about any instability in the vehicle's motion. TTR refers to the duration given to drivers to rectify the current manoeuvring situation, such as decreasing the speed of the vehicle or making adjustments to the steering input, following the TTW reaction. This study establishes that TTW (Time-to-Warn) is designed to provide the shortest response time to drivers, while TTR (Time-to-Response) allows drivers sufficient time to correct their manoeuvres. Figure 3.8 displays the time reactions of heavy trucks, including illustrations of TTW and TTR.

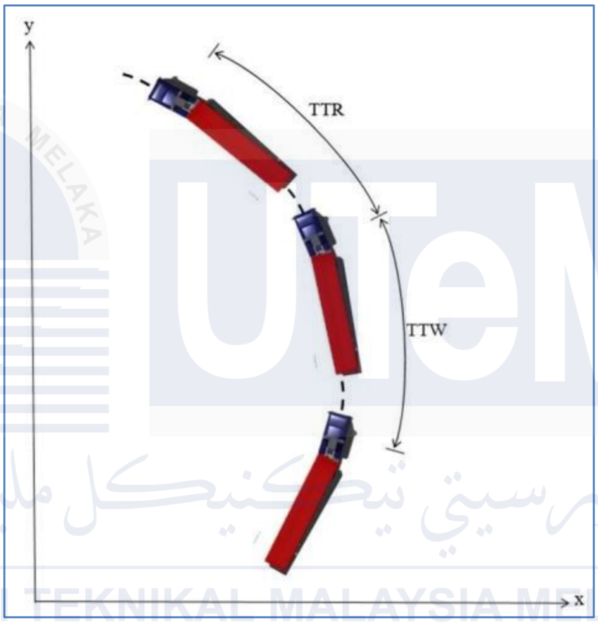

Figure 3. 8 Heavy truck time responses

The rollover index selection involves obtaining the rollover index response by conducting a simulation in MATLAB/Simulink and TruckSim software. The simulation includes step steer cornering at a speed of 100 km/h. This speed is chosen because it will result in the tyre losing contact with the ground and the RI value surpassing 1. An early warning signal is assigned a roll safety factor (RSF) of 75%. Figure 3.9 and Table 3.3 display the reactions of the heavy truck rollover index fot tractor. After a delay of 1 second, when the steering input is supplied to the tractor, the RI algorithm developed by Solmaz reaches the RSF line in 1.61 seconds. Nevertheless, it is evident that there is an interruption in the anticipated RI reaction by Solmaz. This is a result of the influence of the stiffness and damping coefficient of the suspension spring on the reflexes of the vehicle. Meanwhile, the RI algorithm developed by Zhao and Phanomchoeng demonstrates a progressive growth and surpasses the RSF line at 1.59 and 1.58 seconds, respectively. At the same time, the RI method suggested by Odenthal appears to be disrupted within a duration of 1.11 seconds. The abrupt change in steering input from 0 to 60 degrees within 1 second has impacted the lateral acceleration of the vehicle, the angle at which the vehicle rolls, and the height of the vehicle's centre of gravity above the ground. These effects persisted until the vehicle stabilised after 1.1 seconds. The Odenthal rollover index algorithm calculates the impact of the multiplication of the body's lateral acceleration, body roll angle, and height of the body's centre of gravity to the ground. However, based on Table 3.3, it is clear that the RI suggested by Odenthal intersects with the RSF line in 1.51 seconds.

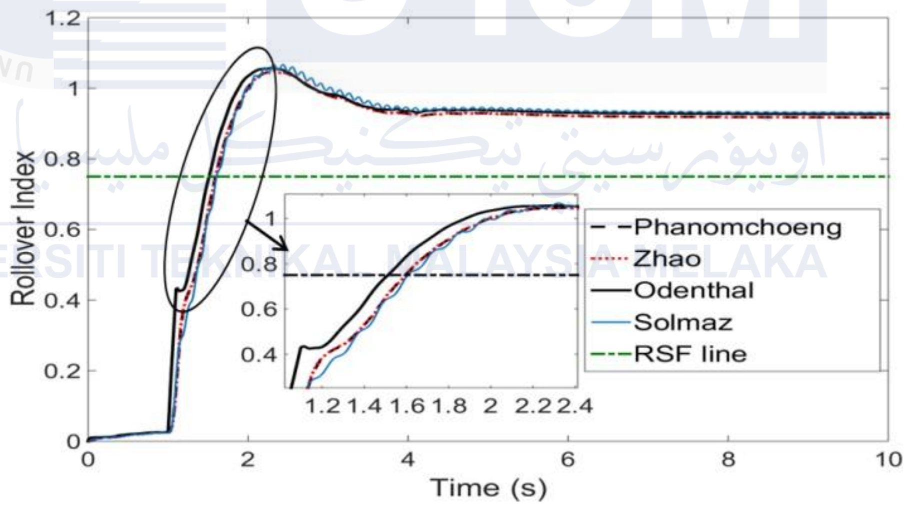

Figure 3. 9 Heavy truck (Tractor) rollover index responses

Table 3. 3 Heavy truck (Tractor) rollover index responses

Author	Truck RI Time Respones
Odenthal	1.51
Solmaz	1.61
Phanomchoeng	1.58
Zhao	1.59

The semi-trailer's rollover behavior also was analyzed using different rollover index (RI) algorithms. Figure 3.10 and Table 3.4 showed the RI responses, with the Odenthal RI algorithm providing the fastest rollover warning compared to the other methods evaluated. The semi-trailer's RI tended to increase more gradually than the tractor, indicating the semi-trailer's motion was closely tied to the tractor's movements.

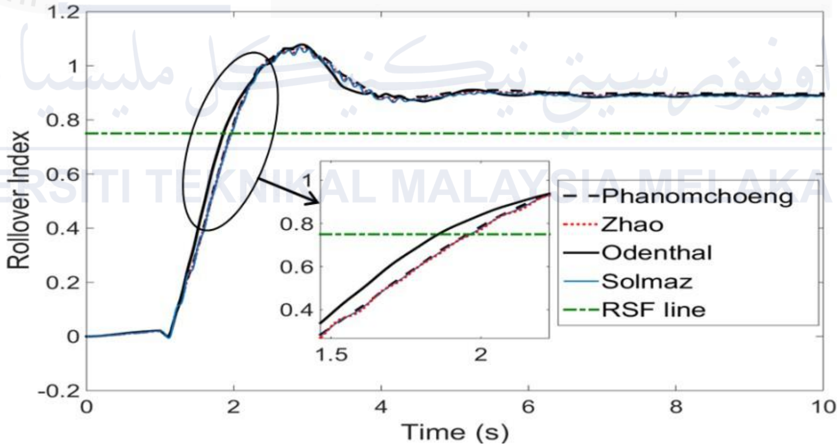

Figure 3. 10 Heavy truck (Semi trailer) rollover index responses

Table 3. 4 Heavy truck (Semi trailer) rollover index responses

Author	Truck RI Time Respones
Odenthal	1.86
Solmaz	1.97
Phanomchoeng	1.95
Zhao	1.96

The simulation results showed the tractor consistently provided faster rollover warning indications compared to the semi-trailer, suggesting the tractor is the better location for an early warning system. The RI algorithm parameters also significantly impacted performance, with approaches incorporating lateral acceleration offering earlier warnings.

As vehicle speed increased from 80-100 km/h, both the tractor and semi-trailer exhibited growing lateral accelerations and rollover indices. The semi-trailer consistently experienced higher lateral accelerations than the tractor, and at 100 km/h the rollover index reached a critical threshold of 1.0, indicating instability. Table 3.5 further detailed the tractor and semi-trailer responses at speeds from 80-100 km/h.

Table 3. 5 Heavy truck response at speed of 80 km/h to 100 km/h

Velocity (Km/h)	Lateral Acceleration (g) For Tractor	Lateral Acceleration (g) For Semitrailer	Roll angle (degree)	Rollover Index
80	0.351	0.392	0.90	0.880
85	0.376	0.401	1.10	0.910
90	0.386	0.416	1.20	0.955
95	0.411	0.434	1.28	1
100	0.433	0.462	1.30	1

The analysis shown in Table 3.5 is revealed the tractor experienced lower lateral acceleration than the semi-trailer as speeds approached the point of tire lift-off. However, at lower speeds of 80-90 km/h, the tractor's lateral acceleration was still smaller, even before the rollover index exceeded 1.0. This suggests the tractor provides earlier warning signals of an impending rollover. The lower lateral acceleration thresholds at the tractor make it the better location to install rollover sensing systems. However, the best rollover index algorithm which is Odenthal only afforded 0.51 seconds of Time to Warn (TTW), less than the recommended 0.70-0.75 seconds for effective Time to Response (TTR). This indicates a need to develop an improved algorithm that can offer earlier warnings. Due to the reason, the Odenthal rollover index must be modified to give faster TTW.

3.4.3 Modified Odenthal Rollover Index

The rollover index RI, according to Odenthal's formulation, is given by:

$$RI = RI_{Odenthal} = \frac{2m_2}{mT}\left[(h_R + hcos\phi)\frac{a_{y,2}}{g} + hsin\phi\right] \tag{3.2}$$

Equation (3.2) is utilized to evaluate the rollover index's capabilities based on Odenthal's fastest warning response time. Furthermore, according to Odenthal et al. (2015):

$$h_R + h\, cos\boldsymbol{\phi} = h_{cg2} \tag{3.3}$$

As a result, equation (3.2) can be modified as follows:

$$RI_{Odenthal} = \frac{2m_2(h_{cg2})a_{y,2}}{mgT} + \frac{2m_2 hsin\phi}{mT} \tag{3.4}$$

The equations involve several variables: m_2 denotes the sprung mass, m represents the total mass, T stands for the track width, h represents the height of the sprung mass centre of gravity, ϕ denotes the roll angle, $a_{y,2}$ represents the body lateral acceleration, g represents the acceleration due to gravity, and h_{cg2} represents the height of the sprung mass centre of gravity with respect to the roll axis.

The formulation proposed by Odenthal, the study tries to calculate a rollover index that is dependable by taking into account the vehicle's dynamics, which include lateral acceleration, roll angle, and the distribution of vertical forces on the tires.

From Equation 3.4, it is evident that the RI performance is influenced by two parameters: the body's lateral acceleration, $a_{y,2}$ and the body's roll angle, φ. The sensitivity and performance of the current Odenthal rollover index have been enhanced by modifying it with the intentional use of parameters Ka and Kr.

Thus, the modified Odenthal rollover index algorithm is defined as

$$RI_{Modified\ Odenthal} = K_a \left[\frac{2m_2 h_{cg2}}{maT}\right] a_{y,2} + K_r \left[\frac{2m_2 h}{mT}\right] sin\phi \tag{3.5}$$

Equation 3.5 introduces the variable Ka, which serves as a gain factor to regulate the impact of applied forces on the sensitivity of the vehicle body's lateral acceleration, denoted as $a_{y,2}$. However, Kr is the coefficient that regulates the influence of the body roll angle ϕ on the reaction of the system. The gain parameters, Ka and Kr, are calculated using the sensitivity analysis technique proposed by (Hafizah Amer et al, 2021) to improve the effectiveness and responsiveness of the modified Odenthal rollover index algorithm. The Ka and Kr values were determined using the Particle Swan Optimisation (PSO) approach, which identifies the optimal balance value for heavy vehicles.

3.4.4 Optimizing Rollover Algorithm Using Sensitivity Analysis of Ka and Kr

The performance of the Modified Odenthal RI is assessed by establishing the optimal values of Ka and Kr using Particle Swan Optimization (PSO). The sensitivity analysis approach involves adjusting the values of Ka and Kr in response to the RI value exceeding 1, and then returning them to their usual condition. Figure 3.10 displays the impact of Ka on the heavy vehicle rollover index. This graph depicts the correlation between the heavy truck rollover index and the TTW. Figure 3.11 illustrates that the value of Ka ranges from 0.97 to 1.10. The selection of these numbers is based on the occurrence of tractor tyre lift-off and its subsequent restoration to the normal condition. At a Ka value of 0.97, the left tyre of the tractor's third axle begins to lift off the ground at 2.15 seconds and recovers to its usual condition after 2.42 seconds. The current maximum RI is 1.0046. At a Ka value of 0.98, the left tyre of the third axle of the tractor begins to lift-off at 2.05 seconds. It recovers to its normal condition after 2.51 seconds, with a maximum RI of 1.0150. Moreover, when the coefficient of acceleration (Ka) reaches its maximum value of 1.10, the left tyre of the third axle of the tractor begins to lift-off at 1.74 seconds and returns to its normal condition after 8.91 seconds. The highest refractive index achieved with this Ka value is 1.1392. Therefore, it can be accurately stated that as the Ka value increases, the duration for the left tyre of the tractor's third axle to lift-off becomes shorter, while the time it takes to return to its normal condition becomes longer. Simultaneously, the maximum refractive index value is also rising.

Nevertheless, the RI value continues to surpass 1 when the Ka value hits 1.11, as indicated by the dotted line in Figure 3.11. It suggests that one side of the tractor tyre is lifted off the ground, increasing the risk of the tractor rolling over. Additionally, the data from the rollover index indicates that the time it takes for the tractor to settle, when the Ka value is between 0.97 and 1.10, remains constant at 4.30 seconds. Furthermore, it signifies that the tractor remains steady after 4.30 seconds, provided that the Ka value falls within the range of 0.97 to 1.10. Figure 3.12 illustrates the impact of Ka on TTW. The relationship between the increase in Ka value and the decrease in warning time is evident. It demonstrates that Ka has a substantial impact on the lateral acceleration of the tractor. This phenomenon occurs because when performing this manoeuvre, the act of turning the steering wheel results in a significant increase in lateral acceleration on the surface with high friction. Empirical evidence demonstrates that the Ka value has the ability to exert an influence on the TTW.

