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Matiane, Arnold Ripfumelo

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UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

Fuel Saving Performance of Low Rolling Resistance Tyres on Heavy Goods Vehicles

Arnold Ripfumelo Matiane

(Student number: 1021961)

School of Mechanical, Industrial and Aeronautical Engineering

University of the Witwatersrand

Johannesburg, South Africa.

Supervisor: DR. M.D. Atkins

A research dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfilment of the requirements for the degree of Master of Science in Engineering.

11 August 2025

DECLARATION

I, Matiane Arnold Ripfumelo, do hereby declare that this dissertation is my own unaided work, except where specifically acknowledged. It is being submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfilment of the requirements for the degree of Master of Science in Engineering. It has not been submitted before for any degree or examination at any other University.

AI tools were used solely for proofreading, language enhancement, and correction of spelling and grammatical errors. The final work remains my own, and I accept full responsibility for its content and accuracy.



_____

Signature of Candidate

11 day of August year 2025

DEDICATION

I dedicate this research project to my late mother, Matiane Tsakani Alice and the important couple in my life, my uncle, Matiane Edward Hlulani and his wife, Mankhabidi MMasutwane Linky, who always believed in me, raised me to be who I am today and for their support throughout my years of schooling.

ABSTRACT

Understanding the real-world fuel-saving potential of low-rolling-resistance (LRR) tyres in heavy goods vehicles (HGVs) is vital for improving operational efficiency and reducing fuel costs in South Africa's logistics sector. This study evaluated two identical Scania R460 HGVs, each paired with 2020 Afrit 25 Cube Side Tipper Links trailers, one fitted with LRR tyres and one with conventional tyres. High-frequency data from the CAN bus was collected over three months across 45,000 km, yielding over 2,200 valid observations analysed using the SRF Miner methodology to isolate stable driving segments based on longitudinal acceleration, accelerator pedal position, RPM, vehicle speed, gear, and throttle position.

LRR tyres demonstrated a statistically significant fuel-saving benefit of 2.72 L/h (7.3%) across all terrain types under both segment-based (78 to 81 km/h) and route-based (79.5 to 80.5 km/h) analyses. Regression analysis confirmed that the benefit was independent of road gradient since slope coefficients were nearly identical for both tyre types (e.g., 536.6 L/h/rad vs. 527.3 L/h/rad uphill). Fuel savings were consistent across terrains, with reductions of 1.87 L/h (5.3%) on uphill, 1.87 L/h (5.4%) on flat, and 1.87 L/h (7.1%) on downhill segments. Slight variations in fuel savings across terrains under the route-based analysis can be attributed to differences in regression model fit, gravitational effects reducing engine load on downhill segments, and smaller sample sizes causing minor statistical fluctuations.

Economically, LRR tyres save R154,143 per truck annually at R20.16/litre, totalling R7.7 million for a 50-truck fleet in South African HGV operations. These findings highlight the operational and economic value of LRR tyres in enhancing fuel efficiency under real-world conditions.

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A special word of thanks goes to Grain Carriers, whose trucks were central to this research, being equipped with Controller Area Network (CAN) systems and fitted with both conventional and Low Rolling Resistance (LRR) tyres, allowing for a comprehensive assessment of fuel efficiency. Additionally, I am grateful to KDG Logistics, whose trucks were instrumental during the initial phase of the project when testing the SRF Logger and refining the data collection system. Their cooperation and willingness to support this study were invaluable. I would also like to extend my gratitude to Michelin for providing the tyres used in this study, which enabled a thorough evaluation of LRR tyre performance under real-world conditions.

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LIST OF ACRONYMS

ACEA - European Automobile Manufacturers Association

API – Application Programming Interface

CAN - Controller Area Network

CO_2 - Carbon Dioxide

CSIR - Council for Scientific and Industrial Research

ERRP - Economic Reconstruction and Recovery Plan

EPA - Environmental Protection Agency

FMS - Fleet Management System

GDP - Gross Domestic Product

GPS - Global Positioning System

HGV - Heavy Goods Vehicle

HVTT - Heavy Vehicle Transport Technology

KDE - Kernel Density Estimation

LLN - Law of Large Numbers

LRR - Low Rolling Resistance

PGN - Parameter Group Number

RPM - Revolutions Per Minute

RFA - Road Freight Association

SAWS - South African Weather Service

SRF - Sample Reduction Framework

STATSSA - Statistics South Africa

CHAPTER 1: INTRODUCTION

This chapter covers the motivation for this research project, the problem in question, the aims, objectives and the scope.

