ROLLOVER WARNING SYSTEM FOR TRACTOR-SEMITRAILER USING A MODIFIED ODENTHAL ROLLOVER INDEX ALGORITHM

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DEDICATION

Specially dedicated to my beloved parents, wife, sons and siblings.

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ABSTRACT

Any accident involving a tractor-semitrailer could significantly affect life and component damage as well as the surrounding environment due to the size of the vehicle. One of the main factors that causes tractor-semitrailer accidents is vehicle rollover instability. Therefore, this study aimed to develop a vehicle instability avoidance system for a tractor-semitrailer by implementing it on an accurate tractor-semitrailer model. In developing the model, a new approach was proposed by adopting a virtual Pacejka tire model in modelling the hitch joint of the tractor-semitrailer. The virtual Pacejka tire model has included a 16 degree-of-freedom tractor-semitrailer within MATLAB/Simulink software and later verified using the TruckSim model and validated with published data. It is observed from the verification and validation results, the tractor-semitrailer model using the virtual Pacejka tire model for the hitch joint showed a similar response to the behaviour of the TruckSim model and published data. In terms of vehicle instability avoidance system, the fastest response of the tractor-semitrailer rollover index based on early warning indicator was selected by utilizing several types of rollover index algorithm proposed by the previous researchers. The step steering manoeuvres simulation at a various speed was conducted using MATLAB/Simulink software to obtain the rollover index. It can be observed from the results that the rollover index algorithm proposed by Odenthal provides the fastest index based on the early warning indicator on the tractor unit. In order to optimise the rollover index performance, the Odenthal rollover index algorithm was modified and optimised using Particle Swarm Optimisation (PSO). Finally, the rollover index algorithm was proposed by integrating the modified Odenthal rollover index algorithm with driver steering and vehicle speed inputs instead of lateral acceleration. The modified Odenthal rollover index algorithm performance was evaluated by conducting an experiment involving the step steering manoeuvres, subjected to various vehicle speeds and load conditions through the Hardware-in-the-Loop (HIL) simulation in the TruckSim driving simulator and MATLAB/Simulink software. It was observed from the experimental results that the modified Odenthal rollover index algorithm produced 12.4% faster Time-To-Warn (TTW) than the Odenthal rollover index for the driver. Thus, the modified Odenthal rollover index algorithm demonstrated a better early warning system for the driver to initiate the corrective action.

ABSTRAK

Sebarang kemalangan yang melibatkan traktor-semitreler akan memberi kesan kepada jangkahayat dan kerosakan komponen serta persekitaran disebabkan oleh saiz kenderaan itu. Salah satu faktor utama yang menyebabkan kemalangan traktor-semitreler adalah ketidakstabilan bergolek kenderaan. Oleh itu, tujuan kajian ini adalah untuk membangunkan sistem pencegahan ketidakstabilan kenderaan untuk traktor-semitreler dengan melaksanakannya pada model traktor-semitreler yang jitu. Dalam membangunkan model ini, kaedah baru telah diperkenalkan dengan menyesuaikan model tayar Pacejka maya dalam memodelkan penyambung traktor-semitreler. Model tayar Pacejka maya telah memasukkan 16 darjah-kebebasan traktor-semitreler ke dalam perisian MATLAB/Simulink dan disahkan menggunakan model TruckSim bersama data yang telah diterbitkan. Diperhatikan daripada keputusan pengesahan, model traktor-semitreler yang menggunakan model tayar Pacejka maya pada penyambung menunjukkan tindakbalas yang sama pada perlakuan model TruckSim dan data yang telah diterbitkan. Dari segi sistem pencegahan ketidakstabilan kenderaan, tindakbalas paling pantas indeks golekan traktor-semitreler berdasarkan petunjuk amaran awal telah dipilih dengan menggunakan beberapa jenis algoritma indeks golekan yang telah dicadangkan oleh penyelidik terdahulu. Simulasi olahgerak mengemudi berperingkat dengan pelbagai kelajuan telah dijalankan menggunakan perisian MATLAB/Simulink bagi mendapatkan indeks golekan. Dapat diperhatikan daripada keputusan simulasi bahawa algoritma indeks golekan yang dicadangkan oleh Odenthal menghasilkan indeks golekan terpantas berdasarkan kepada pengesanan amaran awal pada unit traktor. Bagi mengoptimumkan prestasi indeks golekan, algoritma indeks golekan Odenthal telah diubahsuai dan dioptimumkan dengan menggunakan Pengoptimuman Kawanan Zarah (PSO). Akhirnya, algoritma indeks golekan telah dicadangkan dengan mengintegrasikan algoritma indeks golekan Odenthal dengan pemandu kemudi dan kelajuan kenderaan dan bukannya pecutan sisi. Prestasi algoritma indeks golekan Odenthal yang diubahsuai telah dinilai dengan menjalankan satu eksperimen yang melibatkan olehgerak mengemudi berperingkat, tertakluk kepada pelbagai kelajuan kenderaan dan keadaan beban melalui simulasi penyelakuan *Hardware-in-the-Loop* (HIL) dalam simulator pemanduan TruckSim dan perisian MATLAB/Simulink. Keputusan eksperimen menunjukkan bahawa algoritma indeks golekan Odenthal yang diubahsuai menghasilkan 12.4% masa-untuk-amaran (TTW) yang lebih pantas daripada indeks golekan Odenthal kepada pemandu. Oleh itu, algoritma indeks golekan Odenthal yang diubahsuai mempamerkan sistem amaran awal yang lebih baik kepada pemandu bagi memulakan tindakan pembetulan.