Moreover, as depicted in Figure 3.12, the test results indicate that the optimal Ka value is 1.10. If the Ka value exceeds 1.10, it causes one side of the tractor tyre to lift off the ground, leading to a tendency for the tractor to roll over. This phenomenon will ultimately result in the driver's inability to correct the manoeuvres, leading to an increased likelihood of the tractor rolling over.

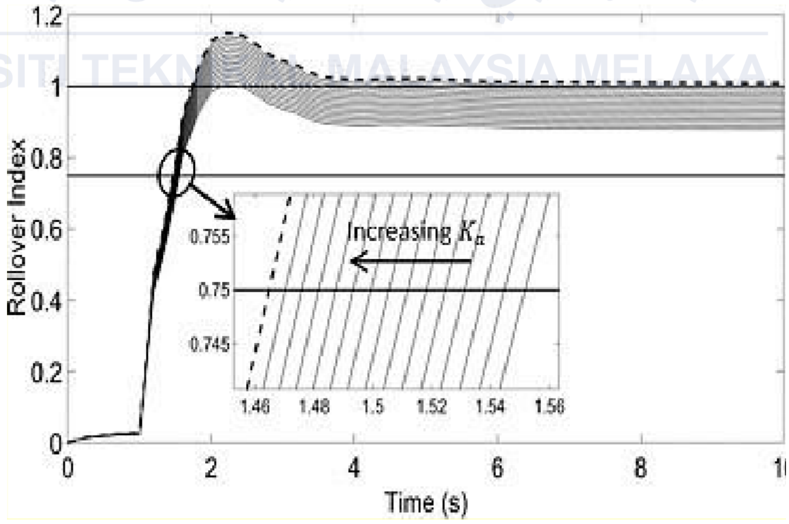

Figure 3. 11 Heavy vehicle Rollover Affected by Ka

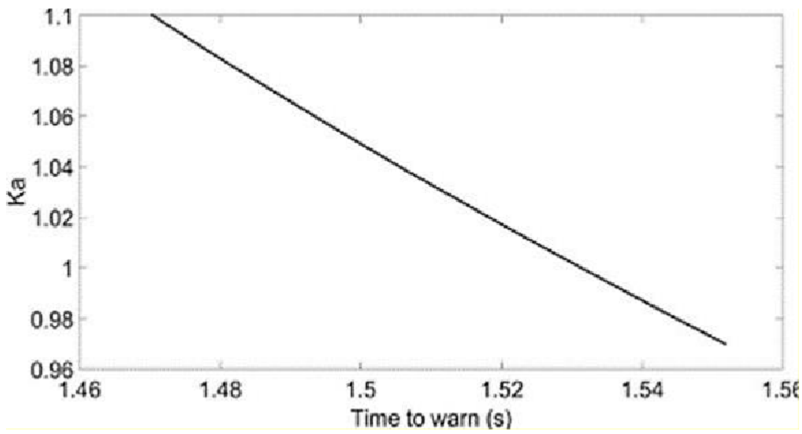

Figure 3. 12 Ka influence on TTW

The sensitivity analysis method is utilised to ascertain the optimal value for Kr. The optimal value of Kr is calculated by employing a similar methodology as Ka, wherein it is contingent upon the RI value surpassing 1 and thereafter returning to its normal state. These determinations are derived from the heavy vehicle step steering manoeuvres conducted at a speed of 100 km/h in TruckSim. Figure 3.13 presents the definition of the tractor rollover index influenced by Kr. The Kr value is initially set at 4.5 and then increases to 11.0 when the tractor tyre begins to lift-off and subsequently returns to its usual condition. At a Kr value of 4.5, the left tyre of the tractor's third axle begins to lift-off at 2.04 seconds and recovers to its usual condition in 2.40 seconds. The current maximum refractive index (RI) is 1.0064. At a Kr value of 0.5, the left tyre of the tractor's third axle begins to lift-off at 1.97 seconds and recovers to its normal condition in 2.48 seconds, reaching a maximum RI of 1.0170.

Moreover, when Kr reaches its maximum value of 11.0, it becomes evident that the left tyre of the tractor's third axle begins to lift-off at 1.57 seconds and returns to its normal state after 8.81 seconds. The highest possible refractive index (RI) that may be obtained from this Kr value is 1.1546. Therefore, as the Kr value grows, the left tyre of the tractor's third axle lifts off more quickly and takes longer to recover to its normal condition. Simultaneously, the maximum refractive index value is also rising.

Nevertheless, the RI value continues to surpass 1 when the Kr value approaches 11.5, as depicted by the dotted line in Figure 3.13. It suggests that one side of the tractor tyre is lifted off the ground, making the tractor more susceptible to rolling over. From a different perspective, the data from the rollover index indicates that the time it takes for the tractor to settle is consistently 4.30 seconds for Kr values ranging from 4.5 to 11.0. Furthermore, it signifies that the tractor remains steady after 4.30 seconds, provided that the Kr value falls between the range of 4.5 to 11.0. Figure 3.14 illustrates the impact of Kr on TTW. It is evident that the TTW demonstrates more speed as the Kr value increases. Moreover, the TTW significantly reduces to 1.19 seconds, as illustrated in Figure 3.14. Hence, the optimal Kr value derived from this test is 11.0. Evidence demonstrates that Kr has a substantial impact on the phenomenon of tractor roll effect. However, it can be noticed from Equation 3.6 and 3.7 that the body's lateral acceleration (ay,2) and body roll angle (ϕ) are the ultimate outcomes of the roll motion, which pose a risk to the driver's control over the vehicle. As a result, the driver has less time to rectify the manoeuvres. Hence, this study takes into account the steering and vehicle speed inputs to enhance the TTW.

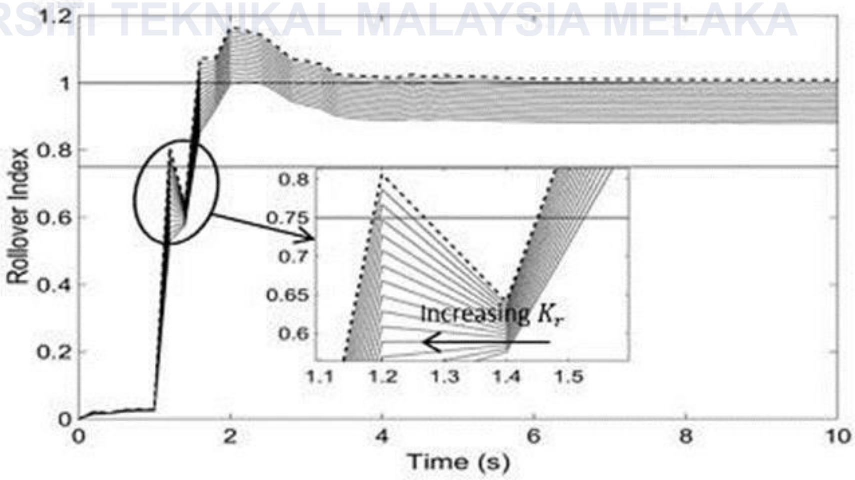

Figure 3. 13 Heavy vehicle Rollover Affected by Kr

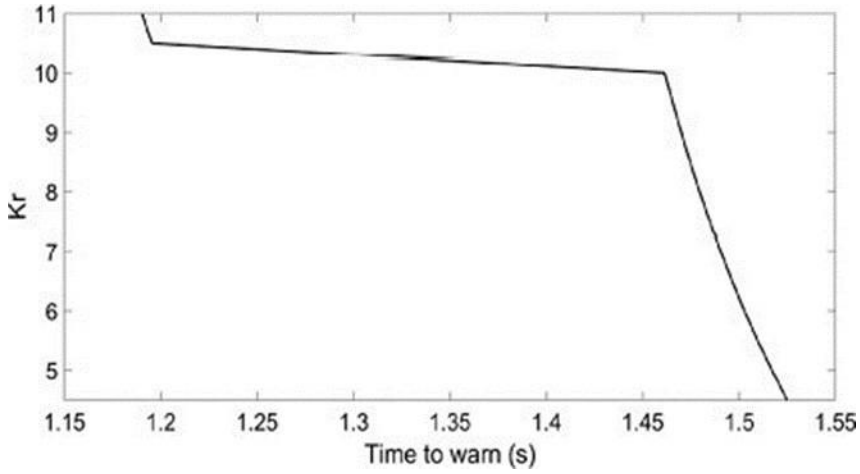

Figure 3. 14 Kr influence to TTW

The study's findings demonstrate the utilisation of the Modified Odenthal Rollover Index (MORI) algorithm, which combines steering input with vehicle velocity inputs to improve the anticipation and avoidance of rollovers. Equations 3.6 and 3.7 will be utilised to apply the MORI algorithm. This implementation will incorporate the steering wheel input and vehicle velocity, with the assistance of the Particle Swarm Optimisation (PSO) technique.

$$a_y = \left[\frac{\frac{v^2}{57.3Lg}}{1 + \frac{Kv^2}{57.3Lg}} \right] \delta$$

(3.6)

$$\ddot{\phi} = \frac{ma_y h_R cos\phi + \ mgh_R sin\phi - \frac{1}{2} k{l_s}^2 sin\phi - \frac{1}{2} c{l_2}^2 cos\phi(\dot{\phi})}{l_{xx} + m{h_R}^2}$$

(3.7)

Equation (3.6) represents the relationship between vehicle speed (v), wheelbase (L), steer gradient (K), and steering angle (δ). Equation (3.7) relates roll acceleration ($\ddot{\phi}$), roll rate ($\dot{\phi}$) roll angle (ϕ), stiffness (k), damping coefficient (c), suspension spring distance (l_2), and roll inertia (I_{xx}).

Nevertheless, it is important to note that, as stated by (Worden and Tomlinson, 2019), the driver's steering angle input during the manoeuvre is influenced by their ability to perceive the vehicle's motion. The vehicle's lateral acceleration serves as the output, and it is assumed that the vehicle maintains a constant velocity and follows a radial curve throughout the manoeuvre.

The roll angle obtained from Equations 3.6 and 3.7 is utilised to modify the roll angle response in the MORI algorithm. This research article distinguishes itself by employing a distinct roll angle estimate method in contrast to the methods proposed in the research works of (Yurtsever et al.,2020).

The Modified Odenthal Rollover Index algorithm utilises the lateral acceleration and roll angle gains, Ka and Kr, obtained via sensitivity analysis (PSO), in conjunction with the steering input and vehicle velocity equations from (Worden & Tomlinson, 2019). Roll angle estimation relies on these input factors.

3.5 Hardware in The Loop

A HIL approach can use to instead evaluate the performance of the rollover index algorithm and warning device in a controlled but realistic simulated environment. This helped test the functionality of the system and such that the system will perform perfectly fine before it could be implemented in the actual vehicle. The HIL simulation combines a virtual vehicle model with real hardware components to provide an accurate and comprehensive modeling of the rollover warning system performance. This is necessary to ensure the safety and reliability of heavy-duty trucks.

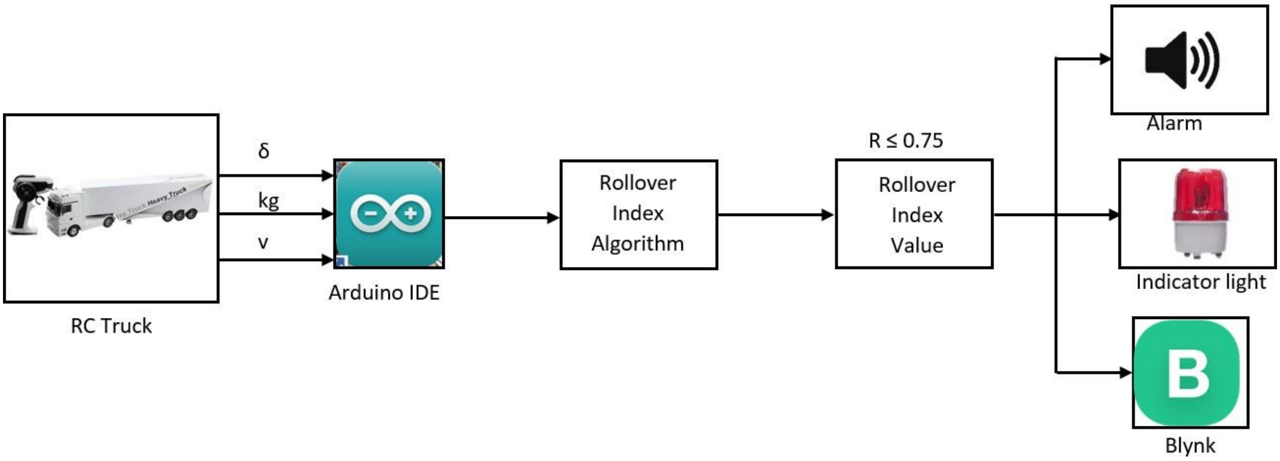

Figure 3. 15 Input from Algorithms in Hardware in the Loop

3.5.1 Remote Control Truck

In addition, a system where input data is gathered from an RC truck to quantify the possibility for rollover by means of the modified Odenthal rollover index (MORI) method is presented. The system works in the following way: after exceeding the safety threshold, an alarm and light indications are activated and the data is sent off for real-time monitoring to a Blynk app. The proposed implementation of the algorithm is tested extensively, while the final implementation is performed on an RC truck.

