DEVELOPMENT OF SIMPLIFY VEHICLE MODEL TO REPRESENT MULTIPLE AXLES WHEELS

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A thesis submitted
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I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Mechanical Engineering Technology (Automotive Technology) with Honours.

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Supervisor Name : Ts. Dr. Muhammad Zaidan Bin Abdul Manaf

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DEDICATION

Firstly, I dedicate to my family and friends, whose unwavering support and encouragement have been a constant source of inspiration.

To my parents for their endless love, patience, and faith in me. Your sacrifices and guidance have paved the way for my achievements.

To my friends, who have always been there to cheer me on and provide the much-needed motivation during challenging times.

Lastly, I would like to dedicate this work to my supervisor, Ts. Muhammad Zaidan Bin Abdul Manap, whose invaluable guidance and support have been instrumental in the completion of this project.

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ABSTRACT

This study provides a comprehensive analysis of the development of a simplified vehicle model designed to represent multiple-axle trucks. It specifically addresses the complexities associated with axle load distribution and dynamic modeling. The dynamics of trucks with multiple axles can be particularly intricate due to an increase in the number of degrees of freedom (DOF), which complicates calculations essential for load distribution and stability assessments. To address these challenges, this research proposes a method that condenses multiple axles into a single-axle model. This simplification is achieved through the implementation of summation methods and precise calculations of moment arm locations, thereby clarifying the model's structure and improving its functionality. The validation of the model was conducted through extensive simulations of acceleration and braking using TruckSim. These simulations examined various conditions, particularly focusing on speed ranges of 60 km/h, 80 km/h, and 100 km/h. The results demonstrated that the simplified two-axle model effectively approximates the dynamics of a three-axle truck, exhibiting minimal errors following the application of tuning values. This finding underscores the model's reliability. This innovative approach significantly reduces the computational complexity traditionally associated with multi-axle truck modeling while maintaining a high degree of accuracy. Consequently, it facilitates enhanced vehicle design and performance optimization. Future research is recommended to extend the model's applicability by incorporating more complex multi-trailer systems and conducting tests under diverse road conditions. Such endeavors would enrich the understanding of vehicle dynamics in real-world applications, contributing to improvements in truck design and safety.

ABSTRAK

Kajian ini menyediakan analisis komprehensif tentang pembangunan model kenderaan ringkas yang direka untuk mewakili trak berbilang gandar. Ia secara khusus menangani kerumitan yang berkaitan dengan pengagihan beban gandar dan pemodelan dinamik. Dinamik trak dengan berbilang gandar boleh menjadi sangat rumit disebabkan oleh peningkatan dalam bilangan darjah kebebasan (DOF), yang merumitkan pengiraan yang penting untuk pengagihan beban dan penilaian kestabilan. Untuk menangani cabaran-cabaran ini, penyelidikan ini mencadangkan kaedah yang memekatkan berbilang gandar menjadi model gandar tunggal. Penyederhanaan ini dicapai melalui pelaksanaan kaedah penjumlahan dan pengiraan tepat lokasi lengan momen, dengan itu menjelaskan struktur model dan menambah baik fungsinya. Pengesahan model telah dijalankan melalui simulasi pecutan dan brek yang meluas menggunakan TruckSim. Simulasi ini mengkaji pelbagai keadaan, terutamanya memfokuskan pada julat kelajuan 60 km/j, 80 km/j dan 100 km/j. Keputusan menunjukkan bahawa model dua gandar yang dipermudahkan secara berkesan menghampiri dinamik trak tiga gandar, menunjukkan ralat minimum berikutan penggunaan nilai penalaan. Penemuan ini menekankan kebolehpercayaan model. Pendekatan inovatif ini dengan ketara mengurangkan kerumitan pengiraan yang dikaitkan secara tradisi dengan pemodelan trak berbilang gandar sambil mengekalkan tahap ketepatan yang tinggi. Akibatnya, ia memudahkan reka bentuk kenderaan yang dipertingkatkan dan pengoptimuman prestasi. Penyelidikan masa depan disyorkan untuk memanjangkan kebolehgunaan model dengan menggabungkan sistem berbilang treler yang lebih kompleks dan menjalankan ujian di bawah keadaan jalan yang pelbagai. Usaha sedemikian akan memperkayakan pemahaman tentang dinamik kenderaan dalam aplikasi dunia sebenar, menyumbang kepada penambahbaikan dalam reka bentuk dan keselamatan trak

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LIST OF SYMBOLS AND ABBREVIATIONS

F	-	Force
x	-	Longitudinal
z	-	Vertical
R	-	Radius
CG	-	Center of gravity
H, h	-	Height
$a, \ddot{x}$	-	Acceleration
$\emptyset, \theta$	-	Angle
m, M	-	Mass
g	-	Gravity
A, B, C, D, a, b, c, d	-	Distance
ω	-	Angular velocity
W	-	Weight/load
L	-	Length

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CHAPTER 1

INTRODUCTION

1.1 Background

The precise modelling of semitrailers within the field of transportation engineering is vital for optimizing vehicle performance, ensuring road safety, and enhancing the efficiency of freight transportation systems. Trucks, predominantly utilized for long-distance goods transportation, typically incorporate multiple axles to distribute the payload effectively and adhere to weight regulations. However, modelling the dynamics associated with multi-axle trucks poses considerable challenges due to the intricate interactions among various components, including axles, wheels, suspension systems, and cargo.

Every vehicle has an axle load. Axle load refers to the weight supported by a single axle of a vehicle. Axle load is typically measured in units of force, such as pounds (lbs), kilograms (kg), or Newton(N) and it represents the total weight exerted on the road surface by all the wheels attached to a single axle of a vehicle. Axle load is critical in safeguarding the structural stability of roads, bridges, and other vital transportation infrastructure. Elevated axle loads can accelerate the degradation of road surfaces, contribute to pavement deterioration, and pose a risk of causing structural harm to bridges.

Figure 1.1 3-axle straight truck

Figure 1.2 2-axle straight truck

Mostly, every truck has multiple axles due to improved weight distribution, compliance with regulations, protection of infrastructure, enhanced safety, and greater versatility in hauling different types of cargo. It will be difficult to calculate the axle load since every axle on the truck will need to be calculated. It will be more complex if the truck contains more axles because it will have many Degrees of Freedom (DOF). Figure 1.1 shows that the truck has 3 axles containing 6-DOF rotational motion of each tire. Unlike Figure 1.2, the truck only has 2 axles, which is equivalent to the 4-DOF rotational motion of each tire. The less DOF, the easier to calculate axle load. Therefore, the objective is to simplify the multiple-axle equation into a single-axle load equation.

Thus, getting truck models right is important for making trucks work well and keeping roads safe. However, figuring out how to model a truck with many axles can be tricky. Axle load, which is how much weight each axle carries, is important for keeping roads and bridges strong. Since most trucks have many axles to spread the weight, figuring out how much each carry is tough. So, making a simple way to calculate axle loads is key. It'll help engineers, researchers, and people in charge of transportation make better choices to make trucks work better and keep everyone safe on the road.

1.2 Problem statement

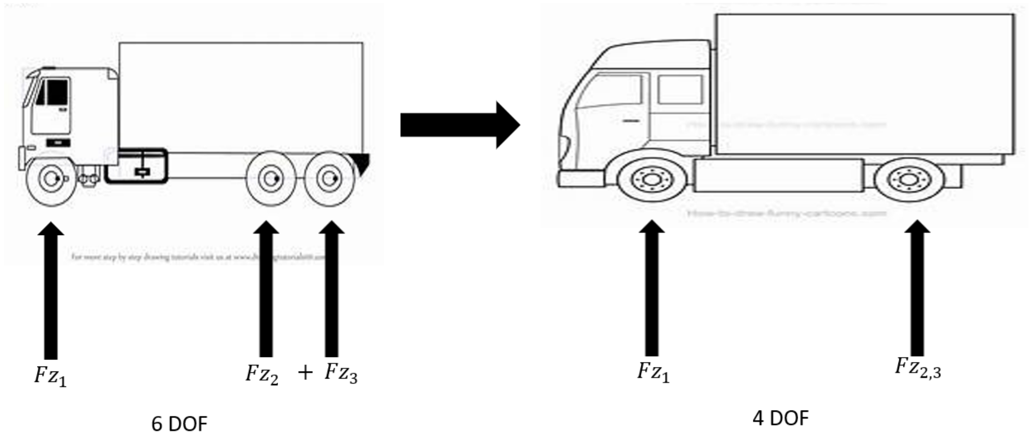

Figure 1.3 Simplify 2-axle to single-axle

Axle load distribution refers to how the total weight of a vehicle is spread across its various axles. This distribution is critical for vehicle stability, handling, safety, and compliance with road regulations. Axle load determination becomes complicated for trucks because most trucks contain more than two axles. When a truck has more axles, more degrees of freedom (DOF) must be considered when calculating. The equation also became more complex. Figure 1.3 shows a truck that has two axles at the rear (Fz_2 and Fz_3) that need to be simplified so that it will be represented by a single axle ($Fz_{2,3}$). When the axles are simplified, the DOF is reduced, and the equation of motion is simpler.

1.3 Research objective

The main aim of this research is to simplify a single-axle truck to represent a multiple-axle truck. Specifically, the objectives are as follows:

i. To develop and verify the load distribution model of rear multi-axle heavy vehicles.

ii. To develop a new method to simplify the rear multi-axle into a single rear axle heavy vehicle.

iii. To verify the load distribution of multi-axle with single-axle rear vehicles using industrial standard simulation software.

iv. To conduct acceleration and braking tests using industry-standard simulation software.

1.4 Scope of work

i. To study the axle configuration of trucks.

ii. To derive the load distribution equation from 3-axle and 2-axle trucks.

iii. To determine the axle load of both rear tires on the 3-axle truck model.

iv. To do a summation of force on the vertical force acting on both rear tires of the 3-axle truck model.

v. To determine the location of the moment arm of the rear tire 2-axle truck model.

vi. To run the acceleration test using TruckSim.

vii. To compare the result of vertical force between the 3-axle and 2-axle trucks.

viii. To determine the tune value for each condition.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In vehicle dynamics, the simplification of multi-axle truck models into single-axle representations is a crucial area of research. This approach reduces computational complexity while preserving the vehicle's fundamental performance features. The main objective is to use simplified models to accurately predict dynamic behavior and load distribution and define axle configuration for various vehicle classifications.

2.2 Background

The trucking industry heavily depends on trucks for the long-haul delivery of goods. It is essential to manage load distribution within these trucks effectively to enhance safety, improve fuel efficiency, and reduce wear on the vehicles. Historically, truck designs have employed single axles; however, the rising need for greater load capacities and better load distribution has resulted in a significant shift toward multiple-axle setups. One innovative method that has gained attention involves simplifying single axles to mimic the functionality of multiple axles. This approach has the potential to improve load distribution without requiring significant alterations to current truck designs.

2.2.1 Previous Studies on Axle Simplification

The simplification of truck axles has emerged as a significant focus within the fields of engineering and design. Prior research on axle simplification serves as a foundational basis for the advancement of simplified vehicle models that can effectively represent multiple-axle systems. (Gao & Sha, 2012) The analysis of vertical load distribution within structural elements underscores the importance of employing simplified models to depict internal force mechanisms accurately. This accuracy is critical for the effective distribution of multi-axle loads in vehicles. Researchers have explored innovative methods such as virtual axle replication, where single axles are modeled to mimic the behavior of multiple axles through advanced simulation techniques. These studies have shown that accurately predicting load distribution dynamics can lead to optimal performance with fewer physical axles, potentially reducing complexity and cutting costs in truck manufacturing and operation (D. Zhou & Chang, 2022). Furthermore, materials science and structural engineering advancements have enabled the development of lighter yet stronger axle components, further contributing to the pursuit of axle simplification.

2.2.2 Impact of Regulations on Axle Configurations

Regulatory frameworks have played a pivotal role in shaping axle configurations for commercial trucks. Government regulations regarding axle weights, spacings, and vehicle dimensions significantly influence truck design and configuration. Over time, changes in regulatory requirements have impacted the evolution of axle configurations, compelling manufacturers to innovate and adapt to meet compliance standards while enhancing performance and efficiency.

For example, regulations aimed at reducing environmental impact and improving road safety have driven advancements in axle designs that prioritize fuel efficiency, load distribution, and vehicle stability (Pushka & Regehr, 2021). Likewise, regulations governing axle weight limits have spurred the exploration of axle simplification strategies to maximize payload capacity while ensuring adherence to legal requirements. As regulatory landscapes evolve, so will axle design and optimization trajectory in commercial trucking.