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LIST OF ABBREVIATIONS

ABC	-	Artificial Bee Colony
ACO	-	Ant Colony Optimization
CG	-	Centre of Gravity
DLC	-	Double Lane Change
DOF	-	Degree of Freedom
GA	-	Genetic Algorithm
GSA	-	Gravitational Search Algorithm
HIL	-	Hardware-in-the-Loop
HTM	-	Heavy Truck Manufacturer
LQR	-	Linear Quadratic Regulator
LTR	-	Load Transfer Ratio
MF	-	Magic Formula
MIL	-	Model-in-the-Loop
MIROS	-	Malaysia Institute of Road Safety Research
MORI	-	Modified Odenthal Rollover Index
MORI	-	Modified Odenthal Rollover Index
MPC	-	Model Predictive Control
NHTSA	-	National Highway Traffic Safety Administration
ORI	-	Odenthal Rollover Index
PID	-	Proportional–Integral–Derivative
PLTR	-	Prediction Load Transfer Ratio
PSO	-	Particle Swarm Optimisation
RAR	-	Rearward Amplification Ratio
RI	-	Rollover Index
RMS	-	Root Mean Square
RSF	-	Roll Safety Factor
SIL	-	Software-in-the-Loop
SLC	-	Single Lane Change
SRT	-	Static Rollover Threshold
SSC	-	Step Steer Cornering

SSF	-	Static Safety Factor
SUT	-	Single Utility Truck
TTR	-	Time-To-Respond
TTW	-	Time-To-Warn
VIL	-	Vehicle-In-the-Loop
DHIL	-	Driver-Hardware-in-the-Loop

LIST OF SYMBOLS

a_1	-	Distance From CG to the First Axle
a_2	-	Distance from Semitrailer CG to the Hitch
A_c	-	Centripetal Acceleration
a_x	-	Longitudinal Acceleration
a_{x1}	-	Tractor Longitudinal Acceleration
a_{x2}	-	Semitrailer Longitudinal Acceleration
a_y	-	Lateral Acceleration
A_y	-	Lateral Acceleration at the CG of the Vehicle
$a_{y,2}$	-	Body Lateral Acceleration
a_{y1}	-	Tractor Lateral Acceleration
a_{y2}	-	Semitrailer Lateral Acceleration
B	-	Stiffness Factor
b_1	-	Distance From CG to the Second Axle
b_2	-	Distance from Semitrailer CG to the Fourth Axle
C	-	Shape Factor
c	-	Cognitive Coefficient
c_1	-	Distance From CG to the Third Axle
c_2	-	Distance from Semitrailer CG to the Fifth Axle
C_x	-	Longitudinal Stiffness of Tyre
C_y	-	Lateral Stiffness of Tyre
D	-	Peak Factor
d_1	-	Distance From CG to the Hitch
E	-	Curvature Factor
e_1	-	Distance From Axle 1 to the Hitch
FL	-	Vertical Tire Forces On The Left Track Tire
FR	-	Vertical Tire Forces On The Right Track Tire
F_x	-	Longitudinal Force
F_{x1l}	-	Longitudinal Tire Force at the Left Sides of Axle 1
F_{x1r}	-	Longitudinal Tire Force at the Right Side of Axle 1
F_{x2l}	-	Longitudinal Tire Force at the Left Side of Axle 2