3.5.2 Arduino IDE

The Arduino IDE plays a very important part in this project because it allows the Rollover Index algorithm and the control circuitry as a whole to be integrated into the ESP32 microcontroller board. The ESP32 is the fundamental processing unit and communicates with the RC truck inputs, enhancing the steering angle, vehicle speed, and load condition switches. The Arduino IDE lets the MATLAB-based Rollover Index algorithm come up in C code, which can then successfully run in real-time on the ESP32. This microcontroller continuously calculates the Rollover Index, on a need basis, using a presaved threshold, and warns suitable outputs, namely alerts and visual signs, of the possibility of rollover. Besides, the ESP32 armed with Wi-Fi capabilities and the Arduino IDE allow the sending to the Blynk app of the

Rollover Index data. This feature allows for remote monitoring and early detection of potential rollover events.

3.5.3 Blynk App

The Blynk app plays a vital role as the interface for remotely monitoring the Rollover Warning Device. It visualizes real-time information about Rollover Index, speed, steering angle, and the status of loading. This can be very useful through the early timely detection for possible rollover incidents, hence giving the user a chance for prompt response. Many enhancements could be looked at to augment the functionalities of this app. To greatly improve the useful features of the app on monitoring and preventing rollovers of heavy vehicles, it is recommended that the data visualization, sophisticated warnings and notifications, operating in conjunction with other systems, and historical data analysis be presented. Through the capabilities of the Blynk app, the Rollover Warning Device could be provided a more advanced and faster solution to further provide enhanced road safety, especially for heavily loaded vehicles.

3.6 Component of The Hardware

An illustrative diagram in Figure 3.16 consolidates all the information. The ESP32 microcontroller will receive input signals from a remote control, steering angle sensor, and speed sensor mounted on the RC truck in order to give inputs to the MORI algorithm on the data. Load-state switches will enable appropriate changes to the settings by the algorithm. The output devices, such as an audible alarm and warning light, are used to warn the driver of rollover hazards. An interface has also been created with the Blynk application using Wi-Fi by sending real-time data such as Rollover Index, speed, steering angle, and load for the real-time monitoring of the state of the vehicle.

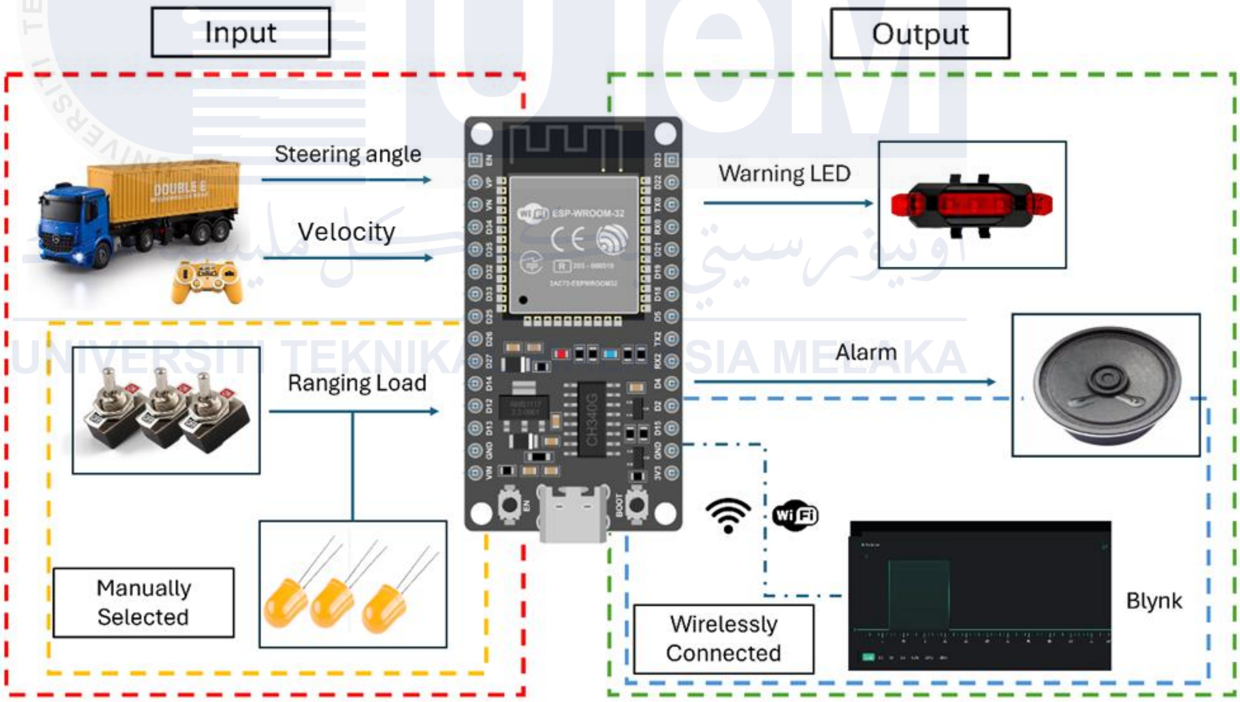

Figure 3. 16 Input and Output for ESP-32 microcontroller

3.6.1 ESP-32

The ESP32 carries out a number of processes. It acquires live sensor data, including steering input, vehicle mass, and speed, from the RC truck. The rollover index is calculated using the Odenthal method and compared to a safety threshold. When suspicions are indicated, the ESP32 outputs warning alarms by an alarm and light indication to the driver. Additionally, the varied wireless connection function to ESP32, comprising Wi-Fi and Bluetooth, is capable of transferring the calculated rollover index and alarm data into the Blynk application running on the user's smartphone for display and monitoring remotely. The ESP32 is suitable for designing with low power consumption to ensure proper performance of the overall system when installed in a heavy vehicle.

3.6.2 Speaker

The speaker/alarm is an essential part of the rollover warning system, providing an audible alert to the driver when the calculated rollover index exceeds the safety limit. This early alertness improves the driver's awareness of the looming likelihood of a rollover, allowing them to adequately apply corrective actions with early effect, and ultimately preventing a probably disastrous rollover accident.

Figure 3. 17 Mini Speaker 2 Watt

3.6.3 Warning LED

The warning LED is an indispensable visual part of the rollover warning system, featuring and showing the status of vehicle stability directly and clearly to the driver. When a rollover index, calculated by the algorithm, is close to or exceeds the safety threshold, the status is indicated by the warning LED, thus adding to the audible alarming and facilitating the situational awareness of the driver. The dual-mode warning system performs the role of helping the driver distinguish and react in a timely manner to possible rollover danger and thereby effectively avoids a rollover accident.

Figure 3. 18 Warning LED

3.6.4 Toggle Switch

A very important user interface component is the toggle switch, which allows the driver to turn the rollover warning system on or off when necessary. This gives the option of letting the system work under certain driving conditions or turning it off under others. As a troubleshooting device, this toggle switch also allows the driver to easily pinpoint a problem with the rollover warning system.

Figure 3. 19 3 pin toggle switch

3.6.5 Steel Enclosure

The steel enclosure houses the automotive grade electronic components for the rollover warning system It either protects the internal workings of the board (from environmental conditions), provides rigidity (to survive the rigors of heavy vehicle operation), and provides electromagnetic interference (EMI) protection. The steel enclosure also enhances the overall appearance and integration of the system, allowing for a consistant and aesthetically pleasing installation in the heavy vehicle interior.

Figure 3. 20 Steel Enclosure

3.7 Summary

This project relies heavily on System-in-the-Loop (SIL) and Hardware-in-the-Loop (HIL) techniques. The SIL component that uses TruckSim and MATLAB/Simulink to develop and improve the Modified Odenthal Rollover Index rollover prediction system. Utilizing vehicle parameters like the lateral acceleration and roll angle, this method can indeed accurately predict the probability of rollover. MORI algorithm parameters are further optimized by PSO algorithm applied to it. The HIL subsystem is a rollover warning system that uses the MORI algorithm, an ESP32 microcontroller, an RC truck, a group of sensors, an RC truck, and a Blynk app. This holistic methodology is employed to develop a dependable and efficient system in order to predict and prevent rollovers of heavy trucks.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter explores the Modified Odenthal Rollover Index (MORI) algorithm designed for heavy vehicle rollover warnings. It assesses the effectiveness of MORI through comprehensive testing, compares it to the original Odenthal method, and discusses its application in real-time monitoring using the Blynk IoT platform to enhance vehicle safety. The implementation of the MORI/Blynk integration is also carried out to further improve safety measures for vehicles.

4.2 Comparative Analysis of MORI and Odenthal Rollover Indices

The research was conducted by using a driving simulator to test the rollover detection algorithm developed for the rollover warning device to verify that the rollover warning device was operational. TruckSim simulator was employed, and the MORI algorithm was implemented using MATLAB/Simulink software. The tractor-semitrailer was tested under Laden (15,000 kg), half-laden (7,500 kg), and unladen (no additional payload) conditions, at low (60km/h), medium (80km/h) and high (100 km/h) speed respectively by a series of step-steering inputs. The purpose was to assess the vehicle's response capabilities under different loading conditions. The results showed that the early warning indicator, the Roll Safety Factor (RSF), maintained a value of 0.75 throughout the test.

4.2.1 Rollover Dynamic in Unladen Condition

Figure 4.1 shows the performance of the MORI and Odenthal rollover mitigation algorithms under a specific operating condition - namely, when the tractor-semitrailer was traveling at a speed of 60 km/h without any additional payload. When a sudden steering input was applied at the 11.37 second mark, the maximum rollover risk metrics produced by the two algorithms were measured. For the MORI system, this value reached 0.57, while the Odenthal index peaked at 0.55. Importantly, at this lower 60 km/h velocity, neither the MORI nor Odenthal indices crossed the critical RSF threshold. This indicated that no early warning would have been provided to the driver under these circumstances. However, a key difference was observed in the time-to-warning, where the MORI approach generated a faster alert compared to the Odenthal method.

The study also examined the tractor-semitrailer's behavior at a higher speed of 80 km/h under the same unloaded conditions in Figure 4.2. In this case, neither the MORI nor Odenthal rollover indices intersected the RSF line, again failing to trigger an early warning.