2.3 Vehicle classification

Vehicle classification is the method used to categorize vehicles into different classes or categories based on various attributes and criteria. This process is vital for regulatory compliance, toll collection, traffic management, safety regulations, and market analysis. The common criteria for vehicle classification include purpose and use, body type, size and weight, fuel type, axle configuration, regulatory categories, and market segments. The main purpose of this study is to identify vehicle classification based on axle configuration by referring to Federal Highway Administration (FHWA) vehicle classifications, as shown in Figure 2.1.

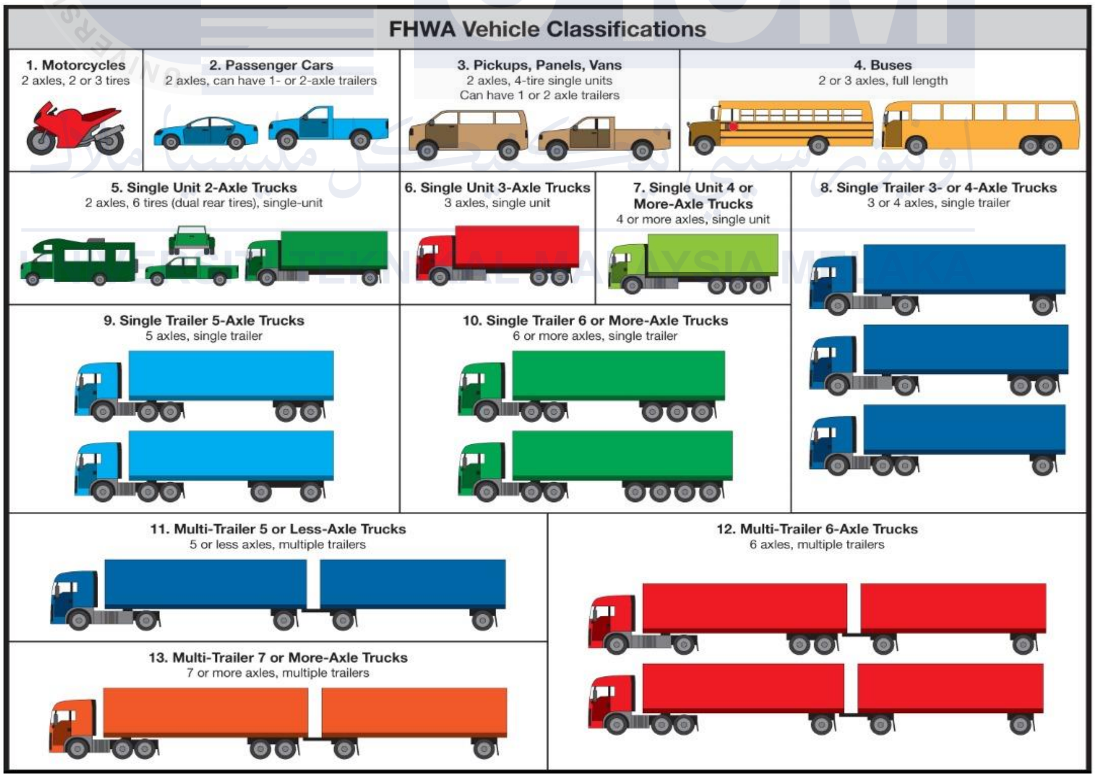

Figure 2.1 Federal Highway Administration (FHWA) vehicle classification

2.3.1 Motorcycles

Motorcycles with 2 axles at the front and rear that hold 1 tire for each axle. However, there is also a motorcycle with 3 tire configurations, as shown in Figure 2.2. Motorcycles are often used in transportation, especially in cities where traffic congestion is a major issue.

Figure 2.2 Yamaha Niken with 3 tires configurations

Motorcycles exhibit numerous advantages over automobiles, particularly in terms of fuel consumption. They are a more economical mode of transportation, a fact that becomes even more pronounced in the case of electric motorcycles. These vehicles demonstrate a decreased potential to contribute to climate change and offer significant cost benefits when powered by renewable energy sources (Cox & Mutel, 2018). Motorcycles are smaller and more maneuverable than cars, making it easier for riders to navigate through traffic and find parking in urban areas with heavy traffic congestion (Wigan, 2002). However, riding motorcycles is riskier than driving other vehicles, with a higher likelihood of accidents and fatalities. Studies show that certain types of motorcycles, such as supersport motorcycles, have much higher rates of rider deaths than other types, largely due to risky behaviors like speeding (Teoh & Campbell, 2010).

2.3.2 Passenger car

Figure 2.3 Mercedes SUV-type passenger car

Passenger cars with two axles and two tires on each axle. Passenger vehicles, as shown in Figure 2.3, commonly known as cars, play a pivotal role in facilitating personal transportation owing to their inherent convenience and adaptability. These vehicles constitute an indispensable component of daily life across various global locales, empowering individuals to traverse distances independently and efficiently. Passenger cars give people personal freedom and convenience. They let you travel whenever and wherever you want, without having to depend on public transport schedules. This flexibility is important for people with busy or irregular schedules. However, Passenger cars have a big impact on the environment, mainly because they produce carbon dioxide, which is a major cause of climate change. In 2013, passenger cars were responsible for about 8.7% of global energy-related CO_2 emissions. Dealing with this environmental issue requires significant actions to achieve sustainability goals (Hao et al., 2016).

2.3.3 Pickup trucks and vans

Figure 2.4 Ford pickup trucks

Pickup trucks and vans usually have two-axle configurations, as shown in Figure 2.4. They are widely used for both personal and commercial purposes and perform a variety of tasks, including transportation of goods, recreational activities, and utility services. One of the primary strengths of pickup trucks and vans lies in their multifunctionality and practicality. These vehicles are designed to tackle varied tasks, from hauling hefty loads and gear, to acting as portable offices. This versatility makes them a critical asset for both businesses and individuals seeking a vehicle capable of efficiently executing diverse roles (Maria Kockelman Yong Zhao & Maria Kockelman, n.d.). Pickup trucks and vans can be more dangerous in accidents, especially for people in smaller cars. When cars crash into these larger vehicles, those in the smaller cars are more likely to be seriously hurt or killed. This is because the larger vehicles are heavier and have stronger structures. So, safety is a big concern when these vehicles are in accidents (Ossiander et al., 2014).

2.3.4 Buses

Figure 2.5 2-axle school bus

There are two types of buses: 2-axle configurations and 3-axle configurations. As shown in Figure 2.5, buses are a critical component of public transportation systems worldwide, providing an essential service for urban and rural communities. They help reduce traffic congestion, lower emissions per passenger, and offer a cost-effective mode of transportation. Buses, especially electric buses, significantly reduce greenhouse gas emissions and improve urban air quality. This transition helps decrease the overall carbon footprint and enhances the sustainability of urban transportation systems. Electric buses face operational challenges because they have a limited range and require significant time for charging. These challenges require large infrastructure investments and can cause operational inefficiencies (B. Zhou et al., 2016).

2.3.5 Single-unit trucks

Figure 2.6 (a) 2-axle single-unit trucks, (b) 3-axle single-unit trucks, (c) 4-axle single-unit trucks.

A single-unit truck has three axle configurations: 2 axles, 3 axles, and 4 axles, as shown in Figure 2.6. Single-unit trucks, vehicles on a single frame with at least two axles and six tires or a gross vehicle weight greater than 10,000 lb, are commonly used for commercial purposes such as local delivery and short-haul transportation. The more axles it has, the more load it can hold. These trucks are important in many industries because they are flexible and have a large capacity (Winebrake et al., 2015). Single-unit trucks are a highly favourable choice for businesses in transporting goods over relatively short distances. These trucks are more economical to operate than larger combination trucks, particularly in short-haul and local delivery scenarios. The design and size of single-unit trucks make them particularly efficient for navigating urban areas and making deliveries within towns or cities. Their manoeuvrability, fuel efficiency, and lower operational costs make them an optimal choice for businesses with localized transportation requirements.

2.3.6 Single trailer trucks

Figure 2.7 Single trailer truck

Single-trailer vehicles as illustrated in Figure 2.7, are widely utilized in logistics and transportation because they carry substantial volumes of goods across extended distances. Typically, these vehicles comprise a truck tractor with a single trailer attached, striking an optimal balance between the ability to carry hefty loads and maneuverability (Elmer et al., 2014). A common setup for lighter loads and good maneuverability is a 3-axle configuration, with two axles on the tractor and one on the trailer. For heavier loads and long-distance transport, the 5-axle setup is commonly used. This setup includes two axles on the tractor and three on the trailer, providing better load distribution and stability. Single-trailer vehicles are highly cost-effective due to their ability to reduce the number of trips, resulting in lower operational costs and fuel consumption. This makes them an ideal choice for long-haul transportation.

Figure 2.8 A multi-trailer truck

However, some trucks can also carry more than a single trailer, known as multi-trailer trucks, also called road trains, as shown in Figure 2.8, which are an important part of the transportation and logistics industry. They consist of a strong tractor truck pulling multiple trailers, making them highly efficient for transporting large amounts of goods over long distances. These trucks are especially useful in large ports and distribution centers for moving containers between different yards, which helps to streamline operations and reduce the need for multiple trips by single-trailer trucks. Carrying multiple trailers at once significantly improves how efficiently they work and lowers overall transportation costs (Tschöke & Boysen, 2017).

2.4 Load distribution in trucks

Load distribution involves allocating or spreading weight across a vehicle, structure, or system designed to carry loads. In trucks or other heavy vehicles, load distribution specifically refers to how weight is distributed among the vehicle's axles, wheels, and sections. Distribution of load in trucks is paramount due to its significant implications for various aspects such as safety, vehicle stability, fuel efficiency, and maintenance costs.

2.4.1 Importance of accurate load distribution

Accurate load distribution is crucial for the longevity and safety of pavement structures, as it ensures that the pavement can endure the stresses imposed by vehicular traffic over its intended lifespan. Incorrect load assessments can lead to uneven stress distribution, causing premature failures such as cracking, rutting, and potholing, which significantly increase maintenance costs. By understanding how loads are distributed across different axle configurations, engineers can design more resilient pavements with optimized layer thickness and materials, enhancing the structural integrity and durability of the pavement. Accurate load distribution models are essential for predicting pavement performance under various loading conditions, thereby preventing early deterioration and ensuring sustained pavement quality (Homsi et al., 2011).

2.4.2 Factors affecting load distribution

Load distribution in pavements is influenced by various critical factors, including vehicle weight, speed, road conditions, and axle configurations. The vehicle's weight determines the magnitude of the load applied to the pavement, and higher weights typically result in greater stress on the pavement structure(Assogba et al., 2020). Table 2.1 shows the impact of vehicle load on axle weight.

Table 2.1 Table of test truck axles weight measured contact surface and pressure under various loading conditions (Assogba et al., 2020).

Side	Tire contact Surface (cm²)				Contact Pressure (MPa)				Axle Weight (kN)
	Left		Right		Left		Right		—
Test truck axles weight, measured contact surface and pressure under Empty truck load									
Tire position	1		2		1		2		—
Front axle	276		238		0.98		1.13		54.80
Tire position	1	2	1	2	1	2	1	2	—
Rear first axle	165	171	103	121	0.70	0.67	1.12	0.95	46.83
Rear second axle	274	274	239	267	0.42	0.42	0.48	0.43	46.83
Test truck axles weight, measured contact surface and pressure under full loading condition									
Tire position	1		2		1		2		—
Front axle	447		443		0.83		0.86		75.53
Tire position	1	2	1	2	1	2	1	2	—
Rear first axle	321	331	292	310	0.78	0.76	0.86	0.81	101.93
Rear second axle	462	462	334	337	0.54	0.54	0.75	0.75	101.93
Test truck axles weight, measured contact surface and pressure under overloading condition									
Tire position	1		2		1		2		—
Front axle	459		375		0.85		1.04		78.61
Tire position	1	2	1	2	1	2	1	2	—
Rear first axle	387	322	267	300	0.86	1.07	1.29	1.15	140.19
Rear second axle	448	448	386	383	0.77	0.77	0.89	0.90	140.19

Vehicle speed affects dynamic loading and impact forces, with higher speeds potentially causing increased stress due to rapid load application. Road conditions, such as surface smoothness and material properties, play a significant role. For instance, road surface irregularities can cause variations in load distribution, leading to localized stress concentrations. Axle configurations and different axle setups impact road surface damage differently. Table 2.2 shows the comparative analyses regarding the root mean square of the vertical dynamic load of the wheel ($F_{t,RMS}$), Dynamic Load Coefficient (DLC), and Dynamic Load-Stress Factor (DLSF) across vehicles with 2-axle, 3-axle, and 4-axle configurations (Sun & Nguyen, 2023).