F_{x2r}	-	Longitudinal Tire Force at the Right Side of Axle 2
F_{x3l}	-	Longitudinal Tire Force at the Left Side of Axle 3
F_{x3r}	-	Longitudinal Tire Force at the Right Side of Axle 3
F_{x4l}	-	Longitudinal Tire Force at the Left Side of Axle 4
F_{x4r}	-	Longitudinal Tire Force at the Right Side of Axle 4
F_{x5l}	-	Longitudinal Tire Force at the Left Side of Axle 5
F_{x5r}	-	Longitudinal Tire Force at the Right Side of Axle 5
F_{xh}	-	Hitch Force at Longitudinal Direction
F_y	-	Lateral Force
F_z	-	Vertical Force
F_{y1l}	-	Lateral Tire Force at the Left Side of Axle 1
F_{y1r}	-	Lateral Tire Force at the Right Side of Axle 1
F_{y2l}	-	Lateral Tire Forces at the Left Side of Axle 2
F_{y2r}	-	Lateral Tire Force at the Right Side of Axle 2
F_{y3l}	-	Lateral Tire Force at the Left Side of Axle 3
F_{y3r}	-	Lateral Tire Force at the Right Side of Axle 3
F_{y4l}	-	Longitudinal Tire Force at the Left Side of Axle 4
F_{y4r}	-	Longitudinal Tire Force at the Right Side of Axle 4
F_{y5l}	-	Longitudinal Tire Force at the Left Side of Axle 5
F_{y5r}	-	Longitudinal Tire Force at the Right Side of Axle 5
F_{yh}	-	Hitch Force at Lateral Direction
$F_{Z,L}$	-	Left Side Tire Force
$F_{Z,R}$	-	Right Side Tire Force
F_{z1l}	-	Vertical Tire Force at the Left Side of Axle 1
F_{z1r}	-	Vertical Tire Force at the Right Side of Axle 1
F_{z2l}	-	Vertical Tire Force at the Left Side of Axle 2
F_{z2r}	-	Vertical Tire Force at the Right Side of Axle 2
F_{z3l}	-	Vertical Tire Force at the Left Side of Axle 3
F_{z3r}	-	Vertical Tire Force at the Right Side of Axle 3
F_{zh}	-	Hitch Vertical Force
g	-	Gravitational Acceleration
g_{best}	-	Best Overall Position
h	-	Height of Body CG to the Roll Centre

h_1	-	Tractor CG Height
h_{cg2}		Height of Body CG to the Ground
h_R	-	Height of the Roll Centre to the Ground
I_{CG}	-	Moment of Inertia of Sprung Mass about *z*-axis
I_w	-	Wheel Track
iw	-	Inertial Weight
I_{xx}	-	Roll Inertia
I_{z1}	-	Second Moment of Inertia at *z*-axis
I_{z2}	-	Semitrailer Second Moment of Inertia at *z*-axis
K	-	Steer Gradient
k_1	-	Axle 1 Spring Stiffness
k_2	-	Axle 2 Spring Stiffness
k_3	-	Axle 3 Spring Stiffness
k_4	-	Axle 4 Spring Stiffness
k_5	-	Axle 5 Spring Stiffness
K_a	-	Gain Parameter of the Body Lateral Acceleration Response
K_r	-	Gain Parameter of the Body Roll Angle Response
K_s	-	Lateral Stiffness Coefficient
K_u	-	Understeer Coefficient
L	-	Wheelbase Of The Vehicle
m	-	Total Mass
m_1	-	Tractor Mass
m_2	-	Semitrailer Mass
m_b	-	Sprung Mass
m_s	-	Body Mass
M_{z1l}	-	Tire Self-Aligning Moment at the Left Side of Axle 1
M_{z1r}	-	Tire Self-Aligning Moment at the Right Side of Axle 1
M_{z2l}	-	Tire Self-Aligning Moment at the Left Side Of Axle 2
M_{z2r}	-	Tire Self-Aligning Moment at the Right Side of Axle 2
M_{z3l}	-	Tire Self-Aligning Moment at the Left Side of Axle 3
M_{z3r}	-	Tire Self-Aligning Moment at the Right Side of Axle 3
M_{z4l}	-	Tire Self-Aligning Moment at the Left Side of Axle 4
M_{z4r}	-	Tire Self-Aligning Moment at the Right Side of Axle 4

M_{z5l}	-	Tire Self-Aligning Moment at the Left Side of Axle 5
M_{z5r}	-	Tire Self-Aligning Moment at the Right Side of Axle 5
M_{zh}	-	Hitch Self-Aligning Moment
N_d	-	No. of Dimensions
N_i	-	No. of Iterations
N_p	-	No. of Particles
p_{best}	-	Best Position Memory
R	-	Radius of Curvature of the Turn
r_1	-	Tractor Yaw Angle
$\dot{r}_1$	-	Tractor Yaw Rate
$\ddot{r}_1$	-	Tractor Yaw Acceleration
r_2	-	Semitrailer Yaw Angle
$\dot{r}_2$	-	Semitrailer Yaw Rate
$\ddot{r}_2$	-	Semitrailer Yaw Acceleration
r_h	-	Hitch Radius
R_ω	-	Wheel Radius
s	-	Social Coefficient
S_{a1l}	-	Tire Longitudinal Slip Ratio at the Left Side of Axle 1
S_{a1r}	-	Tire Longitudinal Slip Ratio at the Right Side of Axle 1
S_{a2l}	-	Tire Longitudinal Slip Ratio at the Left Side of Axle 2
S_{a2r}	-	Tire Longitudinal Slip Ratio at the Right Side of Axle 2
S_{a3l}	-	Tire Longitudinal Slip Ratio at the Left Side f Axle 3
S_{a3r}	-	Tire Longitudinal Slip Ratio at the Right Side f Axle 3
S_{a4l}	-	Tire Longitudinal Slip Ratio at the Left Side of Axle 4
S_{a4r}	-	Tire Longitudinal Slip Ratio at the Right Side of Axle 4
S_{a5l}	-	Tire Longitudinal Slip Ratio at the Left Side of Axle 5
S_{a5r}	-	Tire Longitudinal Slip Ratio at the Right Side of Axle 5
S_h	-	Horizontal Shift
S_v	-	Vertical Shift
T	-	Wheel Track
V	-	Vehicle Speed
v	-	Vehicle Speed
v_{2y}	-	Semitrailer Lateral Speed