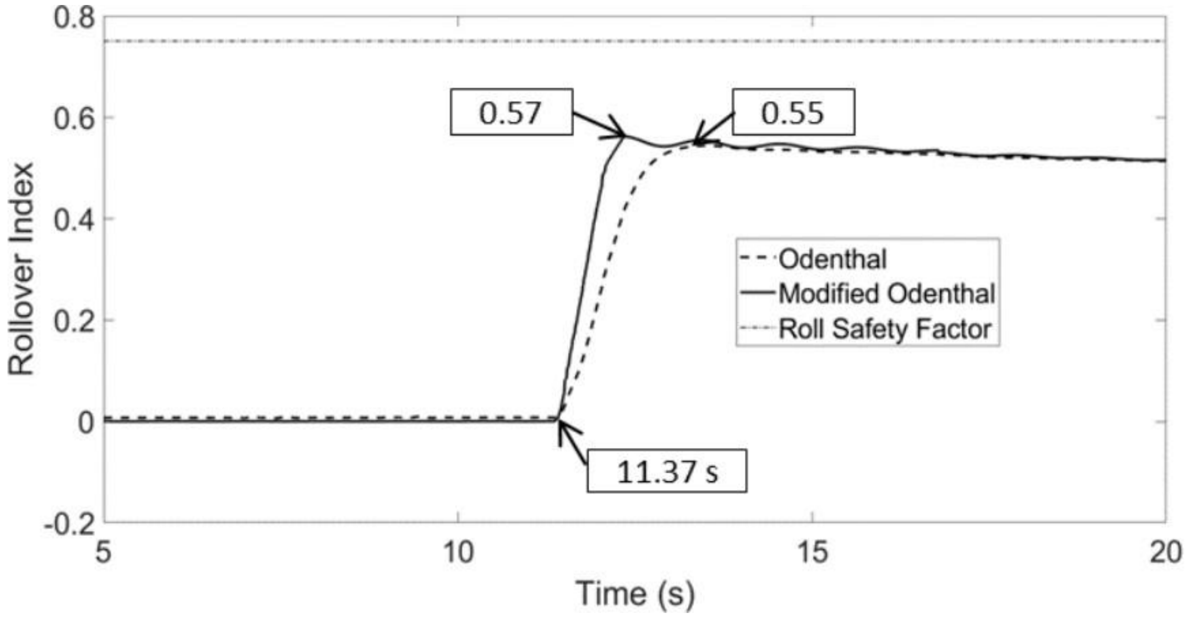

Figure 4. 1 Unladen State with a Velocity of 60km/h

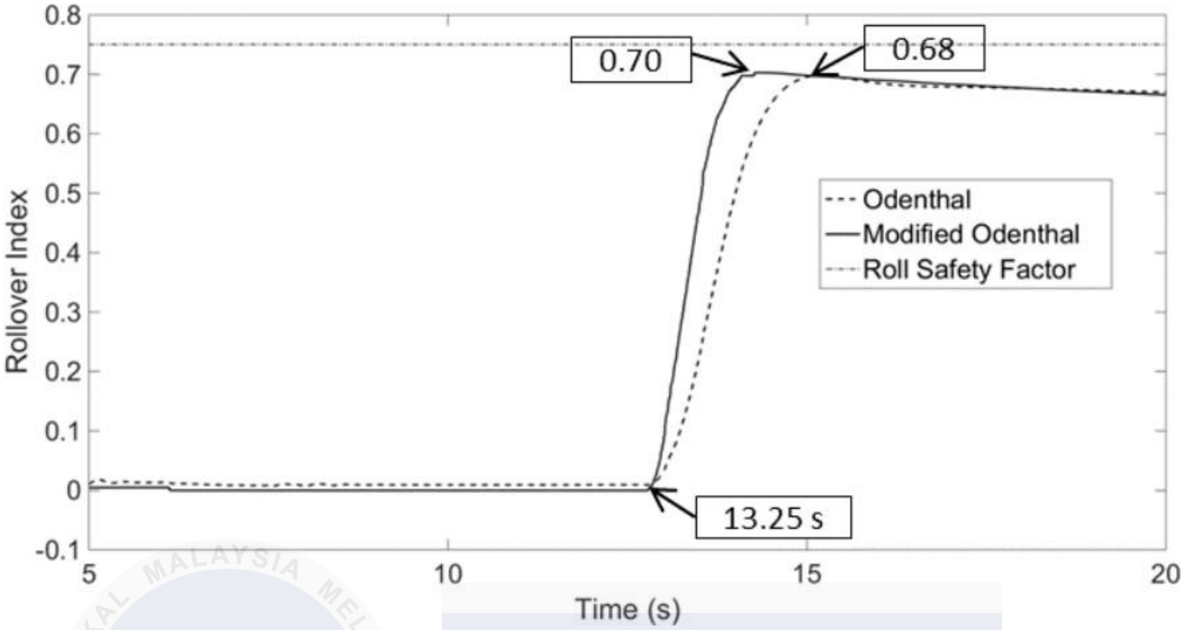

Figure 4. 2 Unladen State with a Velocity of 80km/h

As speed increased from 80 to 100 km/h, both the MORI and Odenthal rollover indices crossed the critical RSF threshold as shown in Figure 4.3. Under the unloaded condition, the MORI generated a higher rollover index of 1.47 compared to 1.25 for Odenthal, crossing the RSF line 0.8 seconds faster. This allowed the MORI to provide a 0.15 second earlier warning to the driver versus 0.95 seconds for Odenthal. The MORI's quicker time-to-warning by 12.4% demonstrates its improved ability to detect rollover risk at higher speeds. Additionally, the Odenthal index exhibited a distinct spike due to the vehicle's high roll motion and inertia in the unloaded, high-speed cornering scenario.

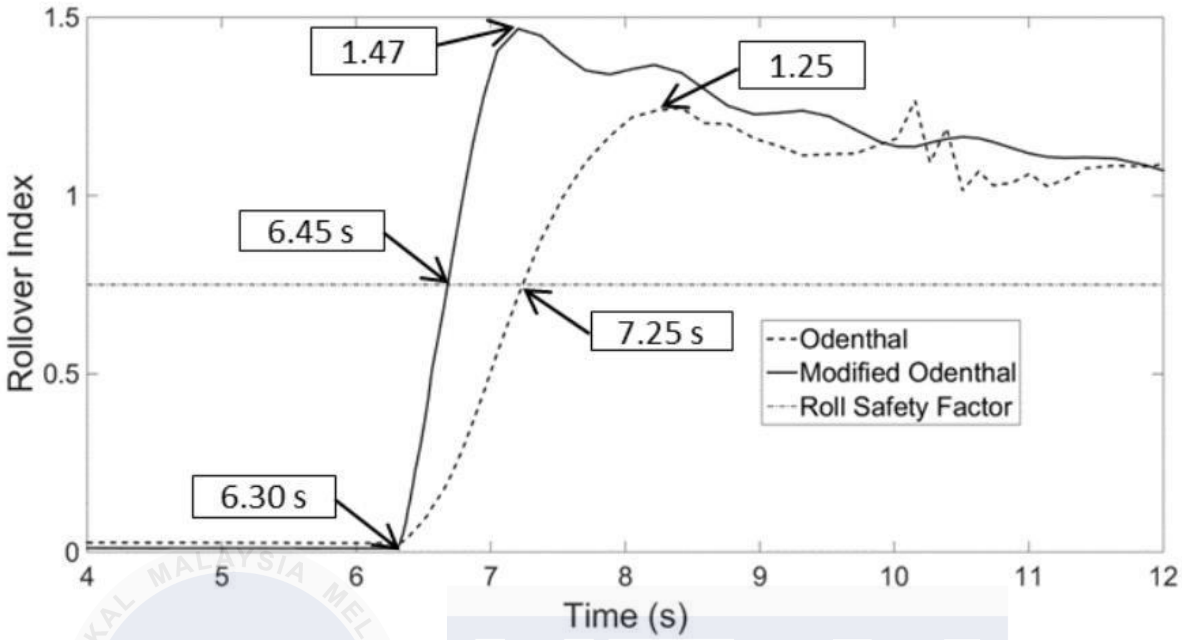

Figure 4. 3 Unladen State with 100kmh of Velocity

4.2.2 Rollover Dynamic in Half-Laden Condition

When evaluating the MORI rollover mitigation system with a half laden 7,500 kg payload added to the tractor-semitrailer with speed of 60 km/h, the Figure 4.4 show an increase in the rollover indices compared to the unladen condition. Specifically, at a speed of 60 km/h and with a sudden steering input applied at 10.3 seconds, the maximum rollover index reached 0.59 for the MORI algorithm and 0.56 for the Odenthal approach. This rise in the rollover indices can be attributed to the higher centrifugal forces generated by the tractor-semitrailer during the cornering maneuver, due to the added weight of the partial payload. However, even with this increased load, the rollover index values did not exceed the critical 0.75 threshold. As a result, neither the MORI nor Odenthal systems triggered an early warning for the driver in this half-laden test case.

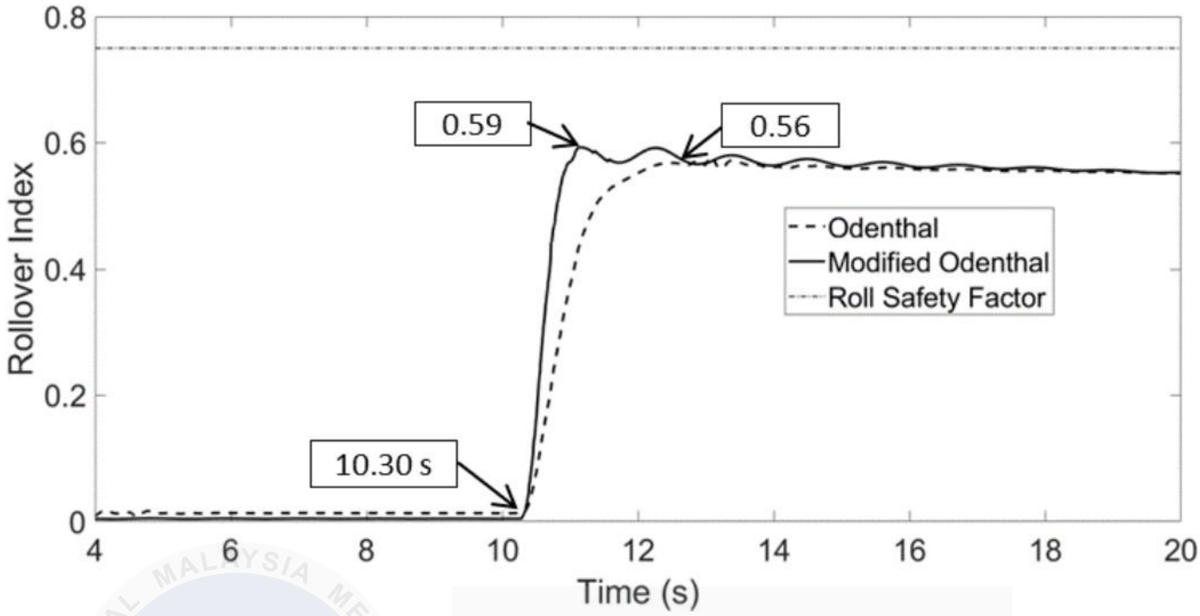

Figure 4. 4 Half-Laden State with a Velocity of 60km/h

When testing the tractor-semitrailer at 80 km/h with a 7,500 kg half-laden condition, the rollover indices increased significantly as the vehicle encountered a sudden steering input as shown in Figure 4.5. The Odenthal algorithm reached a maximum rollover index of 0.81, crossing the RSF stability threshold at 15.01 seconds. In comparison, the MORI system generated a slightly higher peak of 0.82, but intersected the critical RSF line 0.85 seconds sooner. This earlier RSF crossing by the MORI provided a 6% faster time-to-warning for the driver compared to the Odenthal approach. This quicker alert could allow more time for the driver to implement corrective maneuvers and regain stability. The elevated rollover risk was caused by the increased vehicle roll moment of inertia from the added payload, which contributed to the heightened instability during high-speed cornering.

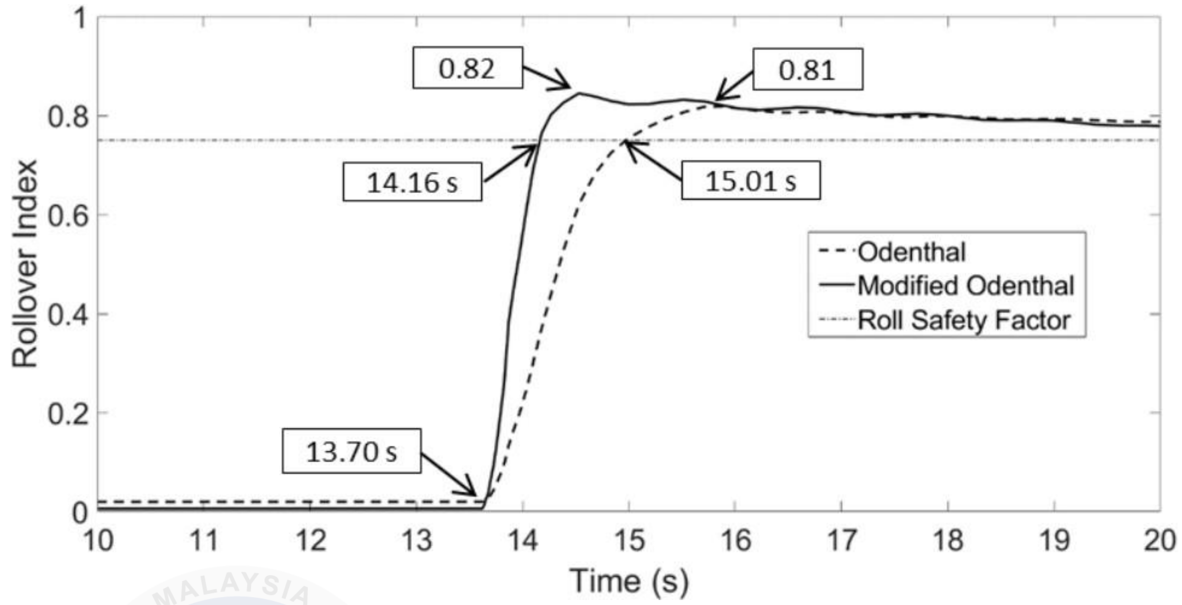

Figure 4. 5 Half-Laden State with a Velocity of 80km/h

Figure 4.6 show the evaluation of the rollover mitigation performance of the MORI and Odenthal algorithms on a half-laden tractor-semitrailer at 95 km/h. With a sudden steering input at 6.41 seconds, the Odenthal rollover index reached 1.11 and crossed the RSF threshold at 7.22 seconds. In comparison, the MORI algorithm generated a slightly higher 1.16 peak, but intercepted the RSF line 0.66 seconds sooner – a 10.1% faster time-to-warning. Given the indices exceeded 1.0, indicating tire lift-off, the MORI's quicker alert could provide the driver critical extra time to implement corrective actions before the vehicle entered a dangerous, unrecoverable condition. The MORI's superior high-speed rollover detection demonstrated its enhanced capabilities compared to the Odenthal system in this challenging partially-laden scenario.