1.1. Problem Statement

Transportation plays a pivotal role in the functioning of any economy, and the efficiency of its operation is vital for fostering economic growth. Within the transportation sector, heavy goods vehicles (HGVs) hold considerable significance, particularly within the logistics and supply chain domains. This is evident in both the European Union, where trucks carry 77% of all freight transported over land (ACEA, 2022), and the United States, where truck transport accounts for about 71% of all freight shipments, generating approximately $800 billion in yearly revenue (Gillespie, 2022).

In South Africa, the transportation industry heavily relies on Heavy Goods Vehicles (HGVs) for the movement of goods (Taylor, 2021; Bridgewater Logistics, 2022). This sector plays a significant role in the country's economy, contributing approximately R270 billion added value to the economy, which accounts for about 6.5% of the GDP and offering an essential service to critical sectors like mining, agriculture, and manufacturing as outlined in the country's Economic Reconstruction and Recovery Plan (ERRP) (STATSSA, 2023).

However, the use of HGVs poses a pressing challenge in terms of fuel consumption and emissions. HGVs consume approximately 30% of the country's total fuel consumption and account for about 13% of South Africa's energy-related CO_2 emissions, according to a 2017 study conducted by the Department of Environmental Affairs (Stevens, 2017; Kienhöfer, et al. 2021). These figures emphasize the urgent need to address these issues to mitigate pollution, reduce fuel consumption, and tackle climate change concerns in the country.

1.2. Background and Justification of the Study

The trucking industry dominates goods transportation in South Africa, accounting for over 80% of total tonne-kilometres (Statista, 2021; Pillay, 2022). However, fuel costs pose a significant burden, comprising up to 40% of operating expenses for trucking

companies (Road Freight Association, 2020; Havenga, et al. 2016). To address this issue, there is a growing emphasis on fuel-efficient technologies for heavy goods vehicles (HGVs) to reduce their carbon footprint and operating costs.

1.2.1. Fuel-Saving Technologies for Heavy Goods Vehicles

Recent advancements in fuel-saving technologies for heavy goods vehicles (HGVs) have focused on optimizing a variety of systems, extending from powertrain components to auxiliary loads (Sharpe, 2017). Figure 1.1 (adapted from Sharpe, 2017) illustrates several critical areas of innovation, including improved engine design, idle reduction measures, advanced transmissions and drivelines, reduced accessory loads, weight reduction through material substitution, aerodynamic enhancements, telematics and intelligent controls, battery electric trucks (BEVs), and reduced rolling resistance tyres. Collectively, these interventions aim to curtail operational costs and environmental impacts by lowering overall fuel consumption and emissions. The subsections that follow provide a detailed examination of each of these technologies.