v_{t1}	-	Tire Speed Of Axle 1
v_{t2}	-	Tire Speed of Axle 2
v_{t3}	-	Tire Speeds of xle 3
v_{t4}	-	Tire Speeds of Axle 4
v_{t5}	-	Tire Speeds of Axle 5
v_{wx1}	-	Longitudinal Wheel Speed of Axle 1
v_{wx2}	-	Longitudinal Wheel Speed of Axle 2
v_{wx3}	-	Longitudinal Wheel Speed of Axle 3
v_{wx4}	-	Longitudinal Wheel Speed of Axle 4
v_{wx5}	-	Longitudinal Wheel Speed of Axle 5
v_x	-	Longitudinal Velocity
v_{x1}	-	Tractor Longitudinal Speed
v_{x2}	-	Semitrailer Longitudinal Speed
v_y	-	Lateral Velocity
v_{y1}	-	Tractor Lateral Speed
Y_y	-	Constant for Tyre Camber Angle
α	-	Lateral Slip Angle
α_1	-	Tire Slip Angle At Axle 1
α_{1l}	-	The Tire Slip Angle at the Left Side Of Axle 1
α_{1r}	-	The Tire Slip Angle at the Right Side Of Axle 1
α_2	-	Tire Slip Angle at Axle 2
α_{2l}	-	The Tire Slip Angle at the Left Side Axle 2
α_{2r}	-	The Tire Slip Angle at the Right Side Of Axle 2
α_3	-	Tire Slip Angle at Axle 3
α_{3l}	-	The Tire Slip Angle at the Left Side Axle 3
α_{3r}	-	The Tire Slip Angle at the Right Side Of Axle 3
α_{4l}	-	Tire Slip Angle at the Left Side of Axle 4
α_{4r}	-	Tire Slip Angle at the Right Side of Axle 4
α_{5l}	-	Tire Slip Angle at the Left Side of Axle 5
α_{5r}	-	Tire Slip Angle at the Right Side of Axle 5
α_h	-	Hitch Slip Angle
β_1	-	Tractor Body Side Slip Angle
β_2	-	Semitrailer Body Side Slip Angle

γ	-	Tyre Camber Angle
δ	-	Steering Angle
$\dot{v}_{x1}$	-	Tractor Longitudinal Acceleration
$\dot{v}_{y1}$	-	Tractor Lateral Acceleration
$\dot{v}_{2x}$	-	Semitrailer Longitudinal Acceleration
$\dot{v}_{2y}$	-	Semitrailer Lateral Acceleration
δ_f	-	Front Wheel Steering Angle
δ_h	-	Hitch Articulation Angle
μ	-	Constant For Tyre Camber Angle
σ	-	Longitudinal Slip Ratio
ϕ	-	Body Roll Angle
ψ	-	Yaw Angle
ω_1	-	Tire Angular Velocity of Axle 1
ω_2	-	Tire Angular Velocity of Axle 2
ω_3	-	Tire Angular Velocity of Axle 3
ω_4	-	Tire Angular Velocity of Axle 4
ω_5	-	Tire Angular Velocity of Axle 5
$\dot{\phi}$	-	Roll Rate
$\ddot{\phi}$	-	Roll Acceleration
ϕ_s	-	Sprung Mass Roll Angle
ϕ_u	-	Axle Roll Angle

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CHAPTER 1

INTRODUCTION

1.1 Research Overview

In recent years, vehicle safety has been in the limelight of the automotive industry due to the high percentage of vehicle accident statistics. In 2015, the annual report of traffic safety by the United States' National Highway Traffic Safety Administration (NHTSA) (1) reported that 35,092 people lost their lives in an estimated of 6,296,000 vehicle accidents in the United States. In these accidents, 2,443,000 people were injured, and 4,548,000 crashes involved property damage. In 2010, the total loss due to vehicle accidents in the United States was estimated at 242 billion dollars. Meanwhile, a high percentage of vehicle accident statistics were also recorded in Malaysia. A Malaysia Transport Statistics 2016 (2) stated that there were 960,569 vehicles involved in an accident in 2016, causing the death of at least 7,152 victims.

Vehicle accidents can be caused by several significant factors and one of the factor is vehicle instability, which occurs when the driver is unable to control the vehicle whilst steering or braking actions. A vehicle rollover is one of the examples of instability phenomena. Rollover risk is increasing with the vehicle's dimensions and weights. Therefore, heavier commercial vehicles will have a higher risk of rollover due to its heavy weights, large size, high center of mass as well as high aspect ratio, and this has been a significant concern worldwide. Road accidents involving commercial vehicle rollovers have a significant impact on economic development, people's lives and property. Statistically, it has been reported in the United States that the rollover accidents contributed 12.4% from the total annual vehicle traffic fatality in 2015, which was an increase of 7.2% from the previous year (1). It was the most significant percentage increase within the past five decades. Moreover, the fatality rate of rollover accidents was found to be significantly higher compared to non-rollover cases. Therefore, to ensure the safe highway operation, active countermeasures and improvement for rollover crashes are the priority to be performed. Consequently, significant research related to the detection, early warning, and prevention of impending rollovers are required to improve vehicle safety on roll motions.