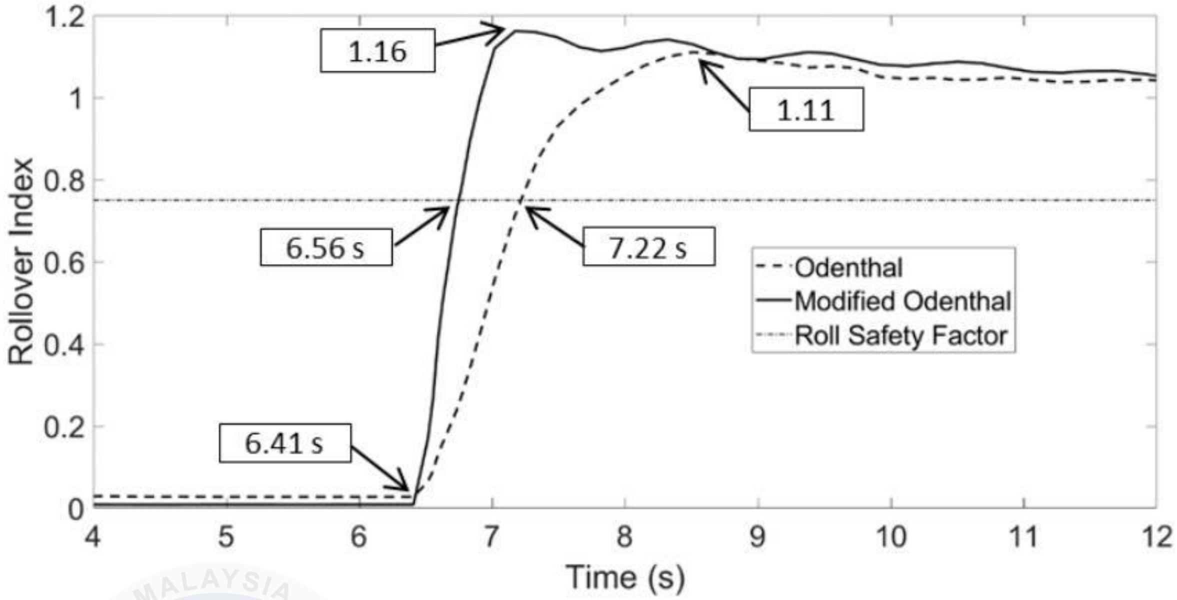

Figure 4. 6 Half-laden State with 95km/h of Velocity

4.2.3 Rollover Dynamic in Full-Laden Condition

Additional tests evaluated the MORI rollover system's performance with a 15,000 kg full laden tractor-semitrailer. At 60 km/h with a 60-degree steering input, both MORI and Odenthal indices peaked but remained below the RSF stability threshold, indicating stability at the lower speed, even fully-laden shown in Figure 4.7. Importantly, MORI provided a faster time-to-warning than Odenthal, though no rollover warning was generated. However, at 80 km/h with the same input, the situation changed shown in Figure 4.8. Indices began rising at 6.55s, with Odenthal intercepting RSF at 7.68s with a 0.92 peak. In contrast, MORI crossed RSF 0.49s sooner, reaching a slightly higher 0.95 index. This unbalanced condition triggered the rollover warning. MORI's enhanced capability to rapidly detect instability at the higher 80 km/h speed, even fully-laden, demonstrated its superior performance compared to Odenthal in this critical scenario.

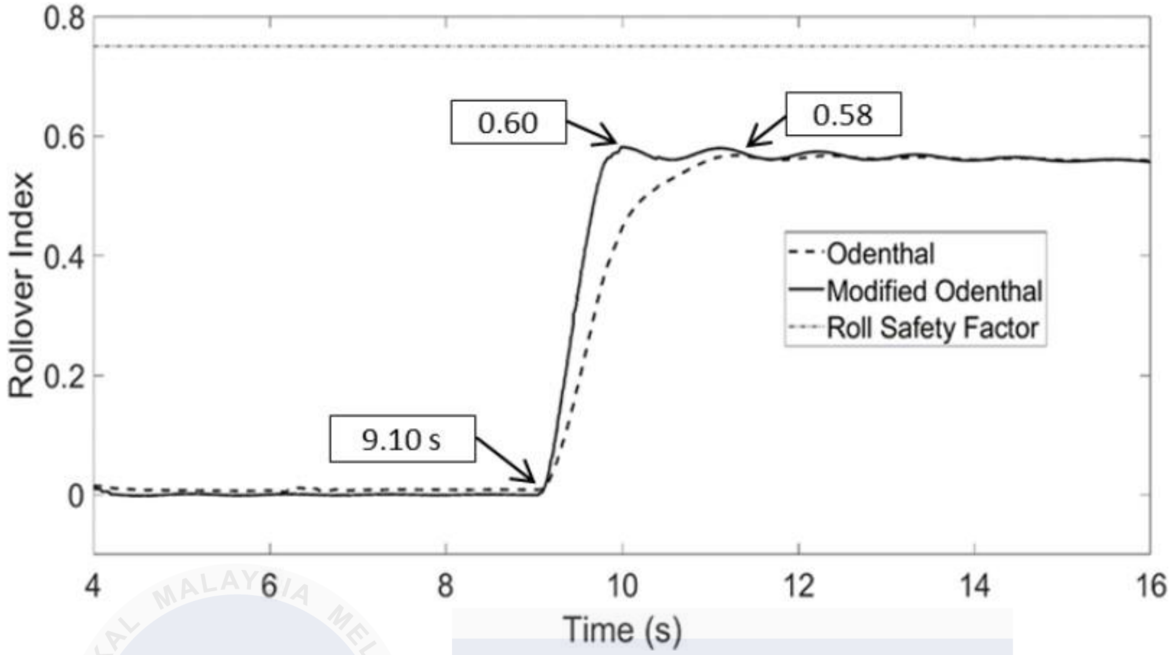

Figure 4. 7 Full laden State with 60km/h of Velocity

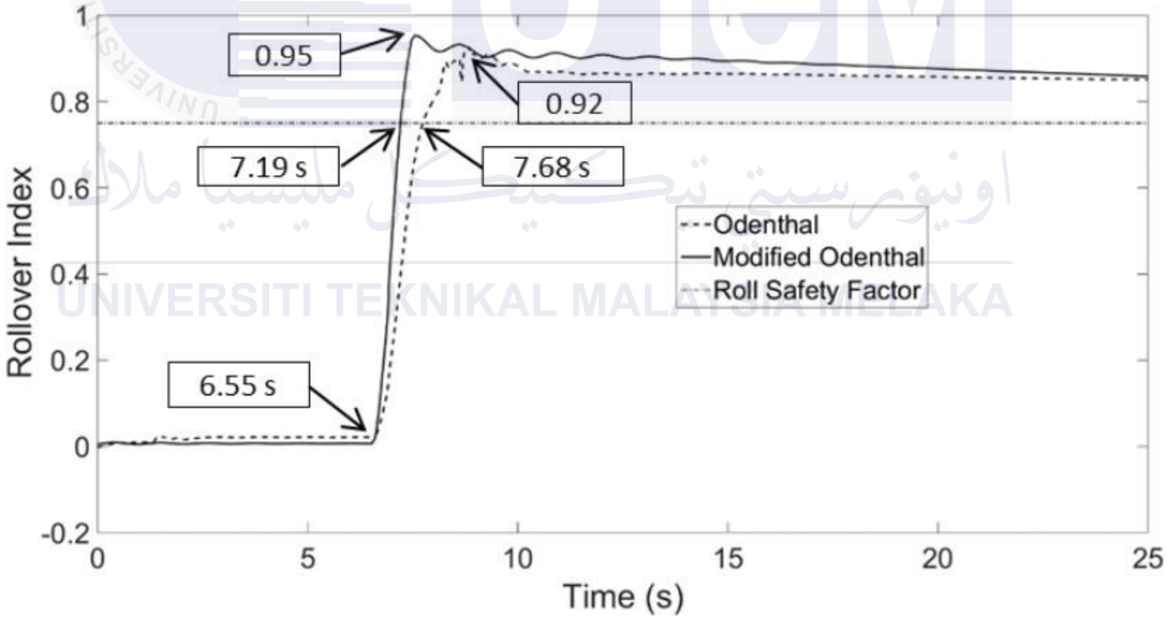

Figure 4. 8 Full laden State with 80km/h of Velocity

To assess the MORI system's performance at maximum load, the test has been conducted the fully-laden tractor-semitrailer at 90 km/h, which is the speed limit determined from simulations to induce extreme rollover risk. Applying a 60-degree steering input, the rollover indices for both MORI and Odenthal began climbing at 7.8 seconds as illustrated in Figure 4.9. However, the Odenthal index crossed the critical RSF threshold at 8.51 seconds, peaking at 1.08. In contrast, the MORI index intercepted RSF 0.57 seconds sooner, at 7.94 seconds, and reached a higher 1.17 maximum. This 7.2% faster time-to-threshold for MORI is significant, as an index over 1.0 indicates complete tire lift-off – a critical unstable condition where the vehicle may rollover or recover. Providing early warning before this lift-off allows drivers to take corrective actions. The MORI's enhanced ability to rapidly detect impending instability, even at 90 km/h fully-laden, demonstrates its superior performance in this high-risk scenario compared to Odenthal.

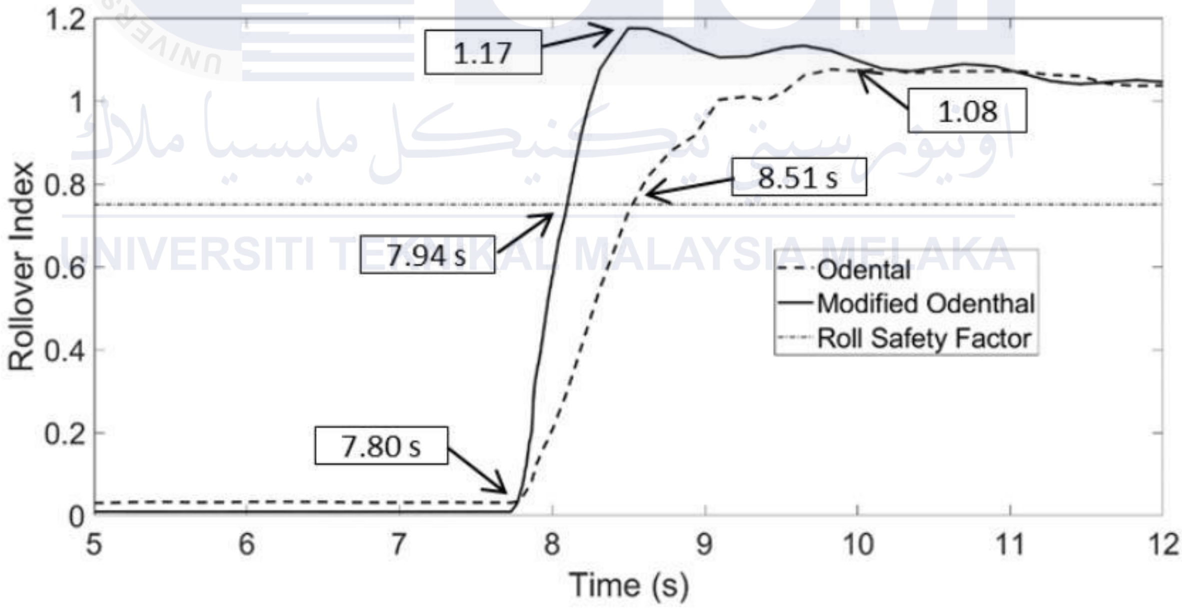

Figure 4. 9 Full laden State with 90km/h of Velocity

The MORI rollover mitigation system demonstrated faster time-to-warning compared to the Odenthal approach across a range of loading and speed scenarios. As shown in the table 4.1

Table 4. 1 MORI response to 3 load condition with ranging speed

Condition	Speed (km/h)	RSF Line			
		MORI (s)	Odenthal (s)	Time Differences (s)	Percentage Improvement (%)
Unladen	60	-	-	-	-
	80	-	-	-	-
	100	6.45	7.25	0.80	12.4
Half laden	60	-	-	-	-
	80	14.16	15.01	0.85	6.0
	95	6.56	7.22	0.66	10.1
Full laden	60	-	-	-	-
	80	7.19	7.68	0.49	6.8
	90	7.94	8.51	0.57	7.2

4.3 Integration of MORI in MATLAB/Simulink and Real-Time Blynk Monitoring

This section explains the implementation of MORI in MATLAB/Simulink and its integration with Blynk IoT for real-time monitoring. It examines the algorithm's performance in both simulated and real-world settings, evaluating its accuracy under various vehicle load conditions. The research confirms MORI's effectiveness as a valuable tool for preventing rollovers in heavy vehicles.

4.3.1 Unladen State MATLAB/Simulink vs. Blynk Performance

When testing the MORI system at 60 km/h without any load, a significant discrepancy was observed between the simulation and the actual results. The MATLAB simulation indicated a peak MORI value of 0.57 at 11.37 seconds following a sudden steering input, as illustrated in Figure 4.10. In contrast, the Blynk app displayed no response since the value did not meet the RSF threshold, as depicted in Figure 4.11.

Further testing at 80 km/h under the same unladen conditions produced similar results, with MORI not crossing the RSF threshold and the Blynk app not displaying any warning output. Figure 4.12 illustrates the findings, suggesting that under unladen conditions, the system may struggle to provide early rollover warnings, even at higher speeds.