Table 2.2 The different dynamic loads at the axles of the different heavy trucks

Parameter	Axle location	Heavy trucks		
		2-axle vehicle	3-axle vehicle	4-axle vehicle
$F_{t,RMS}$ (N)	1st axle	1734.8	7747.3	14.173
	2nd axle	5172.9	3528.4	19.006
	3rd axle		3529.8	8.882
	4th axle			9.044
DLC	1st axle	0.0645	0.2264	0.1608
	2nd axle	0.1163	0.1262	0.1619
	3rd axle	–	0.1262	0.0902
	4th axle	–	–	0.0918
DLSF	1st axle	1.0250	1.3154	1.1571
	2nd axle	1.0818	1.0963	1.1593
	3rd axle	–	1.0963	1.0490
	4th axle	–	–	1.0508

Variations in load due to these factors can significantly influence stress distribution and pavement performance. For example, irregularities in the road surface can cause dynamic load variations that exacerbate pavement wear. Therefore, a comprehensive analysis incorporating these variables is essential for accurate load distribution predictions and efficient pavement design (Jiang et al., 2010).

2.4.3 Methods to measure and verify load distribution

Measurement techniques for load distribution in pavements include sophisticated tools such as weigh-in-motion (WIM) systems and finite element analysis (FEA). WIM systems are sophisticated tools designed to measure the weights of vehicles while they are in motion without requiring them to stop. These systems are crucial for monitoring and managing road usage, particularly in preventing vehicle overloading, which can cause significant damage to road infrastructures and increase maintenance costs. WIM systems utilize various types of sensors, as shown in Figure 2.9**,** embedded in the road surface or installed on bridges to capture data such as axle loads, gross vehicle weights, vehicle speed, and axle configuration (Burnos & Rys, 2017).

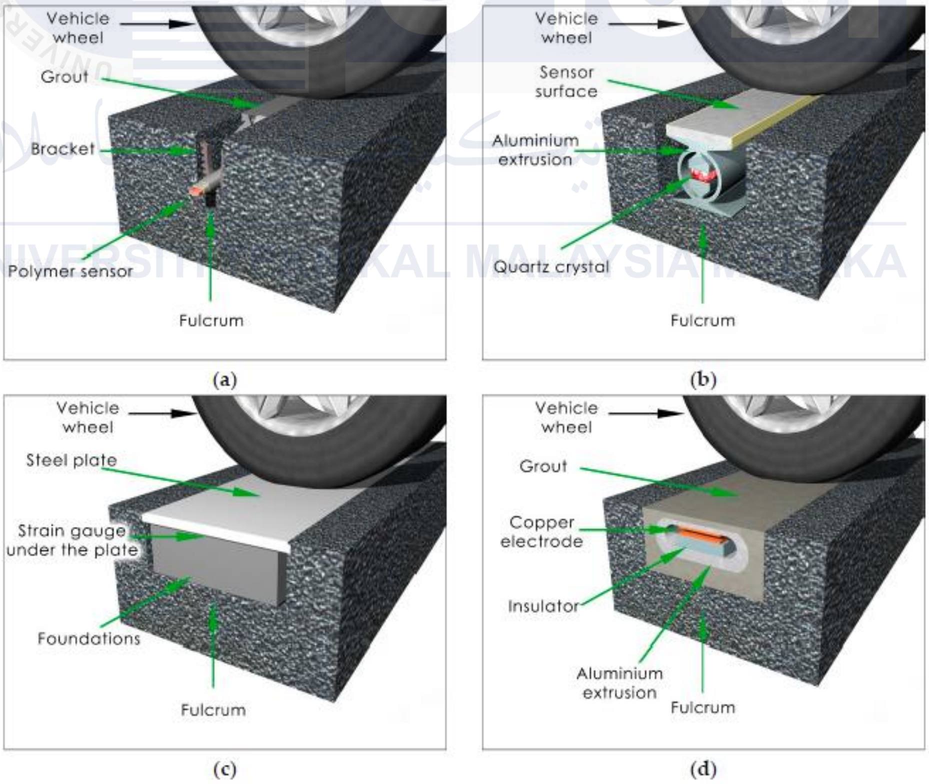

Figure 2.9 Various types of sensors in WIM: (a) Polymer sensor, (b) Quartz sensor, (c) Bending plate sensor, (d) Capacitive sensor.

Factors such as the pavement's temperature, the vehicle's speed, and the type of sensor used can influence the precision of weigh-in-motion (WIM) systems. Research indicates that vehicle speed and temperature may influence the accuracy of axle load sensors in flexible pavements. Advanced Weight-in-Motion (WIM) systems can be supervised by offering essential data for planning infrastructure, managing traffic, and upholding weight regulations. This significantly enhances the safety and efficiency of road networks (Jacob & Feypell-de La Beaumelle, 2010).

2.4.4 Load distribution calculations

Load distribution calculations are crucial for understanding vehicle dynamics, particularly in heavy vehicles like tractor-semitrailers, where longitudinal load transfer during braking and acceleration impacts performance and stability (Abdul Manaf et al., 2023). This study developed a 12-DOF longitudinal model incorporating tractor and semitrailer dynamics, as shown in Figure 2.10, emphasizing the hitch joint modeled to account for longitudinal and vertical forces.

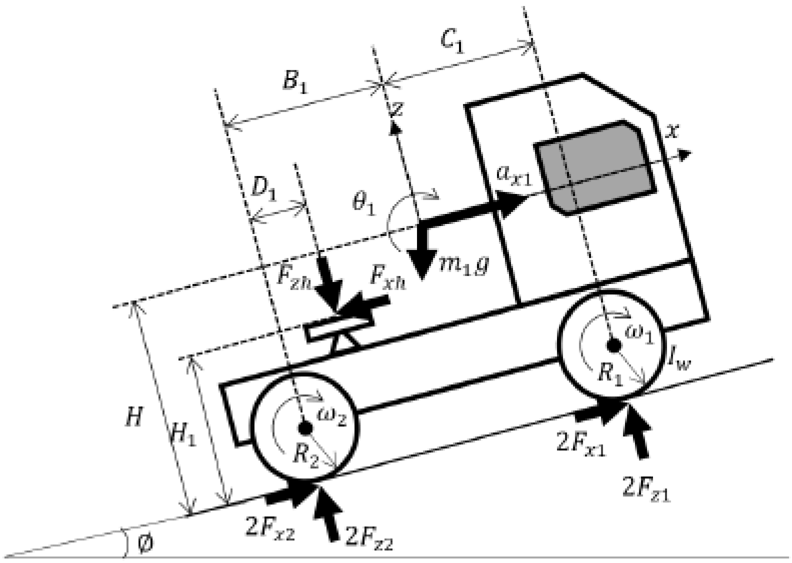

Figure 2.10 A tractor on an inclined surface

Equation (2.0) defines the longitudinal load transfer of the tractor, ΔW_{T1}. K_1 is the value of the uncertainty compensator introduced to the equation to enhance the accuracy of the model. The vertical forces acting on each wheel and the load distribution was derived from Figure 2.10, specifically in equations (2.1) and (2.2) (Abdul Manaf et al., 2023), which consider static load, longitudinal load transfer during acceleration and braking, and hitch forces.

$$\Delta W_{T1} = \frac{m_1 H K_1}{(B_1 + C_1)}\{a_{x1}\} \tag{2.0}$$

$$F_{z1,l/r} = \left[\frac{m_1 g}{2(B_1 + C_1)}\{C_1 cos\emptyset - Hsin\emptyset\}\right] - \left[\frac{m_1 H K_1}{2(B_1 + C_1)}\{a_{x1}\}\right] + \left[\frac{1}{2(B_1 + C_1)}\{(B_1 - D_1)F_{zh} - (H_1)F_{xh}\}\right] \tag{2.1}$$

$$F_{z2,l/r} = \left[\frac{m_1 g}{2(B_1 + C_1)}\{C_1 cos\emptyset + Hsin\emptyset\}\right] + \left[\frac{m_1 H K_1}{2(B_1 + C_1)}\{a_{x1}\}\right] + \left[\frac{1}{2(B_1 + C_1)}\{(B_1 - D_1)F_{zh} + (H_1)F_{xh}\}\right] \tag{2.2}$$

The simulation results were validated against TruckSim data and showed that harsh braking leads to significant and prolonged load transfer to the front wheels, which affects braking performance. On the other hand, load transfer during acceleration, while higher in magnitude, occurs over a shorter duration and thus has less impact on vehicle dynamics. Active control systems such as pneumatic brakes, suspensions, and innovative hitch joint models offer effective solutions to reduce these load transfers by dynamically adjusting brake force and normal load distribution on each wheel. This ultimately improves vehicle stability and performance.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This research work investigates how to simplify a single axle that can represent multiple axles on a truck using the summation of axle load force. This chapter explains how the procedure was done, starting with choosing the vehicle type, simplifying two axles, developing the equation of motion from the vehicle, and simulating the acceleration test and braking test using TruckSim to verify the method.

3.2 Research methodology

This research aims to make a method that can simplify two axles to a single axle. Doing that will simplify the equation of motion to determine the axle load on each axle. This method starts with doing a literature review from several journals. Then, the preparation begins by choosing the vehicle type: a straight truck with three axles. Develop the equation of axle load (load distribution) from the vehicle. Separate it into two models. For the first model, the equation was derived from the 3-axle truck. For the second model, derive the equation of axle load from the same truck but with some modification by doing a summation method on the two axles at the rear tires. The moment arm location must also be determined when doing the summation method. Then, the equation for all models will be simulated using TruckSim to find the result of vertical force from the acceleration test and braking test. Comparing the vertical force results to determine whether the method is verified or not. Figure 3.1 illustrates a flow chart summarising the overall process implemented throughout this work.