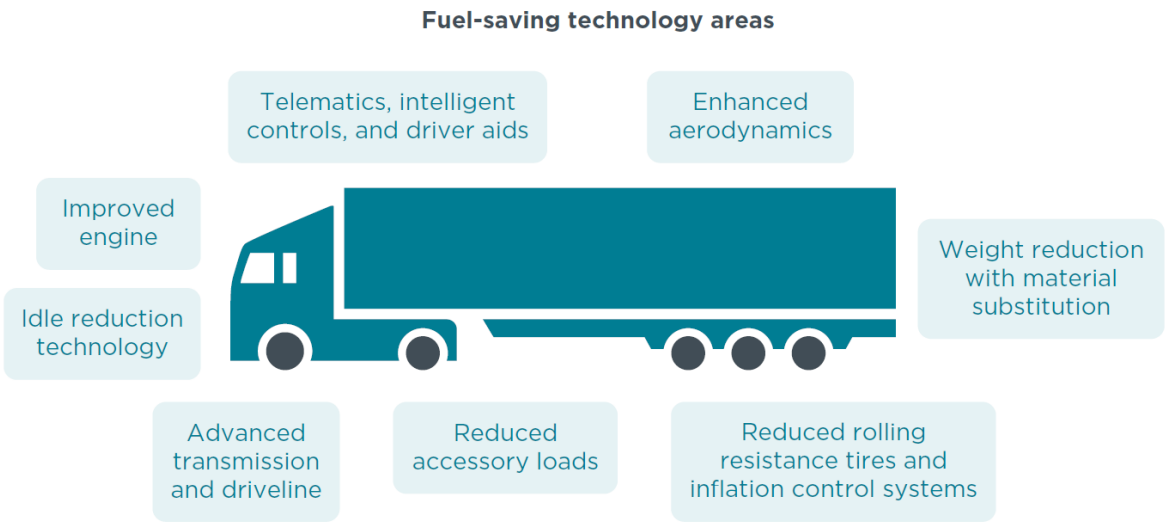


Figure 1.1: *Tractor-trailer fuel-saving technology (from Sharpe, 2017).*

- Improved Engine

Research efforts aimed at enhancing heavy-duty diesel and alternative-fuel engines typically focus on increasing brake thermal efficiency, a measure of how effectively the engine converts fuel energy into usable mechanical power at the output shaft, lowering frictional losses, and refining combustion processes (Clark et al., 2015). Substantial

progress in advanced turbochargers and high-pressure fuel injection systems has been shown to improve brake-specific fuel consumption (the amount of fuel required to produce a unit of power), reducing fuel use by around 8-10% compared to older engine designs (Christensen et al., 2010; Clark et al., 2015). For instance, engine platforms developed under the United States Department of Energy's SuperTruck program have demonstrated brake thermal efficiencies exceeding 50%, compared to baseline efficiencies of approximately 40-42% in conventional heavy-duty engines (Clark et al., 2015). Despite these improvements, practical constraints such as heat dissipation, nitrogen oxides (NO_x) aftertreatment, and increasingly stringent emissions regulations continue to pose challenges and necessitate ongoing research and development (Clark et al., 2015).

- Idle Reduction Technology

Idle reduction technology involves systems that eliminate unnecessary engine idling, thereby reducing fuel burn and associated pollutants (Argonne National Laboratory, 2021). Examples include automatic engine shut-off timers, auxiliary power units (APUs), and shore-power connections for stationary trucks. According to the U.S. Environmental Protection Agency, long-haul trucks can save up to 8% of their total fuel consumption by reducing idle time (EPA, 2019). The choice of idle reduction solutions depends on factors such as driver comfort requirements, route duration, and ambient climate conditions (Argonne National Laboratory, 2021).

- Advanced Transmission and Driveline

Transmission and driveline innovations exert a considerable influence on fuel efficiency. Adopting 6×2 transmission systems, also referred to as "dead axle" or "single drive" tractors, can decrease fuel consumption by around 4% (Lee and Cullinen, 2012). Automated manual transmissions (AMTs) further optimize shift points and engine speeds to reduce torque interruptions (Kobayashi et al., 2009; Christensen et al., 2010). These benefits are most pronounced during acceleration, hill climbing, or stop-and-go driving, highlighting the importance of selecting transmission architectures that match operational conditions (Lee and Cullinen, 2012).

- Reduced Accessory Loads

Reducing parasitic loads from accessories like air compressors, alternators, and air conditioning units can save 1.5% to 4% of fuel in long-haul operations (National Renewable Energy Laboratory [NREL], 2015). High-efficiency components and smart controls, such as electrified cooling fans cutting usage by up to 3% (NACFE, 2016), drive these gains. While individual vehicle savings may seem small, they multiply significantly across a fleet (National Academies of Sciences, Engineering, and Medicine, 2010). However, the high upfront costs of these upgrades can deter adoption (NREL, 2015).

- Enhanced Aerodynamics

Aerodynamic improvements focus on minimizing drag forces acting on the tractor-trailer. Fairings, side skirts, and streamlined mirrors can contribute significantly to reducing air resistance (Christensen et al., 2010). A single aerodynamic surface, such as a roof-mounted deflector, may improve fuel efficiency by over 5% (EPA SmartWay, 2010), while combining multiple surfaces can raise this figure to 15% for older trucks and 3-11% for newer ones (EPA SmartWay, 2010). These enhancements demonstrate their greatest effectiveness at higher speeds and during sustained long-haul operations (Kobayashi et al., 2009; Christensen et al., 2010).