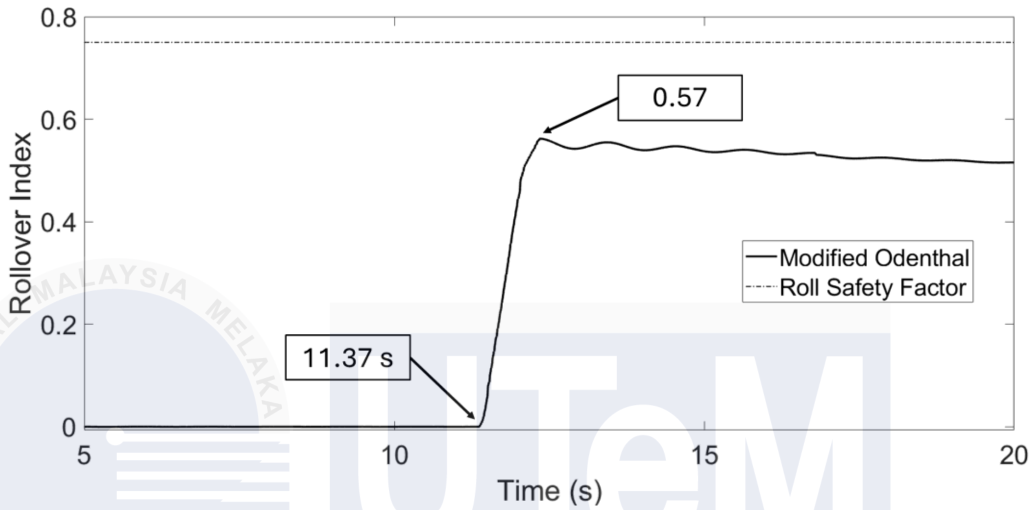

Figure 4. 10 Unladen State with a Velocity of 60km/h in MATLAB

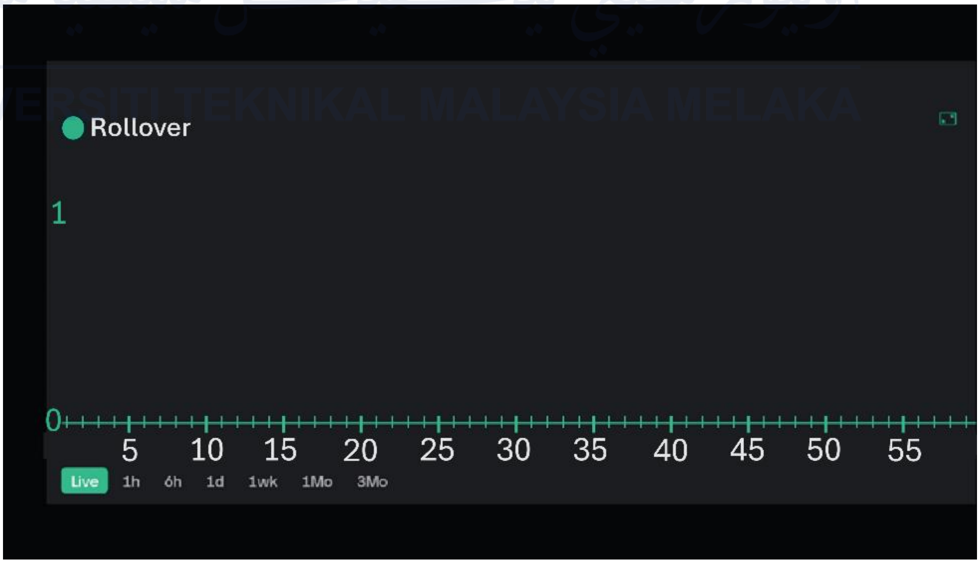

Figure 4. 11 Unladen State with a Velocity of 60km/h in Blynk

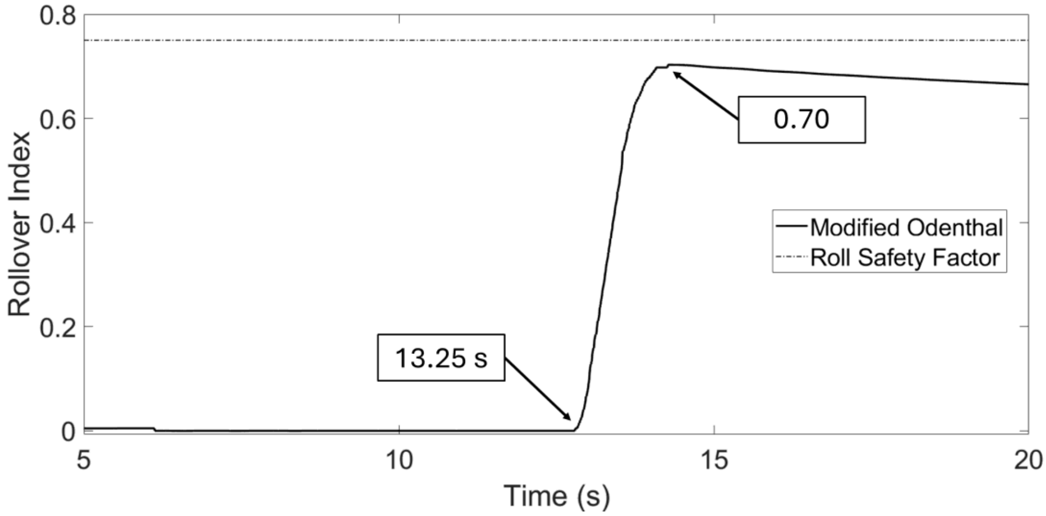

Figure 4. 12 Unladen State with a Velocity of 80km/h in MATLAB

The increase in speed from 80 to 100 km/h without any load had a notable effect on the Modified Odenthal Rollover Index (MORI) performance. As shown in Figure 4.13, the MORI surpassed the critical Roll Safety Factor (RSF) threshold, peaking at a value of 1.47. The system identified the initial crossing of the threshold at 6.45 seconds, giving the operator a 0.15-second early warning before potential rollover conditions could occur. The index then fell back below the RSF threshold at 19.89 seconds, signaling a return to stable operating conditions.

Figure 4.14 illustrates the real-time IoT implementation using the Blynk platform, which demonstrated accurate temporal synchronization with the MATLAB simulation. The digital output effectively mirrored the RSF threshold crossings, switching to a high state precisely at the moment of the initial threshold breach (6.45 seconds) and reverting to a low state at 19.89 seconds. This immediate response validation is essential for confirming the system's ability to perform real-time safety monitoring. The flawless temporal alignment between the simulation and the IoT implementation highlights the reliability and promptness of the Blynk-based monitoring system in delivering critical safety alerts to operators in high-risk situations.

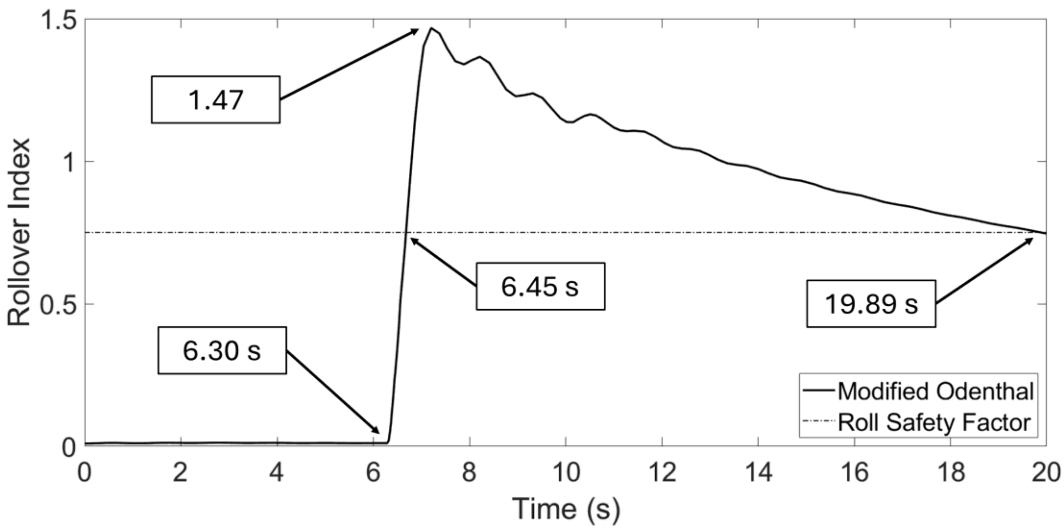

Figure 4. 13 unladen state 100km/h in MATLAB

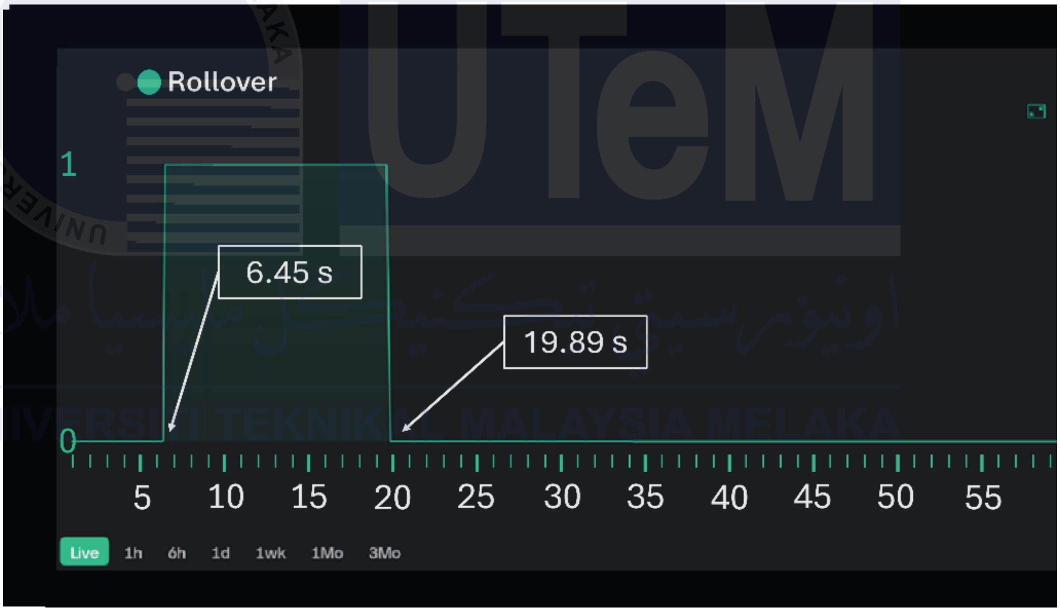

Figure 4. 14 unladen state 100km/h in Blynk

4.3.2 Half-Laden State MATLAB/Simulink vs. Blynk Performance

When evaluating the MORI rollover mitigation system with a half-laden payload of 7,500 kg added to the tractor-semitrailer traveling at a speed of 60 km/h, Figure 4.15 illustrates an increase in the rollover indices compared to the unladen condition. Specifically, at 60 km/h, a sudden steering input applied at 10.3 seconds resulted in a maximum rollover index of 0.59 for the MORI algorithm. This increase in rollover indices can be attributed to the higher centrifugal forces generated by the tractor-semitrailer during the cornering maneuver, due to the added weight of the partial payload. However, even with this increased load, the rollover index values did not surpass the critical threshold of 0.75. Consequently, the MORI system did not trigger an early warning for the driver in this half-laden test case.

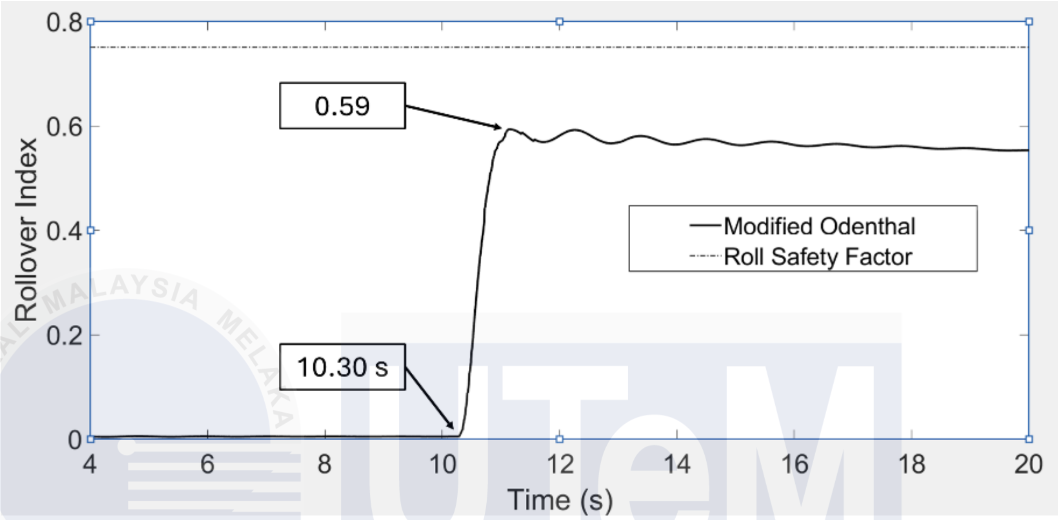

Figure 4. 15 Half-laden state 60km/h in MATLAB

The evaluation of the tractor-semitrailer under half-laden conditions (7,500 kg) at 80 km/h showed notable differences in rollover indices when sudden steering input was applied. As shown in Figure 4.16, the initial dynamic response started at 13.70 seconds, with the Modified Odenthal Rollover Index (MORI) algorithm indicating a swift rise in rollover risk. The index peaked at 0.82, surpassing the Roll Safety Factor (RSF) stability threshold at 14.16 seconds, which signaled a critical stability condition.

The real-time monitoring implementation through the Blynk platform, demonstrated in Figure 4.17, exhibited precise temporal correlation with the simulation results. The digital output accurately captured the threshold crossing event and maintained the alert status until the system detected a return to stable operating conditions at 22.90 seconds. This instantaneous data transmission and processing capability is fundamental for the effective operation of the audible and visual alarm systems, providing operators with crucial response time to execute corrective maneuvers and reestablish vehicle stability.