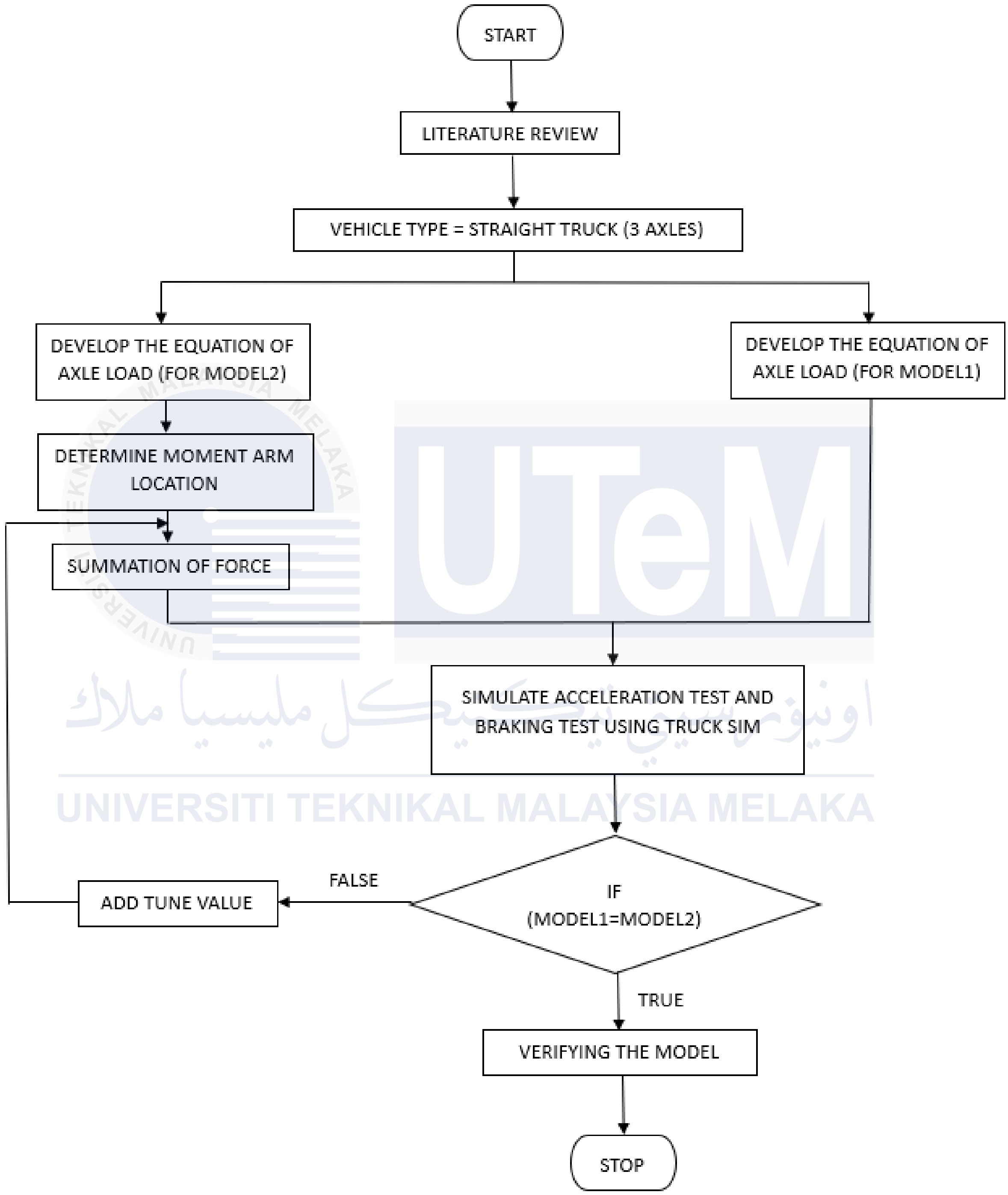

Figure 3.1 Process flow of verifying method

3.3 Development of the load distribution equation

Load distribution, also known as axle load, is the equation that needs to be developed from the truck. Load distribution in vehicle dynamics refers to how the weight of a vehicle and its cargo is distributed across the vehicle's wheels and axles. This distribution is critical because it affects various aspects of a vehicle's performance, including stability, handling, braking, and overall safety. The load distribution can be determined by implementing Newton's second law ($\sum F = ma$). All the degrees of freedom must be considered when deriving the equation, as shown in Figure 3.2.

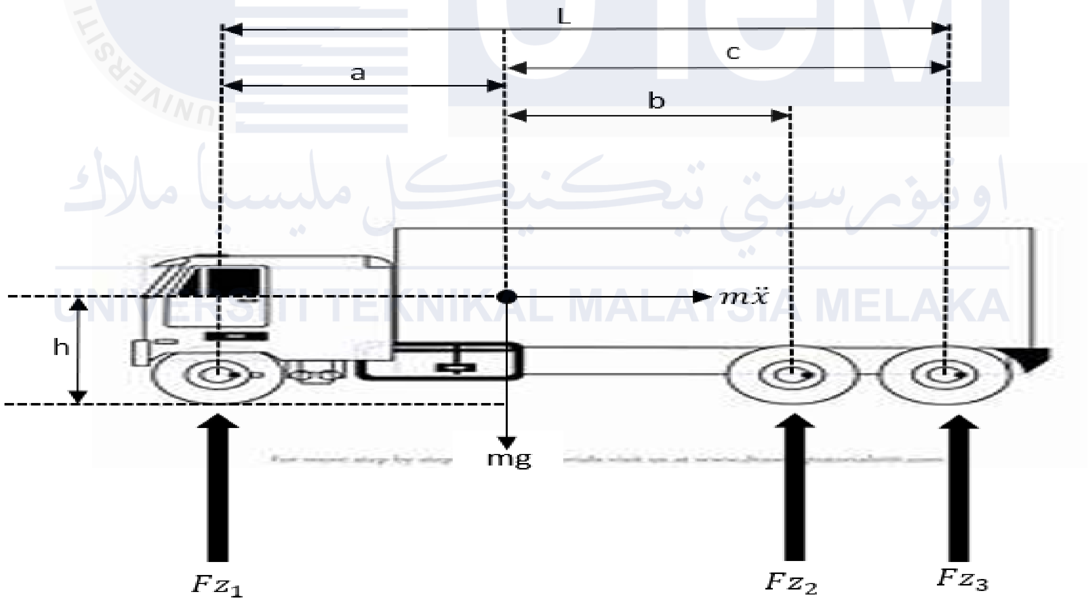

Figure 3.2 Free body diagram of 3 axles truck

Table 3.1 Description of the symbol

Symbol	Description
h	The height of the CG (centre gravity) of the truck
a	The longitudinal distance of the front axle (Fz_1) from the CG of the truck
b	The longitudinal distance of the first rear axle (Fz_2) from the CG of the truck
c	The longitudinal distance of the second rear axle (Fz_3) from the CG of the truck
L	Wheelbase
m	The mass of the truck
g	The acceleration due to gravity
$\ddot{x}$	Acceleration
Fz_1	The vertical tire force at the front tires
Fz_2	The vertical tire force at first rear tires
Fz_3	The vertical tire force at the second rear tires

Based on Figure 3.2, the moments of inertia at the contact point of the first rear tire (Fz_2) is defined in the equation (3.0).

$$\sum +\circlearrowright Fz_2 = 0$$

$$Fz_1(a+b) - mg(b) - Fz_3(c-b) + m\ddot{x}(h) = 0 \quad (3.0)$$

Then, for the moments of inertia at the contact point of the second rear tire (Fz_3) is defined in equation (3.1).

$$\sum +\circlearrowright Fz_3 = 0$$

$$Fz_1(L) + Fz_2(c-b) - mg(c) + m\ddot{x}(h) = 0 \quad (3.1)$$

After that, by taking moments of inertia at the contact point of the front tire (Fz_1) to define equation (3.2).

$$\sum +\circlearrowright Fz_1 = 0$$

$$mg(a) - Fz_2(a+b) - Fz_3(L) + m\ddot{x}(h) = 0 \quad (3.2)$$

The truck is considered static; thus, the acceleration ($\ddot{x}$) equals zero. Then, solve the equations (3.0), (3.1), and (3.2) to derive the axle load on each axle of the truck as shown in equations (3.3), (3.4), and (3.5).

$$Fz_1(a+b) - mg(b) - Fz_3(c-b) + m(0)(h) = 0$$

$$Fz_1 = \frac{mg(b) + Fz_3(c-b)}{(a+b)} \tag{3.3}$$

$$Fz_1(a+b) - mg(b) - Fz_3(c-b) + m(0)(h) = 0$$

$$Fz_2 = \frac{mg(c) + Fz_1(L)}{(c-b)} \tag{3.4}$$

$$Fz_1(L) + Fz_2(c-b) - mg(c) + m(0)(h) = 0$$

$$Fz_3 = \frac{mg(a) + Fz_2(a+b)}{(L)} \tag{3.5}$$

3.4 Development of the equation for 2 axle model

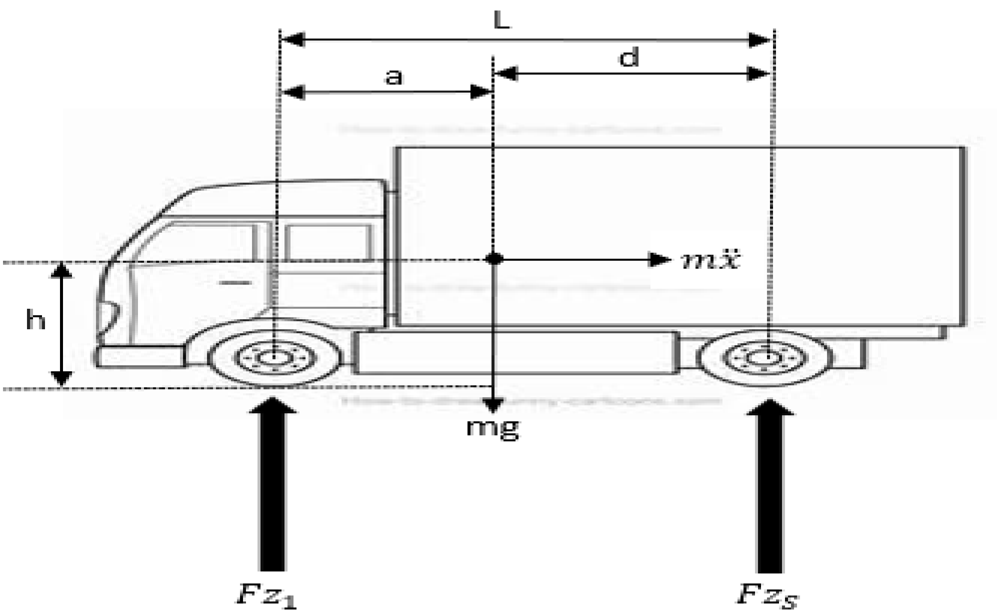

Figure 3.3 Free body diagram of 2 axles truck

The equation for the two-axle model is derived from Figure 3.3. Moments of inertia at the contact point of the front tire are taken to derive equation (3.6).

$$\sum +\circlearrowright Fz_1 = 0$$

$$mg(a) - Fz_S(L) + m\ddot{x}(h) = 0 \tag{3.6}$$

Then, the moments of inertia at the rear tire contact point are defined in equation (3.7).

$$\sum +\circlearrowright Fz_S = 0$$

$$Fz_1(L) - mg(d) + m\ddot{x}(h) = 0 \tag{3.7}$$

Solving the equations (3.6) and (3.7) by assuming the acceleration is zero due to the truck remaining static.

$$mg(a) - Fz_{2,3}(L) + m(0)(h) = 0$$

$$Fz_{2,3} = \frac{mg(a)}{L} \tag{3.8}$$

$$Fz_1(L) - mg(d) + m(0)(h) = 0$$

$$Fz_1 = \frac{mg(d)}{L} \tag{3.9}$$

3.5 Summation of force & determining moment arm location

The summation of force, where the two axles (Fz_2 & Fz_3) at the rear of the truck in Figure 3.2 have been summed to mimic a single axle ($Fz_{2,3}$), as shown in Figure 3.3. The main purpose of the summation force is to simplify the equation of load distribution. The equivalent force ($Fz_{2,3}$) is the sum of the forces acting on the two rear axles, as shown in equation (3.10).

$$Fz_{2,3} = Fz_2 + Fz_3 \tag{3.10}$$

The position of the moment force from the center of gravity of the truck (d) is found by using equation (3.9). Values for L, Fz_1, m and g are taken from the 3-axle truck. The value of d can be determined by solving equation (3.11).

$$d = \frac{Fz_1\,(L)}{mg} \tag{3.11}$$

3.6 Simulation TruckSim

TruckSim is powerful vehicle dynamics simulation software used to analyze and predict the behaviour of trucks under various conditions. Acceleration and braking tests are run in TruckSim to evaluate the results between three-axle trucks and two-axle trucks. This process involves setting up the simulation environment, configuring vehicle parameters, and interpreting the results to ensure the equations from equations (3.11) and (3.12) meet the required standards.