The vehicle's safety performance of the roll motion can be improved by using an early warning signal for an impending rollover. The early warning signal for an impending rollover can be generated by the vehicle rollover warning system. This is to assist the driver to perform a corrective manoeuvre within the proper time. In most cases, the corrective manoeuvre implemented by the driver was restricted to the braking or steering adjustment in order to prevent the roll instability. Time delay happens between the moment when the warning is delivered to the driver and the moment when braking force is generated on the road wheels. The roll instability may occur to the vehicle if the lead time provided by the early warning signal is insufficient to develop braking force. The practicality and effectiveness of a roll instability early warning device depend on the lead-time provided by the warning signal and the ability of impending rollover indicators to generate an early warning. For that reason, the effectiveness of an early warning should be investigated by deploying the dynamic vehicle's responses.

1.2 Problem Statement

The research on the rollover warning systems for commercial vehicles is mainly motivated by severe highway accidents involving a rollover. According to the Large Truck and Bus Crash Facts 2015, it is reported that 12.3% of fatal truck accidents were due to rollovers (3). Rollover also contributed to a 9.9% of injury crashes and 7.9% of tow-away accidents (4–6). Rollover is also strongly associated with severe injuries to the truck driver. In another report by NHTSA, 58% of total injuries to truck drivers are United State tractor-semitrailer accidents involved rollover crashes for 2011-2015 (1). In addition, a report from NHTSA Traffic Safety Fact in 2015 stated that accidents involving combination trucks made up 74% of the total 4,050 fatal crashes involving large trucks (1). Therefore, a combination truck is considered in this study, and its safety features will be enhanced to ensure the safety of drivers and other road users.

Due to the high rate of accidents involving commercial vehicles, a lot of researches on vehicle rollover have been conducted by introducing a variety of rollover evaluation and early warning algorithms. A rollover monitoring and warning algorithm with lateral acceleration was proposed by Rakheja and Piche (7), which will warn if the rollover index value exceeds a critical threshold, which was set to be rollover index value when wheels are about to lift-off. Meanwhile, Chen and Peng (8) proposed a real-time rollover warning algorithm using a lateral acceleration to predict the Time-To-Rollover. However, this approach has raised issues on the practicalities of the algorithm, where it will be subjected to certain restrictions when the rollover threshold will be different depending on specific vehicle models. Furthermore, it is observed that the rollover evaluation and early warning algorithms used the vehicle output responses such as lateral acceleration as an input data for rollover indices. While lateral acceleration can be a good indication of any rollover indices, it can be too late for the driver to perform the corrective actions since the excessive lateral acceleration means the rollover has already happened. Meanwhile, the lateral load transfer ratio (LTR) has been utilized by several researchers to analyse vehicle rollover stability (9–12). The LTR algorithm was practical and straightforward for real-time implementation. Therefore, it becomes the most widely used indicator of a vehicle rollover working condition (13, 14). Several researchers (10–12, 15, 16) established the rollover index algorithm based on the LTR. Due to the stability and influence of the parameters to the vehicle system, the rollover index algorithm proposed by the previous researchers (17–20) are chosen in this study to be analysed and modified in order to improve the rollover index time responses.

Several of the main factors that are causing vehicle rollover conditions are the vehicle type, load position, and the torsional stiffness of the trailer (21, 22). In flatbed trucks, a torsionally flexible trailer with poor roll feedback to the driver has become a significant issue in vehicle rollover action. The tractor has a relatively low center of gravity height and the small tractor roll motion almost separates the driver from the trailer. This condition is causing the driver to be unaware of the trailer rollover instability and unable to take immediate corrective action. According to Malaysia road accident factors in 2011 as shown in Figure 1.1 by Malaysian Institute of Road Safety Research (MIROS), the factors contributing to the road accidents in Malaysia are 80.6% due to human error, 13.2% due to road conditions while vehicle condition contributes only 6.2% (23). Therefore, in this study, the driver's sensitivity to the vehicle rollover instability is improved by proposing the early indication to increase driver awareness and providing sufficient time to the driver to perform corrective action.

Figure 1.1 Malaysia road accident factors in 2011 (23)

The early warning indicator system can be developed by considering an accurate commercial vehicle model for a tractor-semitrailer vehicle. The tractor-semitrailer model is developed to simulate the real vehicle response. Previously, several tractor-semitrailer models have been developed by several researchers, however, there is a limitation in the models (10, 24, 25). The limitation identified in the tractor-semitrailer model is on the hitch joint using fifth wheel coupling which connects the tractor and semitrailer where it represents the dynamic response only. The dynamic response does not totally represent the non-linear characteristics of the fifth wheel (10, 22, 25). Therefore, an accurate fifth wheel coupling model is essential due to the fifth wheel is practically connecting the tractor and semitrailer. A non-parametric model for hitch joint is one of the approach to produce the accurate fifth wheel coupling responses compared to parametric model. This is because the non-parametric model is specifically derived to produce the accurate fifth wheel coupling responses. Thus an accurate consideration of forces and moments transmitted between the tractor and semitrailer will produce accurate vehicle response for the early warning indicator system.