The observed elevation in rollover risk can be attributed to two primary factors: the increased vehicle roll moment of inertia resulting from the 7,500 kg payload, and the dynamic effects of high-speed cornering. The combination of these factors significantly influenced the vehicle's stability characteristics, particularly during sudden steering inputs. The system's ability to detect and communicate these critical stability conditions in real-time demonstrates its effectiveness as a practical safety monitoring solution for commercial vehicle operations.

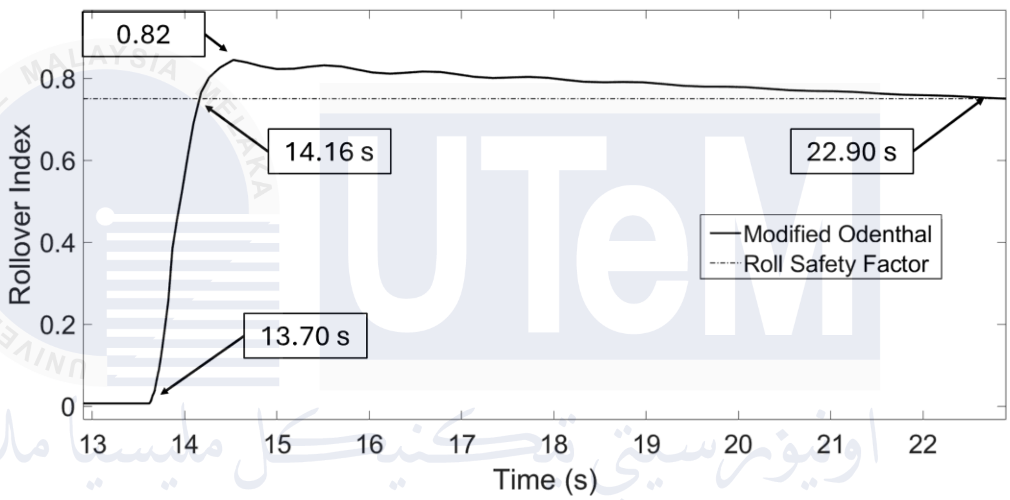

Figure 4. 16 Half-laden state 80km/h in MATLAB

Figure 4. 17 Half-laden state 80km/h in Blynk

Figure 4.18 demonstrates the evaluation of the Modified Odenthal Rollover Index (MORI) performance for a half-laden tractor-semitrailer at 95 km/h. Following a sudden steering input at 6.41 seconds, the MORI exceeded the Roll Safety Factor (RSF) threshold at 6.56 seconds, reaching a peak value of 1.16. The real-time monitoring through the Blynk platform, shown in Figure 4.19, accurately captured this threshold breach, validating the system's rapid detection capabilities. This swift response characteristic provides operators with critical reaction time to implement corrective actions before reaching an unrecoverable state, highlighting MORI's enhanced effectiveness in high-speed stability monitoring.

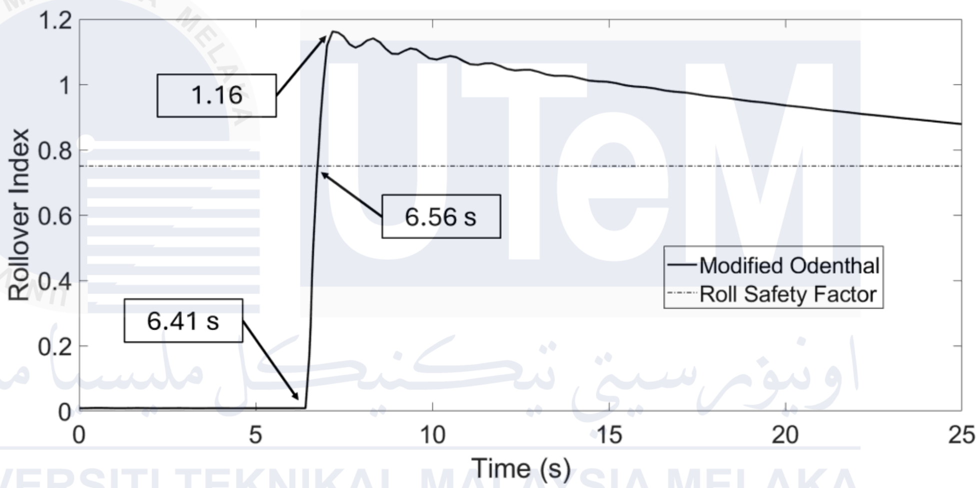

Figure 4. 18 Half-laden state 95km/h in MATLAB

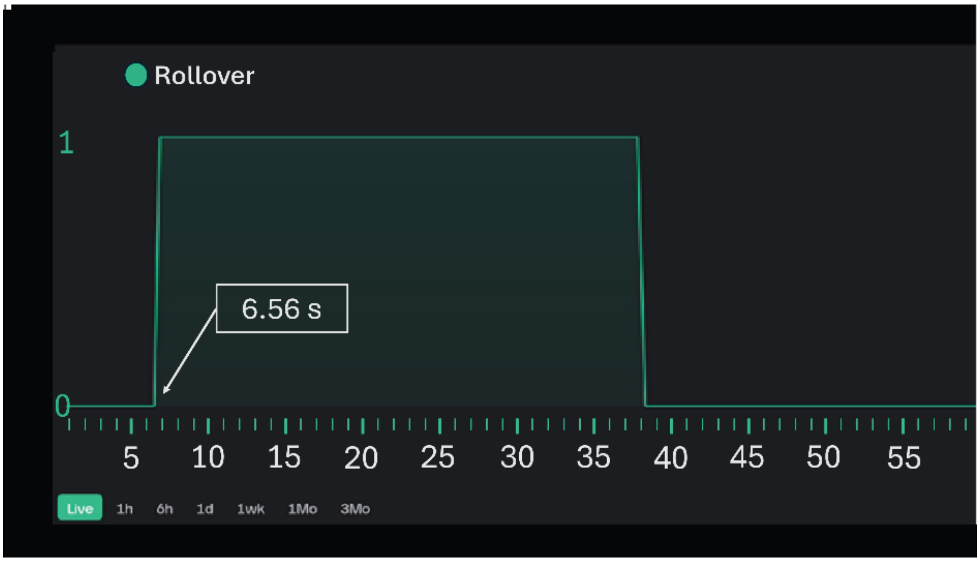

Figure 4. 19 Half-laden state 95km/h in Blynk

4.3.3 Full-Laden State MATLAB/Simulink vs. Blynk Performance

The MORI system's response characteristics were further evaluated under maximum payload conditions (15,000 kg) across varying velocities. Figure 4.20 demonstrates that at 60 km/h with a 60-degree steering input, despite the full-laden configuration, the system maintained stability with MORI values consistently below the Roll Safety Factor (RSF) threshold, thus requiring no warning activation.

However, a significant shift in dynamic behavior was observed at 80 km/h, as illustrated in Figure 4.21. The system detected initial instability at 6.55 seconds, with the MORI exceeding the RSF threshold at 7.19 seconds and reaching a critical peak of 0.95. The Blynk platform's real-time monitoring capability, shown in Figure 4.22, precisely mirrored these threshold transitions, validating the IoT system's reliability in discriminating between stable and unstable operating conditions under maximum payload scenarios.

This precise threshold detection and instantaneous response demonstrate the system's robust performance in distinguishing critical stability conditions without generating false alarms, even under maximum load conditions. Such accuracy in real-time stability monitoring provides crucial safety oversight for commercial vehicle operations in high-risk scenarios.

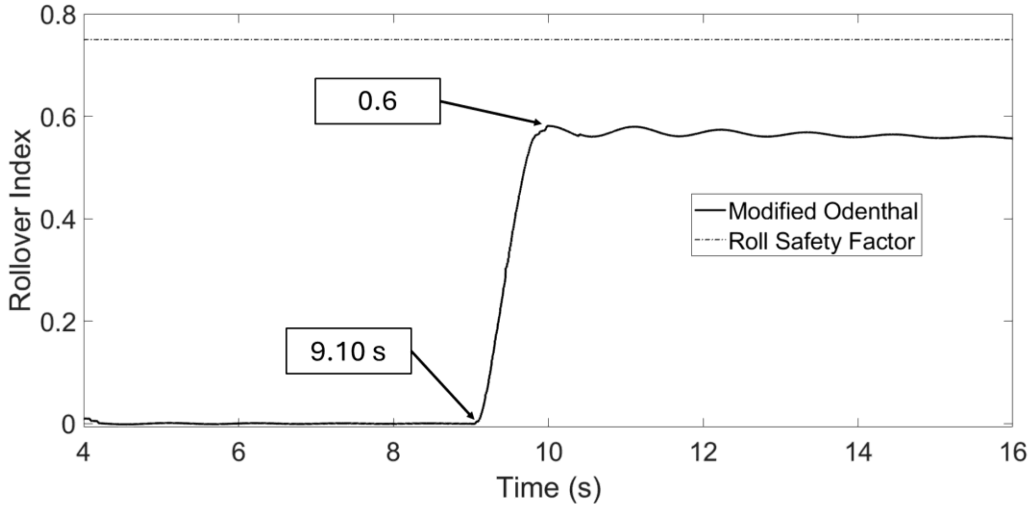

Figure 4. 20 full-laden state 60km/h in MATLAB

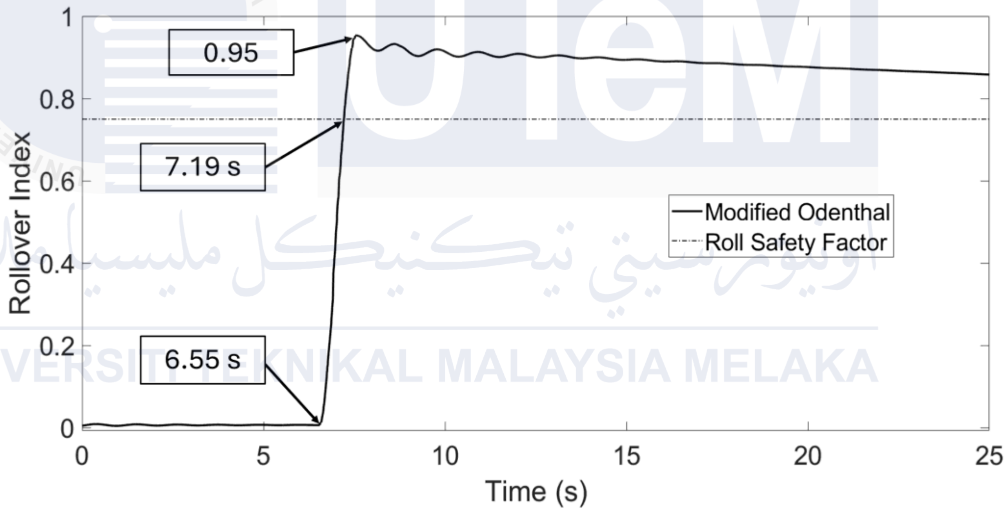

Figure 4. 21 Full-laden state 80km/h in MATLAB

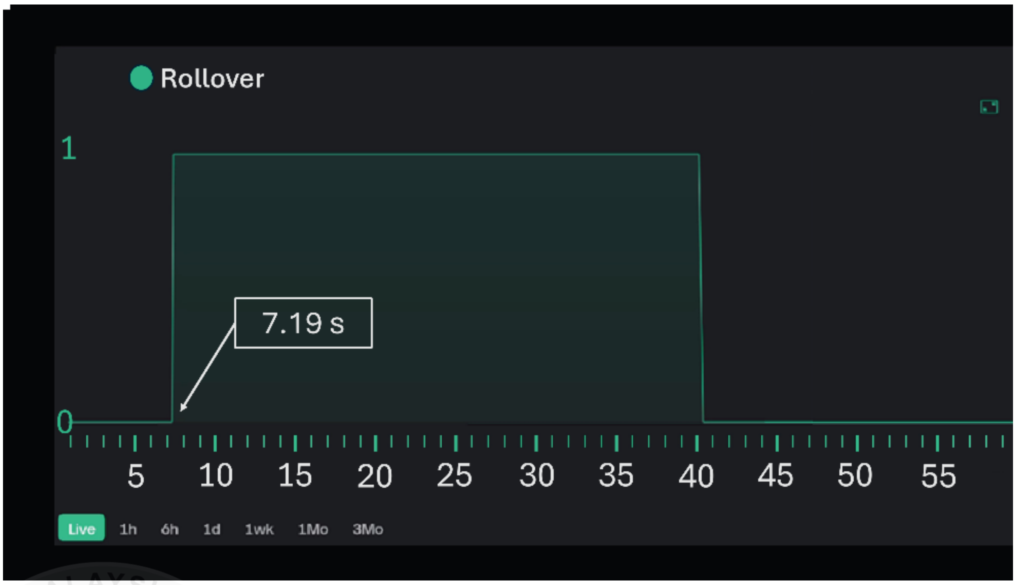

Figure 4. 22 Full-laden state 80km/h in Blynk

The system's performance evaluation at maximum operational parameters involved testing the fully-laden tractor-semitrailer at 90 km/h, identified through simulations as the critical velocity threshold for extreme rollover risk. Figure 4.23 illustrates that upon application of a 60-degree steering input, the Modified Odenthal Rollover Index (MORI) initiated its dynamic response at 7.8 seconds, breaching the Roll Safety Factor (RSF) threshold at 7.94 seconds and ultimately achieving a peak value of 1.17.