3.6.1 Setting Up the Simulation

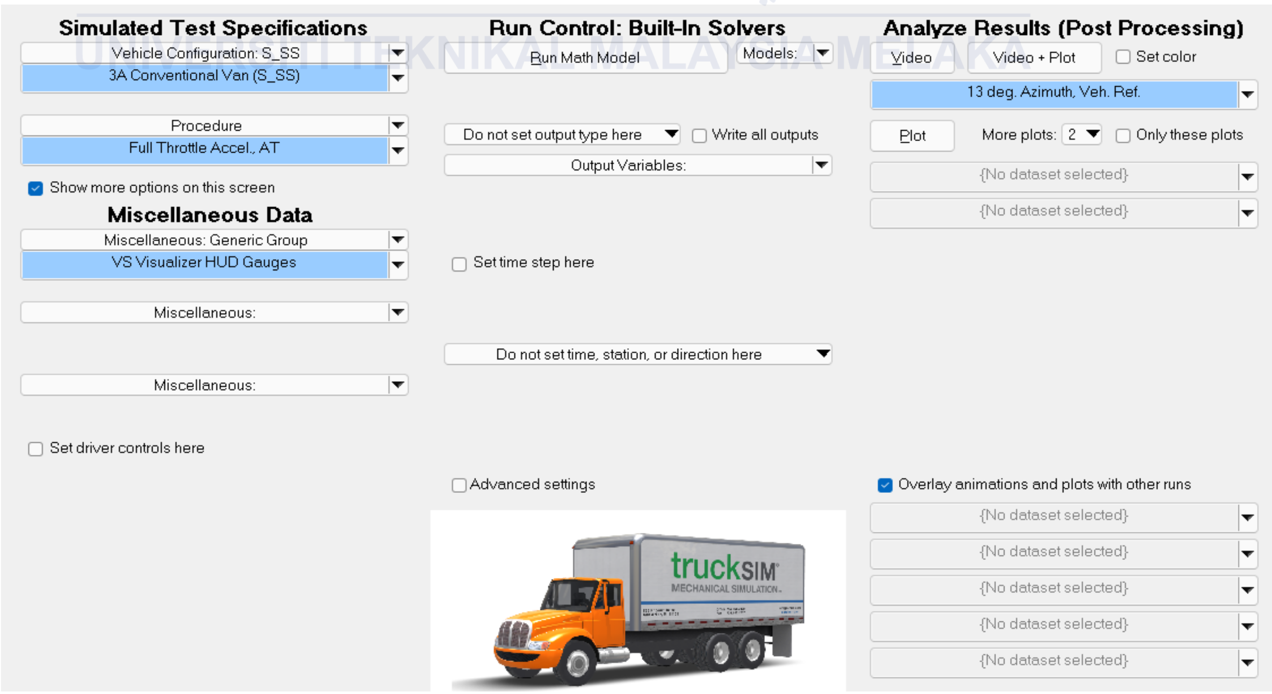

Figure 3.4 TruckSim setting to run acceleration test

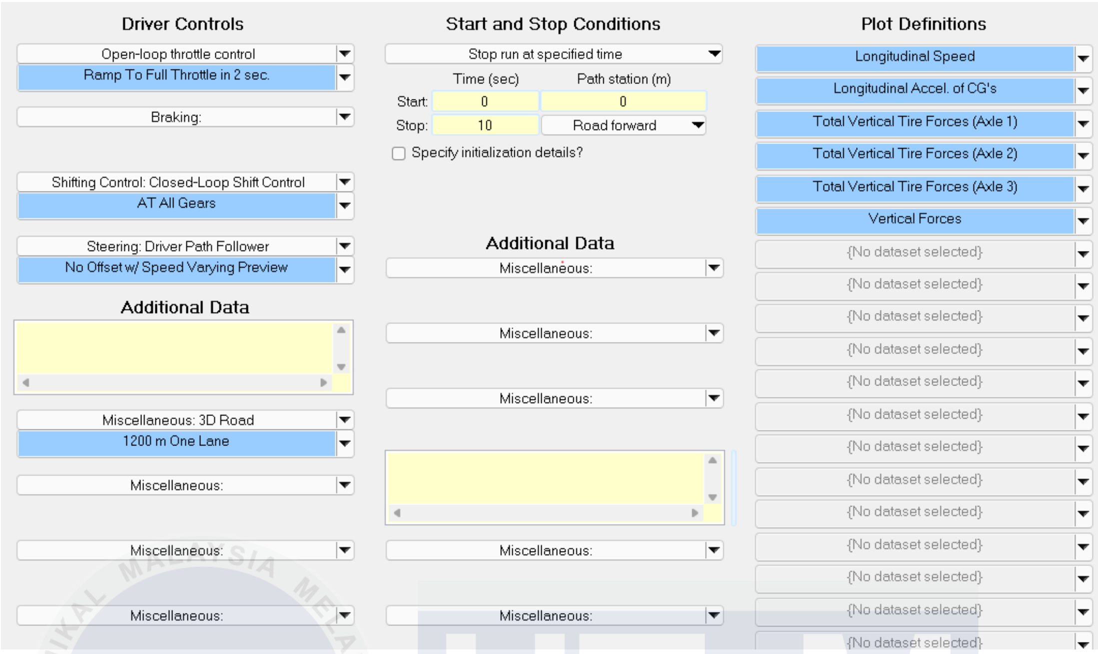

Figure 3.5 Full throttle acceleration, AT Procedure setting

Table 3.2 3A conventional van perimeter

Symbol	Description	Value
h	The height of the CG (centre gravity) of the truck	1.175m
a	The longitudinal distance of the front axle (Fz_1) from the CG of the truck	1.110m
b	The longitudinal distance of the first rear axle (Fz_2) from the CG of the truck	4.120m
c	The longitudinal distance of the second rear axle (Fz_3) from the CG of the truck	1.270m
L	Wheelbase	6.500m
M_s	Sprung mass	4455kg
Fz_1	The vertical tire force at the front tires	41010.04N
Fz_2	The vertical tire force at first rear tires	10724.77N
Fz_3	The vertical tire force at the second rear tires	12450.00N

Choose a 3A conventional van with a perimeter set in the vehicle configuration setting in Table 3.2. Then, a full-throttle acceleration procedure will be defined to run the simulation, as shown in Figure 3.4. In the procedure setting, the transmission has been set to an automatic transmission. Figure 3.5 shows the setting defined full throttle acceleration procedure. For the braking test, the dataset was modified to align with the procedures specific to the braking test. After completing the setting, run the math model and analyze the vertical force result for each axle from the simulation, as shown in Figure 3.6 and Figure 3.7.

Figure 3.6 TruckSim acceleration test

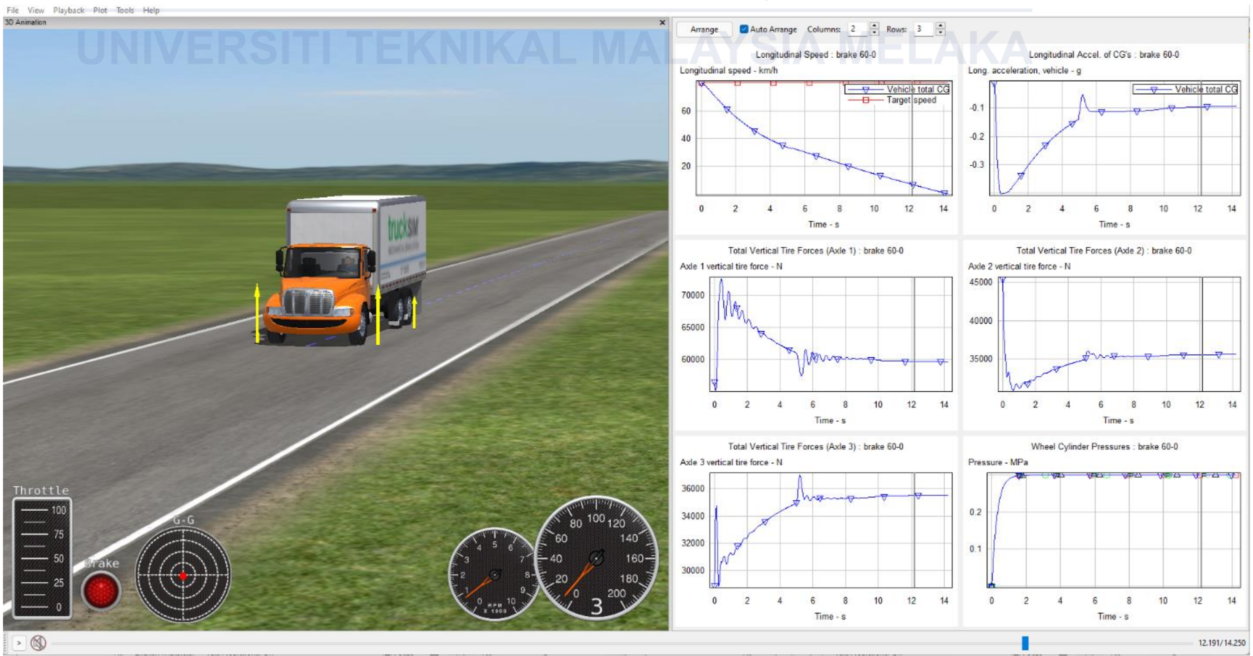

Figure 3.7 TruckSim braking test

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter presents the results and analysis of developing a simplified vehicle model to represent multiple axle wheels. The load distribution equation is used to achieve the research's objective of determining the force summation and the moment arm's location. Then, the acceleration test and brake test for both 2-axle and 3-axle truck models will be simulated to gain the result of vertical force (Fz_2, Fz_3, Fz_S). Then, the results will be compared between the summation of vertical force at axle 2 and axle 3 from the 3-axle truck (Fz_2+Fz_3) and vertical force of axle 2 from the 2-axle truck (Fz_S) to verify the methodology.

4.2 Acceleration test

The acceleration test was performed under three scenarios: 0-60, 0-80, and 0-100 km/h. The vertical forces were plotted against time for these tests. Observations revealed the vertical force of the 2-axle truck (Fz_S) consistently exceeded the summed vertical forces (Fz_2+Fz_3) under all three scenarios, as shown in Figure 4.1, Figure 4.2, and Figure 4.3. The observations occur because the 3-axle truck has more surface contact area due to the wheelbase being 6.5m, while the wheelbase of the modified 2-axle truck is 4.441m. Therefore, the 2-axle truck experiences more load during acceleration.