The main novelty of this research is in the development of a new model for the hitch joint of a tractor-semitrailer using a virtual Pacejka tire model approach and improving the early warning indication of a rollover to the driver. Among previous works (26–30), research on the fifth wheel has been limited especially in replacing the fifth wheel with a virtual Pacejka tire model while establishing the tractor-semitrailer model. In the meantime, the rollover index algorithm is proposed by including the steering input and vehicle speed responses in the rollover index algorithm. In previous works (17–20), the rollover index algorithms were established based on the vehicle output responses such as lateral acceleration. By using the vehicle output responses as an input for rollover warning analysis, the resulting response time is too late for the driver to perform any correction manoeuvre. This is observed during the rollover warning analysis, there is excessive lateral acceleration where rollover has already occurred. Since the acceleration itself was caused by steering input or any disturbance to the vehicle, this study will be proposing a new approach by using steering input and vehicle speed responses to determine the state of rollover for the vehicle. Therefore, this can improve the early warning indication and time to respond will be faster. Significantly, the driver has sufficient time to perform the corrective action.

1.3 Research Objectives

The main aim of this study is to develop a rollover warning system for tractor-semitrailer. Several objectives have been drawn in order to achieve this main aim along the process of completing this study. They are:

(a) To develop and validate a tractor-semitrailer dynamic model with a new non-parametric model of hitch joint.

(b) To modify the Odenthal rollover index algorithm for the tractor-semitrailer rollover warning algorithm.

(c) To optimize the parameters of the modified Odenthal rollover index algorithm for the tractor-semitrailer to improve the rollover warning indication.

1.4 Research Scope

Based on the research objectives, the scopes of this study are defined as the following:

(a) The tractor-semitrailer is developed based on 16 degree-of-freedom vehicle model.

(b) The tractor and semitrailer is modelled with a new non-parametric model of hitch joint using a virtual Pacejka tire model.

(c) The parameters of the tractor-semitrailer model are obtained based on Heavy Truck Manufacturer.

(d) Three handling manoeuvring tests are performed in this study, namely step steer cornering, single lane change and double lane change tests to investigate the tractor-semitrailer responses.

(e) The verification and validation of the tractor-semitrailer model is conducted using the multi-body dynamics modelling software known as TruckSim and the results from the published data.

(f) The rollover index algorithm is developed based on the fastest time response proposed by the previous researchers.

(g) The selected rollover index algorithm is modified in order to improve the performance of the rollover warning system.

(h) The rollover index algorithm for the tractor-semitrailer is proposed by employing a modified rollover index algorithm with driver steering and vehicle speed inputs optimised using Particle Swarm Optimisation (PSO).

(i) The performance of the proposed rollover index algorithm is evaluated through the experiment.

1.5 Research Methodology

The study starts with a literature review stage. Previous works on the rollover warning systems are reviewed in order to familiarise with the overall research framework and identify the research gaps in the field. Several areas are investigated within the research scopes including vehicle model used, classification of commercial freight vehicles, rollover index algorithms, and experimental procedures. This process is repeated throughout overall research in order to ensure the knowledge is still valid.

A vehicle model is developed at the beginning of the study to simulate tractor-semitrailer behaviour in the lateral direction. A precise and accurate model for the tractor-semitrailer is important in developing the rollover warning system. This study starts with the modelling of the mathematical model of tractor-semitrailer using a kinematics equation of motion. In establishing the model, a new approach is proposed by adopting a virtual Pacejka tire model in modelling the hitch joint of the tractor-semitrailer. The virtual Pacejka tire model is included in a 16 degree-of-freedom (DOF) tractor-semitrailer to connect between tractor and trailer. The responses of the tractor-semitrailer model were verified using software known as TruckSim and validated with results from the published data.

The rollover index algorithm is derived after the vehicle model validation process. Several types of tractor-semitrailer rollover index proposed by previous researchers are considered in the derivation process. The best rollover index with the fastest response time is selected. Roll safety factor (RSF) of 75% is used to choose the fastest rollover index. The RSF is identified as the most reliable indicator, which relates directly to the relative roll instability condition (27, 31). The step steer cornering simulation with various speeds is conducted by using TruckSim to obtain the rollover index. The selected rollover index is then modified to optimize the performance in terms of Time-To-Warn (TTW). TTW is the time produced by the rollover index to provide an early warning response to the driver due to the vehicle instability motion. Particle Swarm Optimisation (PSO) is performed to obtain the optimum parameters that optimize the performance of the modified rollover index.