- Weight Reduction with Material Substitution

Curb weight plays a central role in determining fuel efficiency. Reducing a trailer's unladen mass by 25% can yield fuel savings of about 6.5% (Odhams et al., 2010). Lightweight materials, such as aluminium or advanced high-strength steel, improve energy efficiency, especially when accelerating or maintaining cruising speeds (Joost, 2012). Designers must, however, balance weight reduction with structural requirements and safety standards. Substantial load-carrying duties often limit the extent to which truck and trailer weights can be reduced (Odhams et al., 2010).

- Battery Electric Trucks (BEVs)

Battery electric trucks rely on electric motors and onboard battery packs, resulting in zero tailpipe emissions and 15–20% higher energy efficiency through regenerative

braking and idle elimination (Mecalux, 2022). A recent South African demonstration revealed the capability to traverse 600 km from Durban to Johannesburg with a single charging stop (Venter, 2023). Although BEVs hold promise for reducing carbon footprints, barriers include high initial capital expenditure and limited charging infrastructure, especially for long-haul routes (Lee and Cullinen, 2012).

- Telematics, Intelligent Controls, and Driver Aids

Telematics systems, such as those provided by commercial Telematics Service Provider (TSP) units, leverage real-time data to enhance operational efficiency in heavy goods vehicles (HGVs). These systems connect to the vehicle's Controller Area Network (CAN) bus through the Fleet Management System (FMS) gateway, capturing metrics such as cumulative fuel consumption, distance travelled, and speed at sampling intervals ranging from 6 to 60 seconds (Atkins et al., 2023; Szalay et al., 2015). Fleet managers utilize this data to monitor key performance indicators, including idle duration and driver behaviour, which enables targeted interventions to reduce operational costs. Research demonstrates that integrating TSP units with driver training programs can achieve fuel savings of 5 to 7% in long-haul operations by addressing inefficiencies like excessive idling and harsh braking (NACFE, 2020; Walnum & Simonsen, 2015).

In contrast, the SRF-Logger, a novel high-resolution vehicle monitoring system developed by the Centre for Sustainable Road Freight at the University of Cambridge, provides advanced capabilities beyond conventional TSP units, which typically update data every 60 seconds (fleet tracking) or record CAN bus data at a maximum interval of 6 seconds (Atkins et al., 2023). Operating at a 10 Hz sampling rate (0.1-second intervals), the SRF-Logger records detailed data channels such as vehicle speed, fuel use, combination vehicle weight, and elevation changes, offering significantly higher granularity (Atkins et al., 2023; Na & Cebon, 2022). Intelligent controls, including predictive cruise control and eco-routing algorithms, leverage GPS and topographic data to optimize driving strategies, potentially delivering fuel savings of 8 to 10% across varied terrains (González et al., 2019; Xiang et al., 2015).

- Reduced rolling resistance tyres

Low Rolling Resistance (LRR) tyres have emerged as a prominent solution for improving fuel economy and reducing operating costs in the trucking industry. LRR tyres are specifically designed to minimize the energy loss caused by rolling resistance between the tyre and the road, resulting in lower fuel consumption (Lee and Cullinen, 2012; NACFE, 2020). Compared to other fuel-saving technologies discussed earlier, LRR tyres offer distinct advantages that make them an ideal choice for optimizing fuel efficiency in heavy-duty trucks. Rolling resistance contributes for 30% to 33% of a truck's fuel expenditure. Low rolling resistance tyres are a simple approach for fleets to minimize fuel usage at little or no additional cost (NACFE, 2020). However, the total cost of ownership of LRR tyres, including factors such as durability and maintenance, remains uncertain (BigRoad, 2021; Roeth, 2020).

In the trucking industry, LRR tyres have gained popularity due to their potential for fuel savings. According to research done by the North American Council for Freight Efficiency (NACFE), the use of LRR tyres can result in up to a 4% improvement in fuel efficiency for long-haul trucks (NACFE, 2017). This improvement in fuel efficiency can translate to significant cost savings for trucking companies, which has led to an increased adoption of LRR tyres in the industry.