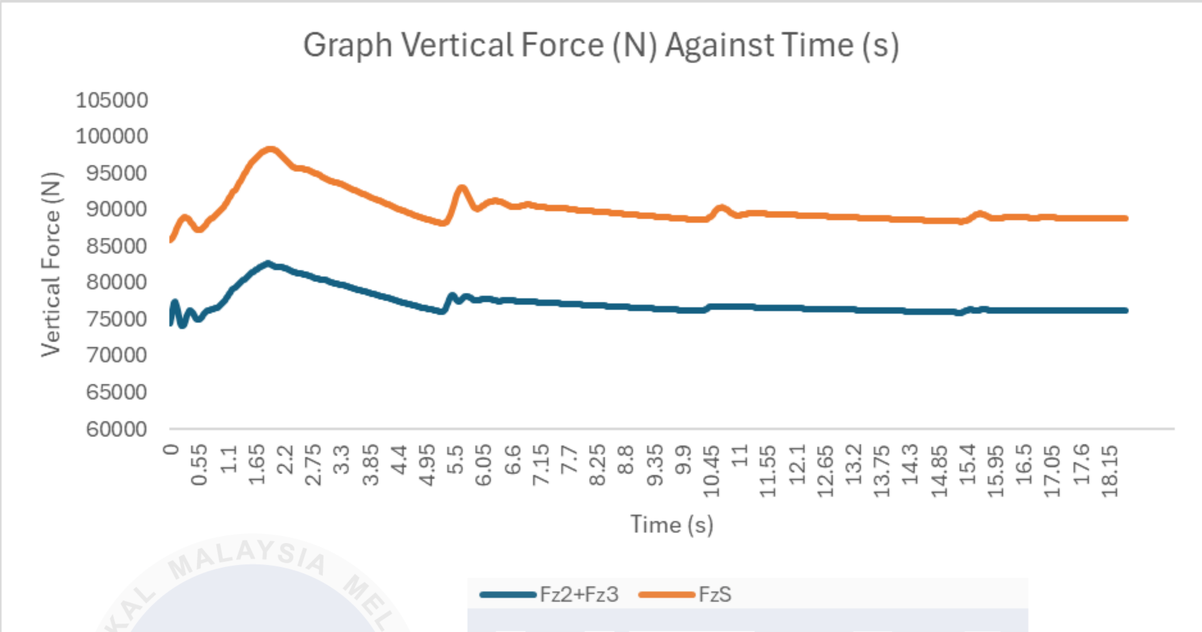

Figure 4.1 Result of acceleration test from 0 to 60 km/h

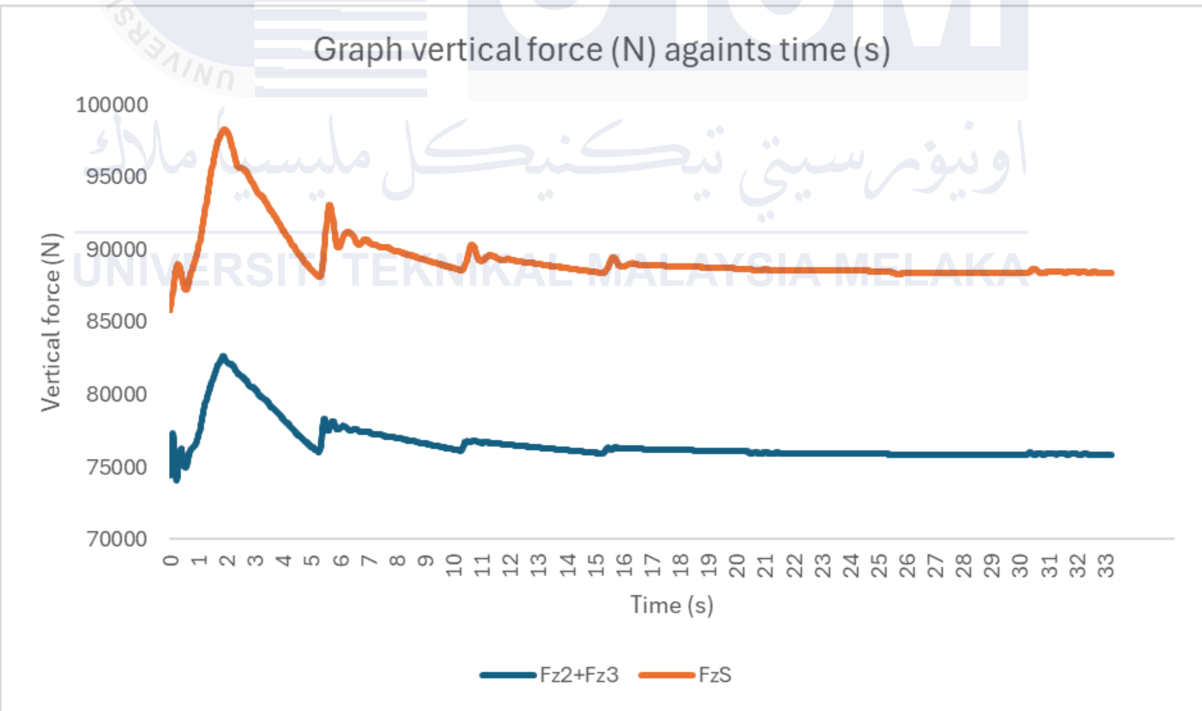

Figure 4.2 Result of acceleration test from 0 to 80 km/h

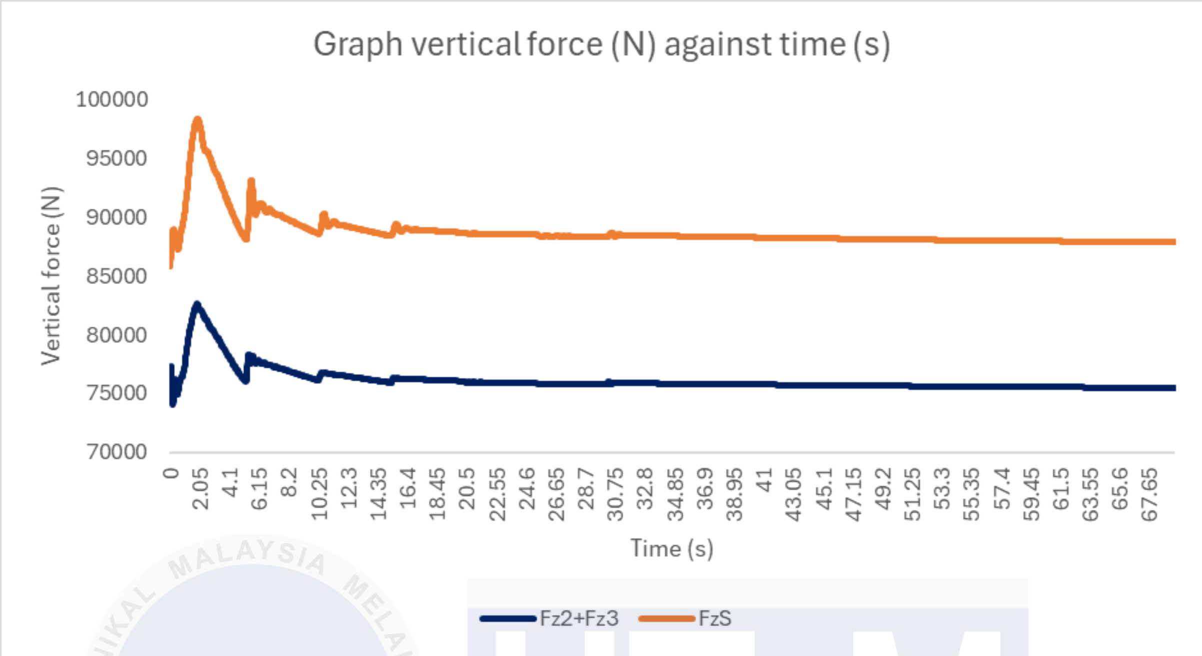

Figure 4.3 Result of acceleration test from 0 to 100 km/h

4.3 Brake test

Braking simulations were carried out for speeds of 60-0, 80-0, and 100-0 km/h under constant brake pressure of 0.3MPa. The vertical forces were analyzed over the deceleration period, revealing a notable reduction in vertical forces as braking progressed, with (Fz_S) again exceeding (Fz_2+Fz_3). braking test results, shown in Figures 4.4, 4.5, and 4.6 for 60-0 km/h, 80-0 km/h, and 100-0 km/h, reveal a consistent pattern where (Fz_S) remains greater than (Fz_2+Fz_3). The higher vertical forces in the 2-axle truck during braking can be attributed to the shorter wheelbase concentrating the load on fewer axles, even as braking shifts more weight to the front axle. When braking test from 60 km/h, the result of vertical force for a 2-axle truck (FzS) as shown in Figure 4.4, has a different pattern than other results for 80 km/h and 100 km/h. This is because the 2-axle truck shifts less weight to the front axle when braking from 60 km/h. Thus, the truck's front suspension system effectively absorbs shock without causing excessive bouncing. Meanwhile, when braking from 80 km/h and above, the 2-axle truck shifts more weight to the front axle causing more excessive bouncing.

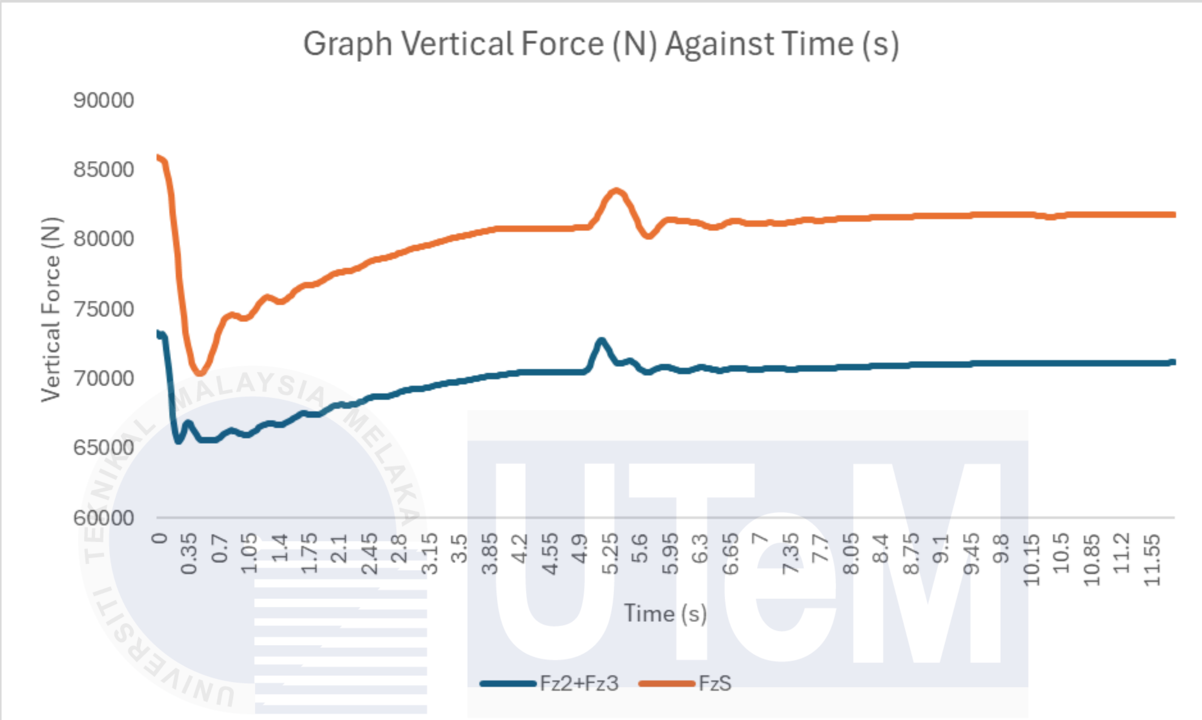

Figure 4.4 Result of brake test from 60 to 0 km/h

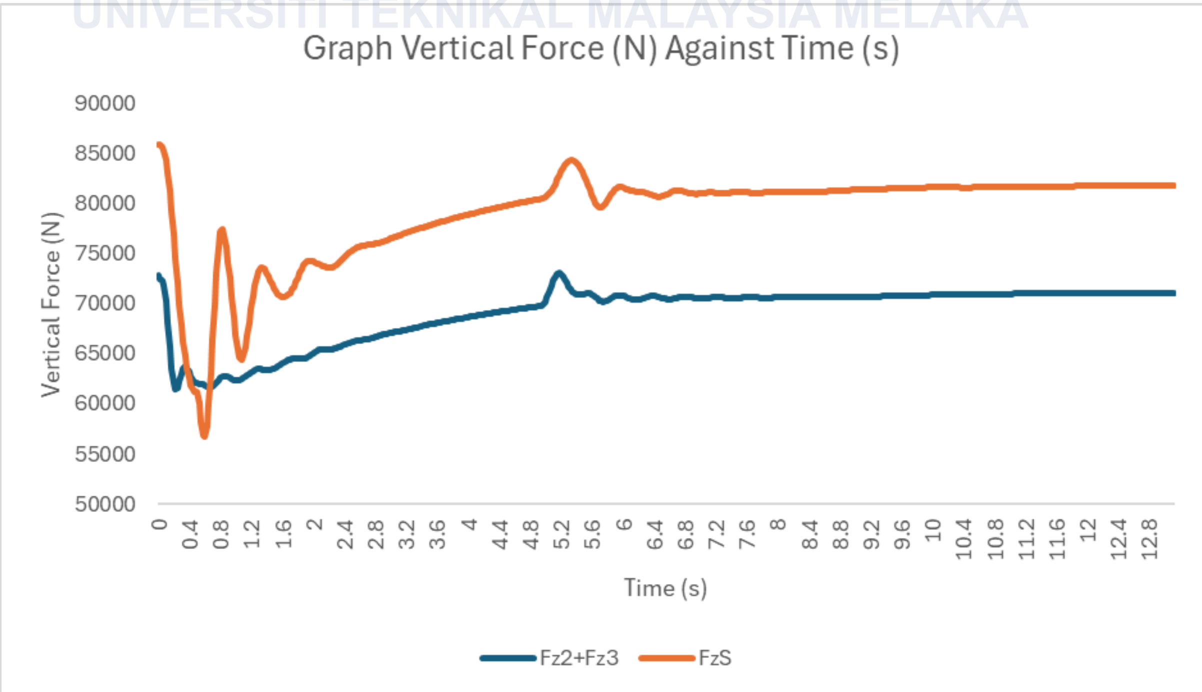

Figure 4.5 Result of brake test from 80 to 0 km/h

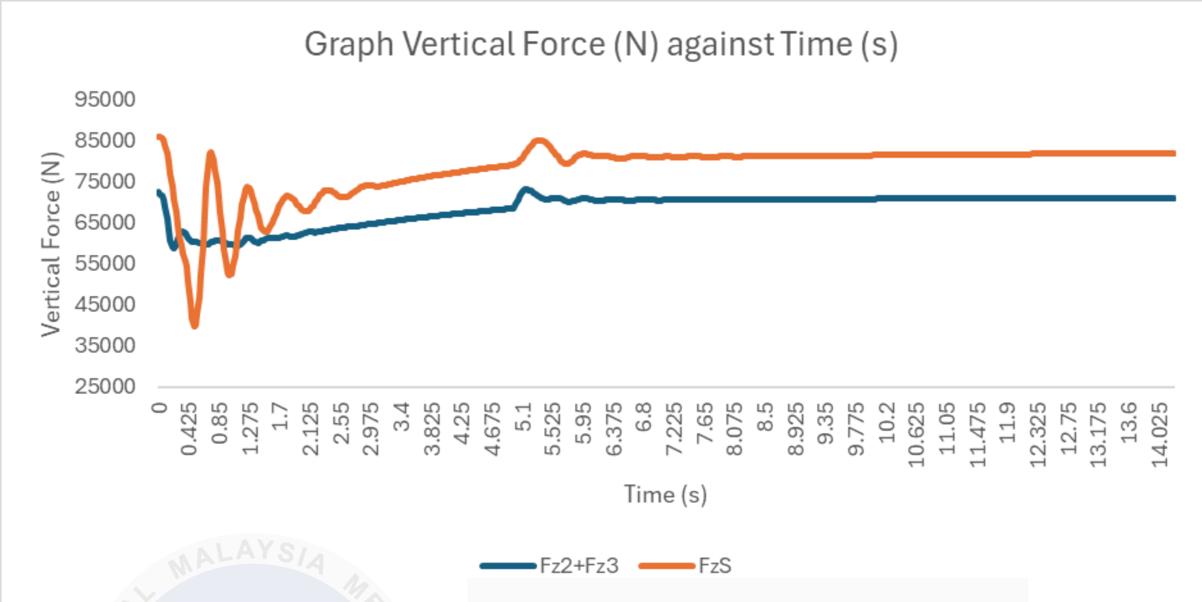

Figure 4.6 Result of brake test from 100 to 0 km/h

4.4 Determine tune value

A tuning value was introduced to validate the methodology and minimize errors, representing the average difference between (Fz_2+Fz_3) and Fz_S. Then, the tuning value was added to the equation (3.6) to represent tuned data (Fz_2+$Fz_3 + Tune\ value$). Figures 4.7, 4.8, and 4.9 show the effects of applying this tuning value during acceleration tests for 0-60 km/h, 0-80 km/h, and 0-100 km/h, where the tuned data (Fz_2+$Fz_3 + Tune\ value$) aligns closely with Fz_S. The tune values differ for each speed where the tune value for 60 km/h is 12964.82, the tune value for 80 km/h is 12799.9798, and the tune value for 100 km/h is 12616.81. Table 4.1 illustrates the percentage error of vertical force from the acceleration test.