Finally, the tractor-semitrailer model and rollover warning system are combined and the performance of the rollover index algorithm is evaluated by experimental work using Hardware-in-the-Loop (HIL) simulation with TruckSim driving simulator and MATLAB/Simulink. The research flow and methodology were undertaken in this study is shown in Figure 1.2.

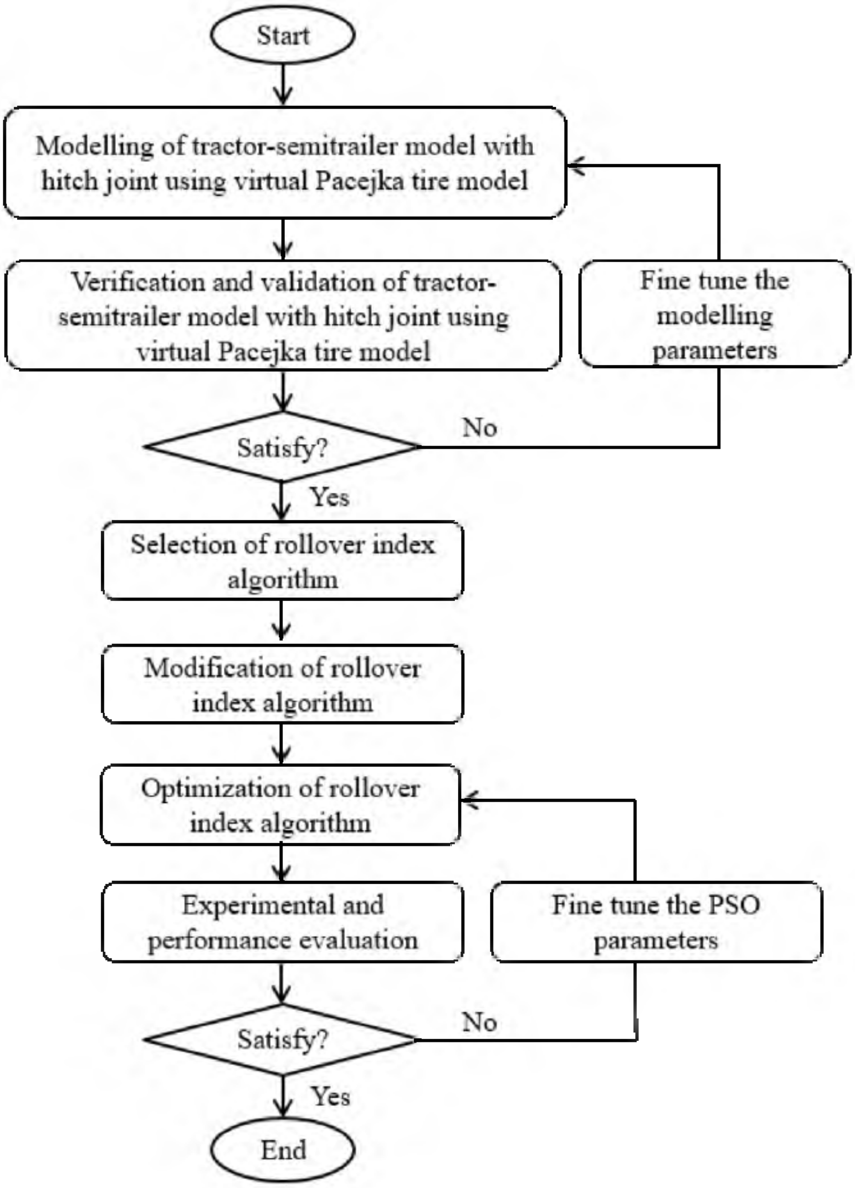

Figure 1.2 Research flow and methodology were undertaken in this study

1.6 Research Contributions

The purpose of this research is mainly to enhance the tractor-semitrailer safety features by proposing a new approach in modelling of hitch joint of a tractor and semitrailer and improving the early warning indication of the rollover instability to the driver. The new approach in modelling of hitch joint of a tractor-semitrailer is proposed by adopting a virtual Pacejka tire model. The virtual Pacejka tire model is to be accurately similar to the fifth wheel coupling characteristics, where it accommodates loads and rotates on its axis. Meanwhile, in this study, the new rollover index algorithm proposed, particularly involves the response from steering wheel angle and vehicle speed which is to be more accurate and able to reduce the processing time. This will provide the fastest Time-To-Warn (TTW) to the driver and excess Time-To-Respond (TTR). Significantly, the driver has ample time to perform the corrective action to avoid the rollover condition. This approach will eventually minimize the sensors required which will consequently reduce the cost of the rollover indication system. As such, vehicle accident statistics will be reduced.

1.7 Structure and Layout of the Thesis

This thesis consists of six chapters. Chapter 1 is the introductory chapter, which presents the research overview, problem statement, research objectives, research scopes, research methodology, summary of research contribution and the overall outline of this thesis. The remainder of this thesis is organized as follows:

Chapter 2: This chapter presents reviews of past literature on topics that are related to this study. The topics include classification of freight vehicle, hitches mechanism, articulated heavy vehicle dynamics model and a concept in early warning indication. The previous work on rollover index were also reviewed in this chapter. Finally, the research gaps that have been identified and potential research direction is presented.