The IoT implementation through the Blynk interface, depicted in Figure 4.24, exhibited precise temporal synchronization with the simulation data. The system maintained its fidelity in both the detection of threshold crossings and the recognition of stability recovery points, avoiding false positives that could potentially induce adverse operator responses. This accuracy is particularly crucial given that MORI values exceeding 1.0 indicate complete tire lift-off conditions—a critical state of instability where vehicle recovery becomes uncertain

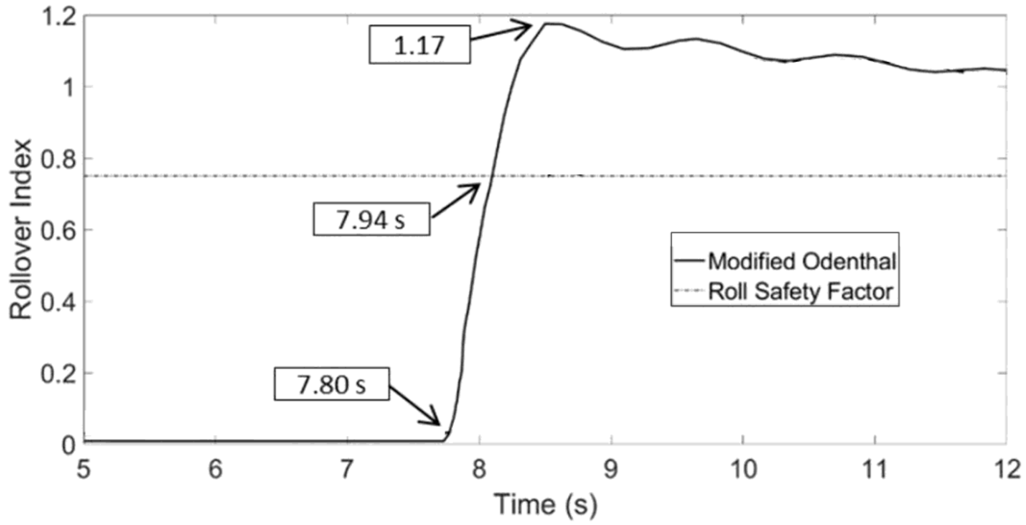

Figure 4. 23 Full-laden state 90km/h in MATLAB

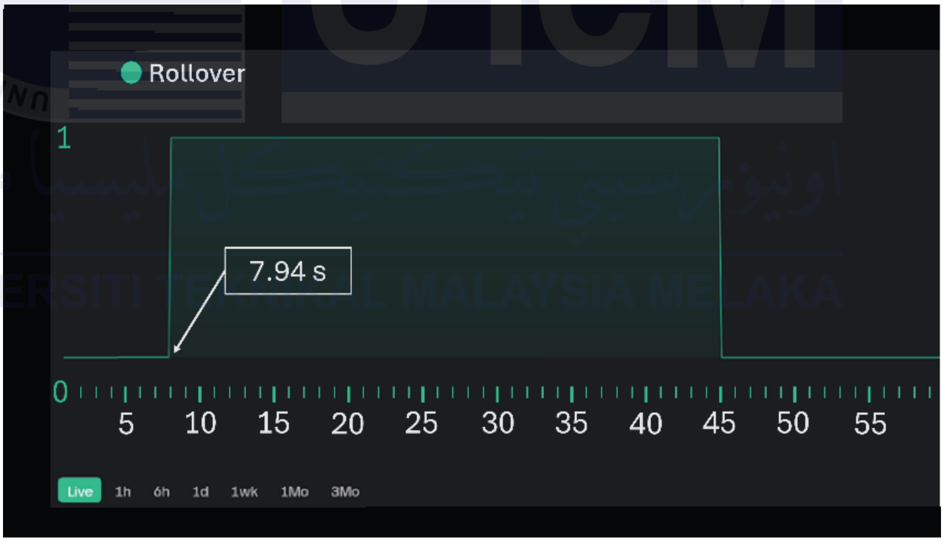

Figure 4. 24 Full-laden state 90km/h in Blynk

The Table 4.2 shows identical RSF threshold crossing times in MATLAB and Blynk, confirming the system's accuracy and reliability.

Table 4. 2 RSF Threshold Crossing Times in MATLAB and Blynk

Condition	Speed (km/h)	RSF Line		
		MATLAB (s)	Blynk (s)	Time Differences (s)
Unladen	60	-	-	-
	80	-	-	-
	100	6.45	6.45	0.00
Half laden	60	-	-	-
	80	14.16	14.16	0.00
	95	6.56	6.56	0.00
Full laden	60	-	-	-
	80	7.19	7.19	0.00
	90	7.94	7.94	0.00

4.4 *Summary*

This chapter analysed the performance of the Modified Odenthal Rollover Index (MORI) as a rollover mitigation system for heavy vehicles. A comparative study with the Odenthal index was conducted using the TruckSim simulator across various loading conditions and speeds. Results showed that MORI consistently provided faster time-to-warning, particularly in high-speed and loaded scenarios, demonstrating its enhanced rollover detection capabilities.

The integration of MORI in real-time monitoring using the Blynk IoT platform was also evaluated. The system showed excellent alignment between simulation and real-time outputs, confirming its reliability for practical applications. Overall, MORI proved to be a robust tool for improving heavy vehicle stability and safety.

CHAPTER 5

CONCLUSIONS

5.1 Conclusion Regarding Result

This study has successfully achieved its primary objectives of developing an advanced rollover warning system for heavy-duty trucks and integrating an IoT system to facilitate real-time monitoring. The results, as presented in the Literature Review, Methodology, and Results and Discussion, provide robust evidence supporting the effectiveness and reliability of both the developed warning system and the IoT integration, which collectively enhance the safety of heavy-duty vehicles.

The first objective, which focused on the development and enhancement of the rollover warning system, was accomplished through a comparative analysis of the MORI and Odenthal system designs. Using MATLAB/Simulink and TruckSim, a series of simulation tests were conducted to evaluate the rollover detection accuracy of both systems. The findings from the step steer test, which examined the vehicle's response to critical steering inputs, demonstrated that the MORI system provided superior performance compared to the Odenthal system, yielding a 12.4% improvement in stability at the unladen state with a velocity of 100 km/h. This improvement underscores the enhanced predictive accuracy of the MORI system in identifying potential rollover scenarios, making it a more reliable and effective solution for preventing rollover accidents in heavy-duty trucks. These results validate the successful achievement of the first objective, confirming the system's capability to improve vehicle stability under challenging driving conditions.

The second objective, which involved integrating an IoT system with the rollover warning device for real-time monitoring, was successfully completed. The MATLAB block diagram was converted to C language for integration with the Integrated Development Environment (IDE), enabling real-time monitoring of key parameters through the Blynk app. Testing under conditions ranging from unladen at 60 km/h to full-laden at 90 km/h confirmed the system's ability to transmit data instantly and reliably. A key comparison during the testing phase was the response time between MATLAB/Simulink and the Blynk app. The data comparison revealed that the transmission times were identical, with no measurable difference (0%) in response time. This demonstrates that the integration of the IoT system with the Blynk app ensures instantaneous data processing, making the system highly reliable for real-time monitoring. The results further validate the effectiveness of the IoT solution in providing rapid, reliable alerts, improving safety and operational efficiency in heavy-duty vehicle management, actionable data, further enhancing the system's reliability and overall performance.

5.2 Recommendation

The Modified Odenthal Rollover Index (MORI) algorithm integrated into this system has proven to be an effective tool for alerting drivers to potential rollover risks, providing valuable time for drivers to react and prevent accidents. Additionally, the system incorporates IoT-based monitoring via the Blynk app, allowing for real-time vehicle condition monitoring. The instantaneous data transmission from the device to the app ensures that drivers and fleet managers can respond quickly to emerging risks. However, like any innovative product, there is always room for further enhancement.

5.2.1 Integration with GPS

To further enhance the system’s capabilities, it is recommended that a Global Positioning System (GPS) module be integrated into the device. This would enable continuous tracking of the vehicle’s location, providing valuable contextual information alongside rollover data. Real-time location tracking could improve situational awareness, especially in isolated or remote areas, and allow fleet managers to monitor vehicle movement and behavior more effectively. GPS data could also be used to enhance emergency response protocols by pinpointing the exact location of vehicles in critical situations.

5.2.2 Development of Custom App with Enhanced Data Visualization

While the Blynk app provides real-time monitoring, the development of a customized application tailored specifically to this system would offer several advantages. A proprietary platform would allow for the prioritization of key features, such as advanced data visualization and real-time analytics, which would be essential for more detailed vehicle monitoring. The current digital graphs provided by Blynk offer only binary feedback (1 for rollover, 0 for stable). By developing an analog graph system, continuous vehicle dynamics could be visualized, offering greater insights into factors such as steering input, vehicle tilt, and other variables leading up to a rollover event. This would enable more detailed, incremental analysis of the data, allowing fleet managers and drivers to assess the risk of a rollover more precisely and in real-time. Furthermore, this custom application could also enable the integration of additional features, such as GPS tracking, vehicle speed, and tilt angles, allowing for a more comprehensive and dynamic monitoring system. The ability to tailor data presentation would also facilitate easier comparison with simulation results from tools such as MATLAB/Simulink, providing more actionable insights and improving the overall accuracy of risk assessments.

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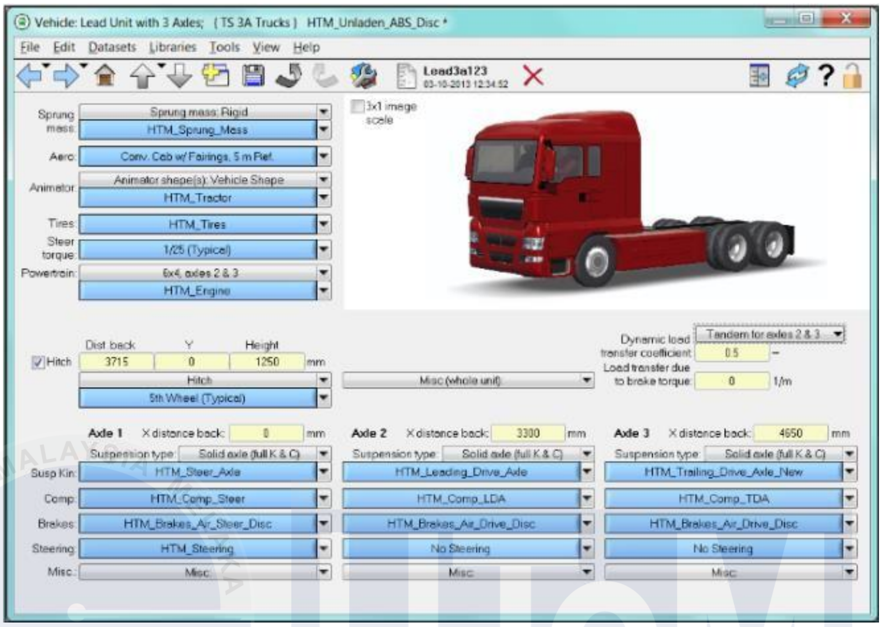
APPENDICES



Appendix 1 Vehicle appearance setting

23% detected as AI

The percentage indicates the combined amount of likely AI-generated text as well as likely AI-generated text that was also likely AI-paraphrased.

Caution: Review required.

It is essential to understand the limitations of AI detection before making decisions about a student's work. We encourage you to learn more about Turnitin's AI detection capabilities before using the tool.

Detection Groups

1 AI-generated only 20%
Likely AI-generated text from a large-language model.

2 AI-generated text that was AI-paraphrased 3%
Likely AI-generated text that was likely revised using an AI-paraphrase tool or word spinner.

Disclaimer
Our AI writing assessment is designed to help educators identify text that might be prepared by a generative AI tool. Our AI writing assessment may not always be accurate (it may misidentify writing that is likely AI generated as AI generated and AI paraphrased or likely AI generated and AI paraphrased writing as only AI generated) so it should not be used as the sole basis for adverse actions against a student. It takes further scrutiny and human judgment in conjunction with an organization's application of its specific academic policies to determine whether any academic misconduct has occurred.

Frequently Asked Questions

How should I interpret Turnitin's AI writing percentage and false positives?
The percentage shown in the AI writing report is the amount of qualifying text within the submission that Turnitin's AI writing detection model determines was either likely AI-generated text from a large-language model or likely AI-generated text that was likely revised using an AI-paraphrase tool or word spinner.

False positives (incorrectly flagging human-written text as AI-generated) are a possibility in AI models.

AI detection scores under 20%, which we do not surface in new reports, have a higher likelihood of false positives. To reduce the likelihood of misinterpretation, no score or highlights are attributed and are indicated with an asterisk in the report (*%).

The AI writing percentage should not be the sole basis to determine whether misconduct has occurred. The reviewer/instructor should use the percentage as a means to start a formative conversation with their student and/or use it to examine the submitted assignment in accordance with their school's policies.

What does 'qualifying text' mean?
Our model only processes qualifying text in the form of long-form writing. Long-form writing means individual sentences contained in paragraphs that make up a longer piece of written work, such as an essay, a dissertation, or an article, etc. Qualifying text that has been determined to be likely AI-generated will be highlighted in cyan in the submission, and likely AI-generated and then likely AI-paraphrased will be highlighted purple.

Non-qualifying text, such as bullet points, annotated bibliographies, etc., will not be processed and can create disparity between the submission highlights and the percentage shown.