$$Fz_{2,3} = Fz_2 + Fz_3 + Tune\ Value \quad (4.1)$$

Table 4.1 Percentage error for acceleration test

Acceleration test	Average of summation vertical force 3-axle truck (N)		Average of vertical force 2-axle truck (N) Fz_S	%error
0-60 km/h	Fz_2+Fz_3	77200.48163	90165.30513	16.79%
	Fz_2+Fz_3 + $Tune\ value$	90165.30163		0.00%
0-80 km/h	Fz_2+Fz_3	76628.24221	89428.222	16.70%
	Fz_2+Fz_3 + $Tune\ value$	89428.22201		0.00%
0-100 km/h	Fz_2+Fz_3	76120.35	88737.15429	16.57%
	Fz_2+Fz_3 + $Tune\ value$	88737.15867		0.00%

A similar alignment is observed in braking tests, as illustrated in Figures 4.10, 4.11, and 4.12 for 60-0 km/h, 80-0 km/h, and 100-0 km/h, respectively. The tune values also differ for each speed when braking where the tuning value for 60 km/h is 10187.20679, the tuning value for 80 km/h is 9991.83878, and the tuning value for 100 km/h is 8993.799. Table 4.2 illustrates the percentage error of vertical force from the braking test.

Table 4.2 Percentage error for braking test

Braking test	Average of summation vertical force 3-axle truck (N)		Average of vertical force 2-axle truck (N) Fz_S	%error
60-0 km/h	Fz_2+Fz_3	69948.6	80135.81	14.56%
	Fz_2+Fz_3 + $Tune\ value$	80135.8086		0.00%
80-0 km/h	Fz_2+Fz_3	69075.45	78968.49	14.32%
	Fz_2+Fz_3 + $Tune\ value$	79067.28634		0.12%
100-0 km/h	Fz_2+Fz_3	68403.05	77952.67	14.89%
	Fz_2+Fz_3 + $Tune\ value$	78588.46286		0.82%

The results indicate that the tuning value effectively reduces the percentage error, thereby aligning the vertical force data of the simulated 3-axle truck with the measurements obtained from the 2-axle truck. This outcome demonstrates the reliability and effectiveness of the proposed methodology.

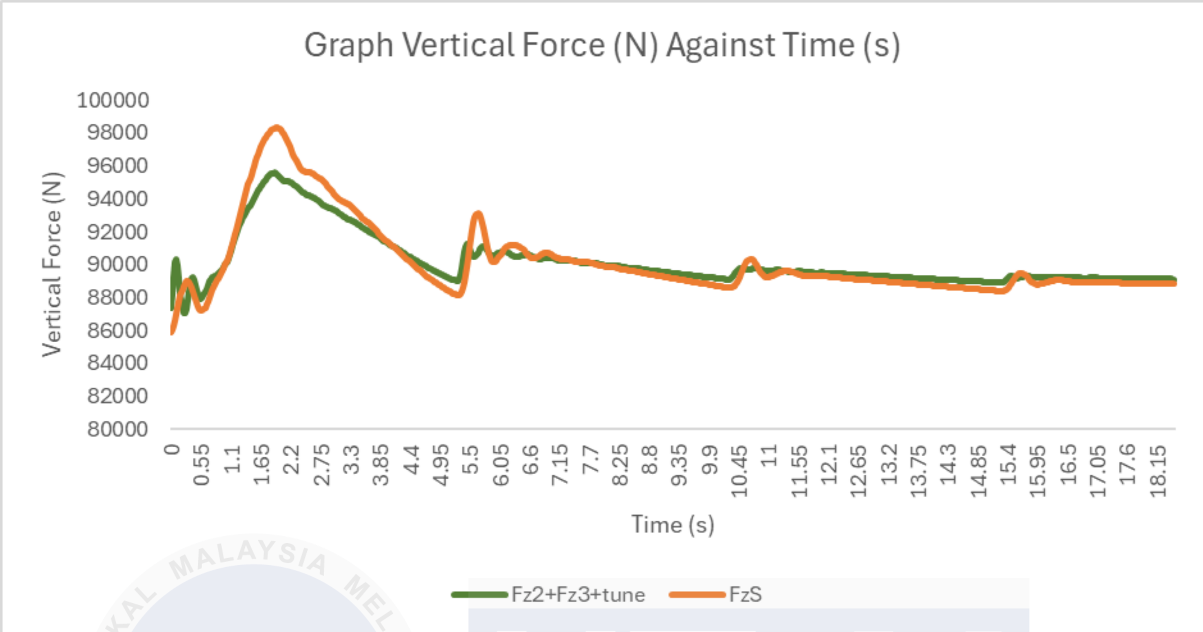

Figure 4.7 Acceleration test result from 0-60 km/h between (Fz_2+Fz_3 + $tune\ value$) and Fz_S

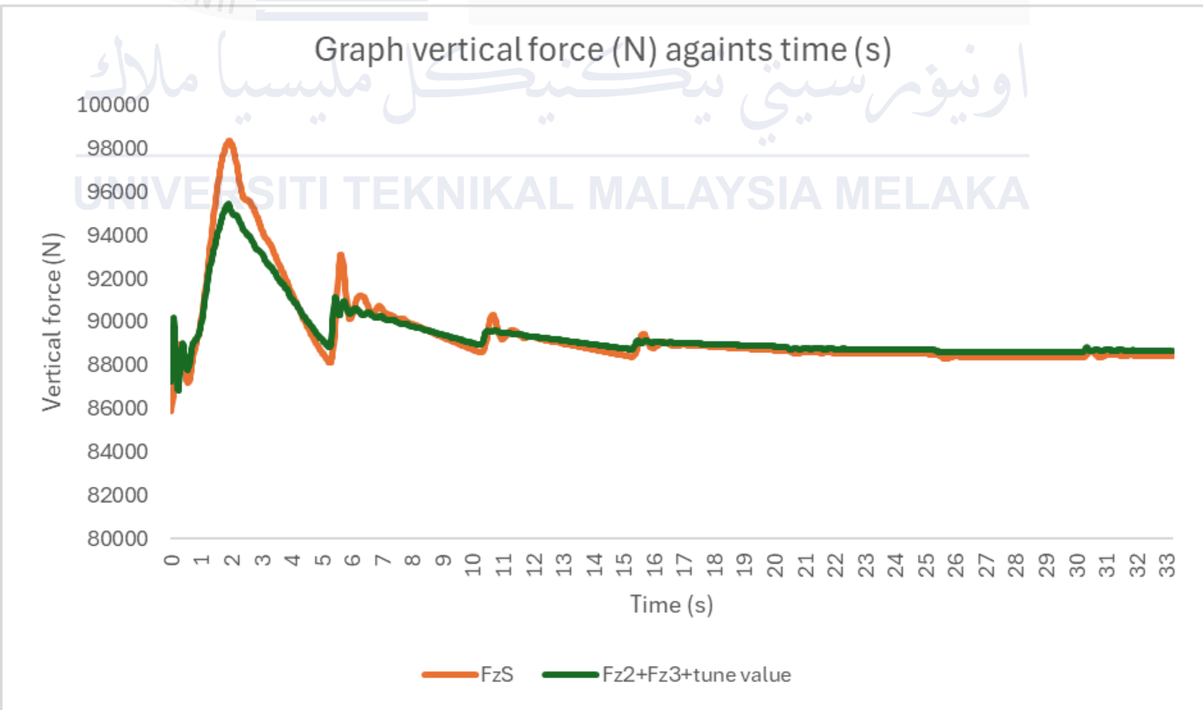

Figure 4.8 Acceleration test result from 0-80 km/h between (Fz_2+Fz_3 + $tune\ value$) and Fz_S

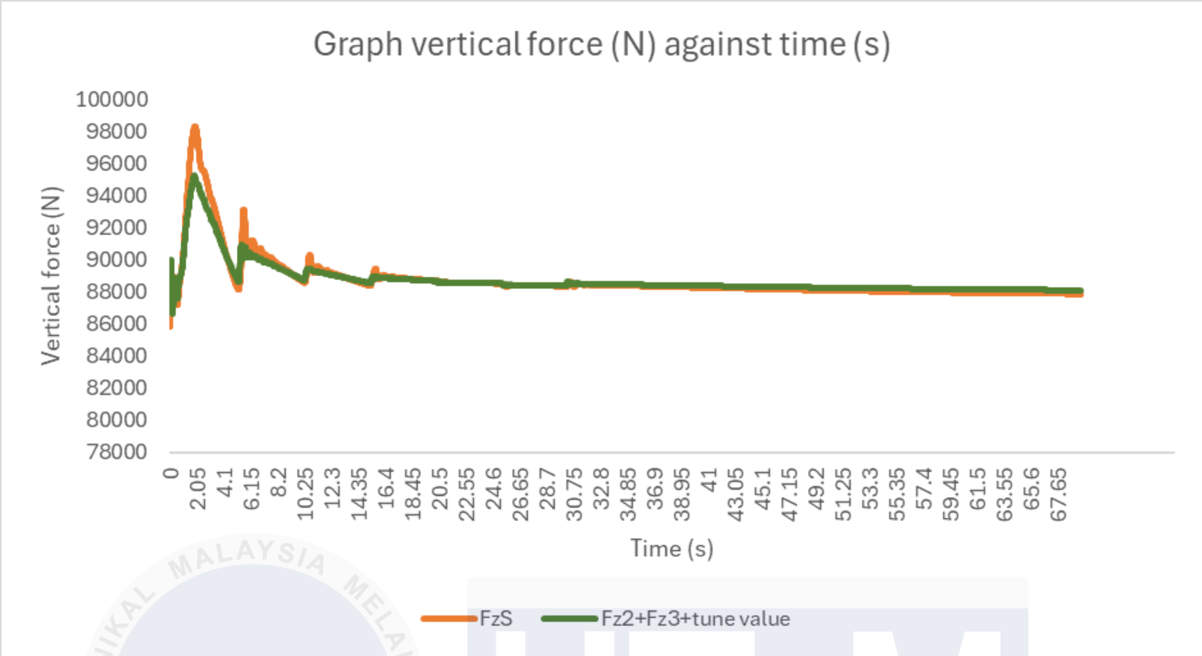

Figure 4.9 Acceleration test result from 0-100 km/h between $(Fz_2+Fz_3 + tune\ value)$ and Fz_S