Furthermore, LRR tyres constitute an efficient and practical approach to improving fuel efficiency in heavy goods vehicles (HGVs). Once fitted, they consistently reduce fuel consumption without requiring complex auxiliary systems or ongoing driver oversight, delivering measurable benefits over the tyre’s operational lifespan (Goodyear, 2023; Atkins et al., 2023). In contrast to technologies such as telematics or predictive cruise control, which necessitate continuous driver training or real-time data processing, LRR tyres function independently of additional operational oversight (Hu et al., 2022; Atkins et al., 2023). This operational autonomy and ease of deployment establish LRR tyres as a viable option for trucking companies pursuing sustainable and cost-effective practices.

LRR tyres effectively target rolling resistance, a primary factor in HGV fuel consumption, by reducing the energy dissipated through tyre deformation during road contact (Goodyear, 2023). Unlike aerodynamic modifications that minimize drag via

streamlined profiles or advanced powertrains that optimize torque delivery through transmission enhancements, LRR tyres employ silica-enhanced rubber compounds and optimized tread patterns to limit deformation losses (Michelin, 2023). This design approach improves fuel efficiency in long-haul conditions, enabling HGVs to achieve reduced fuel consumption and lower carbon dioxide emissions, distinct from the broader systemic improvements offered by alternative technologies (Goodyear, 2023; Hu et al., 2022).

Several studies have investigated the fuel saving potential of LRR tyres for trucks in other countries. Na and Cebon (2022) found that LRR tyres resulted in a fuel saving benefit of 2.11 L/h with plus or minus 0.20 L/h, equivalent to a percentage reduction of 6.89% to 8.37% compared to a baseline of flat road fuel consumption. The United States Department of Energy reported fuel savings of up to 4% for heavy-duty trucks with LRR tyres (Morrow, et al. 2013), while a study in Europe found potential fuel savings of up to 7% for long-haul trucks (Palm, et al. 2011).

1.2.2. Relevance of LRR Tyres in South Africa

The applicability of international findings on low rolling resistance (LRR) tyres to the South African context remains uncertain due to distinct local factors influencing fuel efficiency. Driving conditions, including traffic patterns, average speeds, and road congestion, vary significantly and can alter the fuel-saving potential of LRR tyres. For instance, heavy congestion on the N1 highway near Johannesburg, where average speeds drop to 20-30 km/h during peak hours, increases idling and stop-start cycles, potentially reducing LRR tyre benefits by up to 2-3% compared to free-flowing conditions (Havenga et al., 2016; Atkins et al., 2023). Additionally, South Africa's climate, with high temperatures in summer (often exceeding 30°C), may accelerate tyre wear, further affecting rolling resistance and fuel consumption (Zhang et al., 2017).

Road infrastructure quality and design also play a critical role, directly impacting rolling resistance. South Africa's road network includes well-maintained highways like the N3 alongside poorly maintained rural roads with uneven surfaces, increasing rolling resistance by up to 10% on degraded sections (Kienhofer et al., 2021). The country's diverse topography, spanning flat coastal plains, the steep Drakensberg gradients (e.g., 10% inclines), and undulating inland hills, adds complexity. Steep ascents, such

as those on the Van Reenen's Pass (elevation gain of 569 m), elevate fuel consumption by approximately 5-7% compared to level terrain, challenging LRR tyre efficacy under such conditions (Atkins et al., 2023; Na & Cebon, 2022).

Moreover, South Africa's vehicle fleet, predominantly diesel-powered with an average age exceeding 10 years, and its reliance on high-sulphur diesel (up to 50 ppm), differ from fleets and fuels in Europe or North America (STATSSA, 2023; Atkins et al., 2023). These specifications, older engines with lower efficiency and heavier vehicle weights (often 50-55 tonnes), can diminish LRR tyre performance, while fuel properties may increase combustion inefficiencies, reducing overall savings. LRR tyres mitigate rolling resistance, which accounts for 30-33% of HGV fuel use, by minimizing hysteresis losses through advanced rubber compounds and tread designs (NACFE, 2020; Kienhofer et al., 2021). However, localized studies are essential to quantify these benefits, as international savings can be significantly reduced on South Africa's challenging routes with substantial elevation changes, such as the N3 corridor, where fuel consumption increases by approximately 17% on steeper segments compared to flatter terrain (Atkins et al., 2023; Kienhofer et al., 2021).