Chapter 3: The research procedures related to the development of the mathematical model of tractor-semitrailer with a new approach in modelling of hitch joint using the virtual Pacejka tire model are introduced in this chapter. The tractor-semitrailer with a new approach in modelling of hitch joint using virtual Pacejka tire model equations is derived in this study and modelled in MATLAB/Simulink software. The developed tractor-semitrailer with fifth wheel using virtual Pacejka tire model is verified using TruckSim for double lane change and step steer cornering tests and validated with the results from the published data for single lane change and step steer cornering tests. The results of the verification and validation are discussed in this chapter.

Chapter 4: In this chapter, the selection of the tractor-semitrailer rollover index algorithm is performed based on the early warning indication is detailed. The response of several rollover index algorithms proposed by the previous researchers are simulated by using the tractor-semitrailer model in MATLAB/Simulink software. From the simulation, the fastest rollover index algorithm proposed by the Odenthal is identified. The effect of varying vehicle conditions to the Odenthal rollover index performance for tractor-semitrailer is studied. The effect of varying speeds, steering inputs and load conditions to the Odenthal rollover index are discussed. Then, the Odenthal rollover index algorithm is modified in order to optimize the rollover index response. The sensitivity analysis is conducted on the parameters of the modified Odenthal rollover index algorithm which are K_a and K_r to produce the fastest response of Time-To-Warn (TTW). The range of K_a and K_r obtained from sensitivity analysis are used as the initial values for parameter optimisation analysis using Particle Swarm Optimisation (PSO).

Chapter 5: In this chapter, the modified Odenthal rollover index algorithm integrated with vehicle speed and steering inputs is introduced. The Particle Swarm Optimisation (PSO) is used to optimize the parameters of the modified Odenthal rollover index algorithm integrated with vehicle speed and steering inputs. The experimental evaluation on the modified Odenthal rollover index algorithm using vehicle speed and steering inputs is presented to evaluate the performance of the proposed rollover index algorithm. The performance evaluation of the modified Odenthal rollover index by incorporating vehicle speed and steering inputs with varying load conditions are discussed in this chapter.

Chapter 6: Finally, this chapter summarises the works done in this entire study, providing conclusions and some recommendations for future research works.

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LIST OF PUBLICATIONS

Journal with Impact Factor

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2. **Hafiz Harun, M.**, Hudha, K., Samin, P. M., Abu Bakar, S. A., Amer, N. H. and Kadir, Z. A. (In Press). A Modified Odenthal Rollover Index Algorithm for Tractor-Semitrailer using Steering and Vehicle Speed Inputs. International Journal of Heavy Vehicle Systems, Inderscience, pp. 1-22. **(Q2, IF: 0.915)**

Indexed Journal

1. **Harun, M.H.**, Hudha, K., Samin, P.M., Bakar, S.A.A. and Ubaidillah, U. (2020). Stability and Roll Effect of the Straight Truck Suspension System. *Journal of Advanced Manufacturing Technology*, Vol. 14, No.1, pp. 89-100. **(Indexed by SCOPUS)**

2. **Hafiz Harun, M.**, Hudha, K., Samin, P. M. and Abu Bakar, S. A. (Under Review). Tractor-Semitrailer Rollover Index Selection Based on Early Warning Indication. *International Journal of Engineering Systems Modelling and Simulation,* Inderscience, pp. 1-9. **(Indexed by SCOPUS)**

3. **Hafiz Harun, M.**, Hudha, K., Samin, P. M., Bakar, S. A. A., Amer, N. H. and Kadir, Z. A. (Under Review). Investigation on the Effect of Varying Vehicle Conditions to the Rollover Warning System Performance for Tractor-Semitrailer. *Journal of Mechanical Engineering and Sciences*, pp. 1-13. **(Indexed by SCOPUS)**

Indexed Conference Proceedings

1. **Hafiz Harun, M.**, Samin, P. M., Hudha, K., Bakar, S. A. A. and Md Saad, A. (2019). Modelling and Verification of Tractor Ride Model. In *IOP Conference Series: Materials Science and Engineering,* Vol. 469, No. 1, pp. 1-10. **(Indexed by SCOPUS)**

Patent

1. Khisbullah Hudha, **Mohamad Hafiz Harun**, Zulkiffli Abd Kadir, Noor Hafizah Amer, Pakharuddin Mohd Samin, Saiful Anuar Abu Bakar. Rollover Warning System for Heavy Vehicle using Modified Odenthal Rollover Index Algorithm. **(Patent Search)**

Invention and Innovation Awards

1. Khisbullah Hudha, **Mohamad Hafiz Harun**, Zulkiffli Abd Kadir, Noor Hafizah Amer, Mohd Sabirin Rahmat, Muhammad Luqman Hakim Abdul Rahman, Muhammad Akhimullah Subari. Rollover Warning System for Heavy Vehicles. Malaysia Technology Expo 2020. **(MTE 2020 Silver Award)**