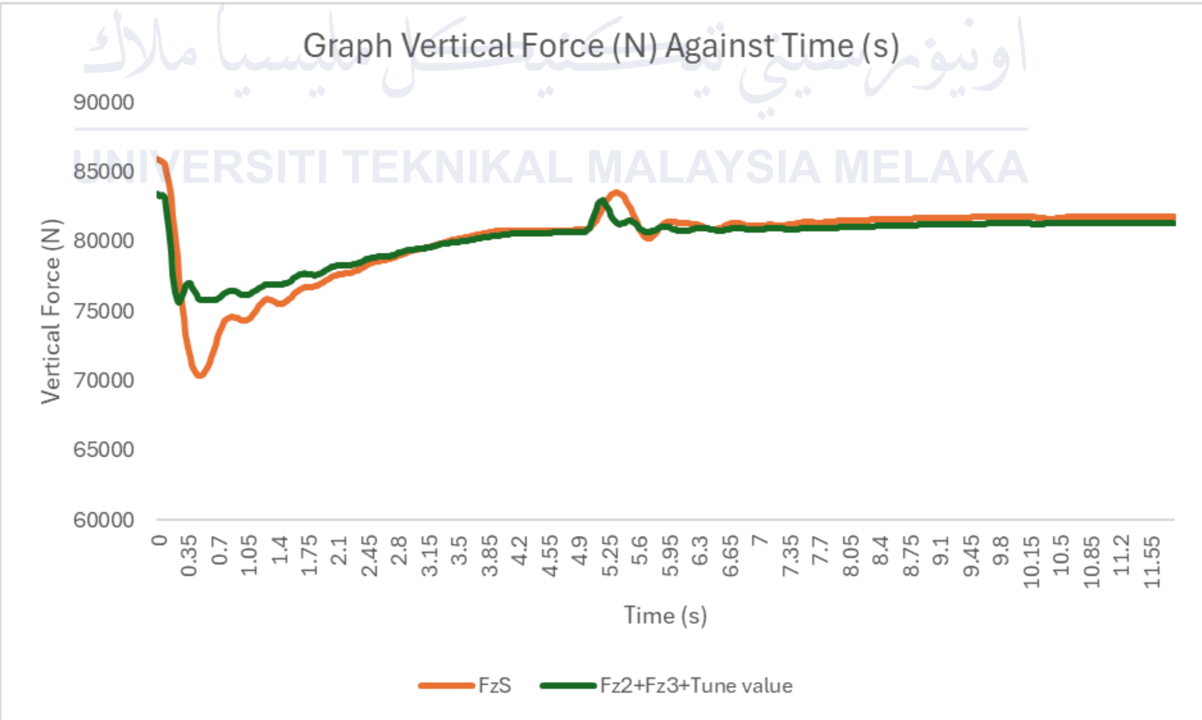

Figure 4.10 Braking test result from 60-0 km/h between $(Fz_2+Fz_3 + tune\ value)$ and Fz_S

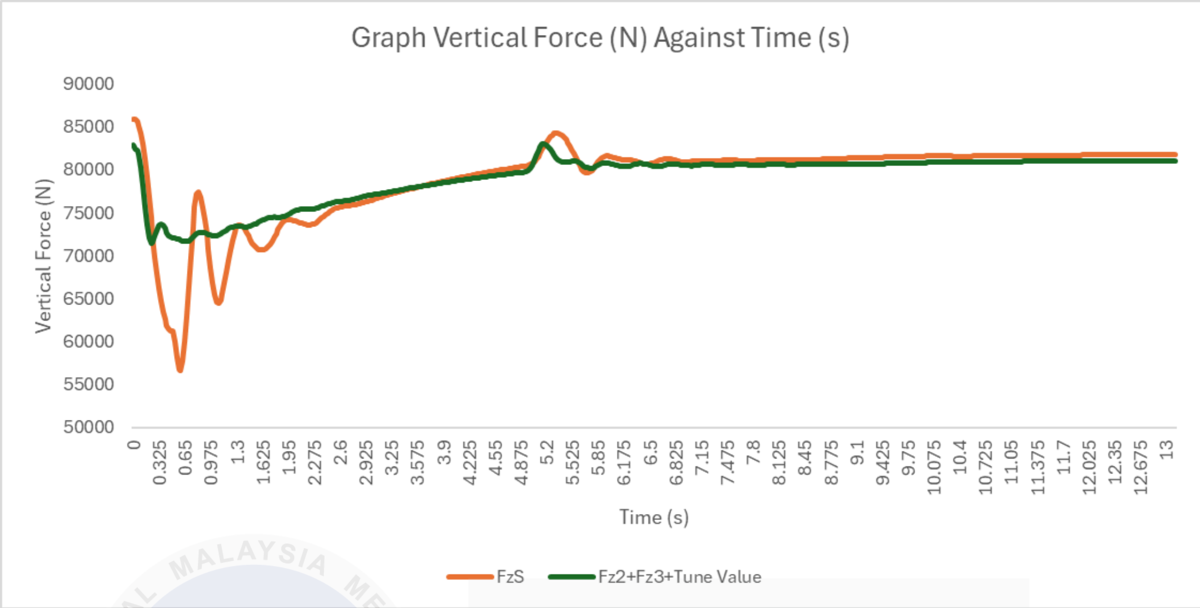

Figure 4.11 Braking test result from 80-0 km/h between (Fz_2+Fz_3 + $tune\ value$) and Fz_S

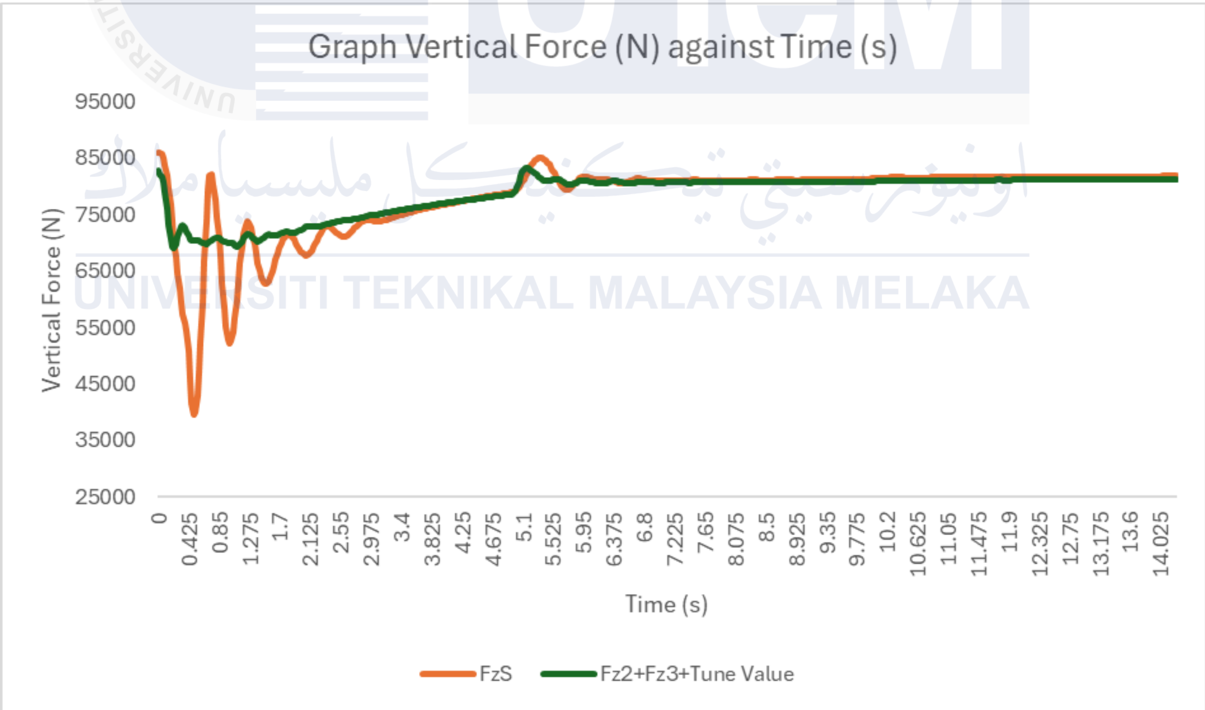

Figure 4.12 Braking test result from 100-0 km/h between (Fz_2+Fz_3 + $tune\ value$) and Fz_S

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The primary objective of this study was to develop a simplified single-axle truck to represent the multiple-axle truck aimed to simplify the axle load equation. The conclusions drawn from the results can be summarized as follows:

The acceleration test findings show that the simpler 2-axle truck consistently exerts more vertical force than the 3-axle truck across all measured speed scenarios (0-60 km/h, 0-80 km/h, and 0-100 km/h). This variation can be due to the 2-axle truck's shorter wheelbase, which results in a larger weight concentration on fewer axles. Nonetheless, the data support the claim that the simplified model can accurately simulate multi-axle trucks when the appropriate calibration values are used.

During the braking tests at speeds of 60 km/h, 80 km/h, and 100 km/h, a consistent finding emerged: the vertical force exerted on the two-axle vehicle exceeded the total forces operating on the three-axle design. This behaviour can be due to the concentrated load associated with the shorter wheelbase, as well as weight transfer to the front axle during the deceleration phase. Notably, at lower speeds, the front suspension of the 2-axle truck provided efficient shock absorption, reducing excessive bouncing. At greater speeds, however, the load shifts became much more noticeable.

The use of tuning parameters has significantly reduced the differences seen between the simplified 2-axle and 3-axle designs. The data collected after tuning show a significant correlation between the two models, with tuning values varying with speed for both acceleration and braking scenarios. The tuning values for acceleration from 0 to 60, 0 to 80, and 0 to 100 km/h are 12964.82, 12799.9798, and 12616.81, respectively. The tuning values for the brake tests at 60, 80, and 100 km/h were 10187.20679, 9991.83878, and 8993.799, respectively. This upgrade increased the simplified model's reliability, allowing it to more correctly reproduce the dynamics of multi-axle trucks.

After applying the tuning values, the percentage error for vertical forces between the original and simplified models was significantly reduced. During acceleration testing from 0-60 km/h, 0-80 km/h, and 0-100 km/h, the percentage error fell from roughly 16.78% to 0.0%, 16.70% to 0.00%, and 16.57% to 0.00%, respectively. Similarly, in the braking tests, the error decreased from 14.56% to 0.00% when braking from 60 km/h. Otherwise, braking from 80 km/h and 100 km/h reduced the percentage error from 14.32% to 0.12% and 14.89% to 0.82%, respectively. These results demonstrate the effectiveness of the proposed methodology in improving accuracy while streamlining axle layout.

In conclusion, the findings support the claim that the simplified vehicle model is an effective and reliable tool for analysing axle load distributions in multi-axle trucks. The verified methodology provides a realistic solution for optimising vehicle design, improving load distribution, and increasing transport efficiency. This study sheds light on the topic of transportation engineering and lays the groundwork for the future use of simplified models in real-world settings.

5.2 Recommendation for future works

In future research, the goal is to broaden the study by including more complex vehicle configurations, such as multi-trailer systems and vehicles with more than three axles. This addition will help validate the simplified model's applicability to a broader range of heavy vehicles. By tackling these advanced configurations, the study hopes to improve understanding of vehicle dynamics, ensuring that the model remains relevant and successful in a variety of operating circumstances.

The study should emphasise the use of extensive simulations to account for a variety of road characteristics, including uneven, sloping, and rough surfaces. Furthermore, these simulations should include dynamic load situations, such as changes in vehicle weight and distribution, to rigorously evaluate the model's performance in conditions that closely resemble real-world settings.

It is equally critical to supplement these simulations with real-world testing to validate the model's accuracy. This validation may include the use of weigh-in-motion (WIM) devices, which are meant to detect vehicle weight as it passes a sensor implanted in the road surface. Furthermore, specialised testing equipment can be used to collect exact data on vehicle dynamics, road interactions, and load responses under a variety of scenarios.

Researchers will be able to determine the model's dependability and efficacy by carefully comparing simulation results to actual field test measures. This thorough approach not only improves the rigour of the findings, but also assures that the model can be confidently utilised in actual situations.

APPENDICES

APPENDIX A Gantt Chart PSM 1

Task	W1	W2	W3	W 4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
Introduction														
1.1 Background														
1.2 Problem statement														
1.3 Research objective														
1.4 Scope of work														
1.5 Research methodology														
Literature review														
2.1 Introduction														
2.2 Background														
2.3 Load distribution in trucks														
2.4 Vehicle classification														
Methodology														
3.1 Introduction														
3.2 Development of the load distribution equation														
3.3 Summation of force & determining moment arm location														
3.4 Development of the equation for 2-axle model														

3.5 Simulation TruckSim														
Preliminary result														
4.1 Introduction														
4.2 Result of the acceleration test														
4.3 Summary														
Conclusion														
5.1 Conclusion														

APPENDIX B Gantt Chart PSM 2

Task	W 1	W 2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
Result and Discussion														
4.1 Introduction														
4.2 Acceleration test														
4.3 Braking test														
4.3 Determine tune value														
Conclusion and Recommendation														
5.1 Conclusion														
5.2 Recommendation for future works														

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