Despite their potential, LRR tyre adoption faces challenges in South Africa. High upfront costs, as noted in Norway (Strube & Gotaas, 2017), remain a barrier, with prices 5-10% above conventional tyres, deterring cash-strapped fleets (Michelin, 2023). Additionally, rough road surfaces, common in rural areas, can limit savings to 2-4% compared to 7% on smooth highways, due to increased friction (Zhang et al., 2017; Kienhofer et al., 2021). This project aims to assess LRR tyre impacts on HGVs in South Africa, considering driving conditions, road quality, costs, and availability. By providing localized data, it seeks to clarify benefits, potentially 4-6% fuel savings, and challenges, informing policy to reduce HGV fuel use and emissions.

The aim of this project is to assess the impact of LRR tyres on HGVs in South Africa, considering the local driving conditions, road quality, cost, and availability of these tyres. This will provide valuable insights into the potential benefits and challenges associated with the adoption of LRR tyres in the South African trucking industry and could inform policy decisions aimed at reducing fuel consumption and emissions from HGVs.

1.3. Aim and Objective

1.3.1. Main Aim

The main aim of this project is to assess the impact of LRR tyres on HGVs in South Africa, considering the local driving conditions, road quality, cost, and availability of these tyres.

1.3.2. Specific Objectives

- To investigate the impact of LRR tyres on fuel consumption in HGVs operating in South Africa.
- To compare the fuel consumption of trucks equipped with low rolling resistance tyres to those with conventional tyres.
- To assess the cost-benefit of using low rolling resistance tyres for trucking companies in South Africa.
- To develop a better understanding of the factors that influence fuel consumption in HGVs in South African conditions.

1.4. Hypotheses

- HGVs equipped with LRR tyres during in-service test will consume less fuel and emit fewer emissions compared to those equipped with conventional tyres in South African conditions.
- Vehicle weight, and road gradient will significantly influence fuel consumption on HGVs in South Africa.
- The potential fuel savings and emissions reductions that can be achieved by using LRR tyres on HGVs in South Africa will be significant, and comparable to or greater than estimates from other regions.

1.5. Scope of the Project

This project assessed the impact of low rolling resistance (LRR) tyres on heavy goods vehicles (HGVs) in South Africa. The study investigated fuel consumption, vehicle efficiency, and economic feasibility within the local trucking industry.

To achieve this, the project involved several key steps:

- **Sample and Data Selection:** Two identical Scania R460 heavy goods vehicles (HGVs), each paired with 2020 Afrit 25 Cube Side Tipper Links trailers, underwent in-service testing on South African roads. One vehicle and its trailer were fitted with conventional tyres, referred to as "black tyres" due to their standard rubber composition, while the other vehicle and its trailer were equipped with low rolling resistance (LRR) tyres, termed "green tyres" for their fuel-efficient design. Data was collected over a period of three to four months, during which each vehicle completed over 190 trips. Fuel consumption, speed, vehicle weight, road elevation, and environmental data were gathered using onboard sensors, GPS devices, and weighbridge records to ensure a comprehensive analysis.

- **Driving Conditions and Testing Environment:** The tests were conducted under real-world conditions typical of South Africa’s trucking industry, distinguished by its broad range of terrains and climates. These unique conditions include flat coastal plains prone to humidity, rugged inland hills with sharp gradients, and rural routes with inconsistent pavement quality, spanning provinces such as Gauteng, Free State, Western Cape, Eastern Cape, and KwaZulu-Natal.

- **Fuel Consumption and Performance Analysis:** The study focuses on comparing the fuel consumption of the HGVs equipped with green tyres to those with black tyres, particularly under constant-speed driving conditions. Specific emphasis was placed on performance metrics between speeds of 78-81 km/h, which represent typical long-haul trucking operations. Data analysis was centred on determining the percentage of fuel savings achieved with green tyres under these conditions, as well as identifying the driving factors

influencing fuel efficiency, such as vehicle weight, road gradient, and environmental conditions.

- **Weight Distribution and Load Variability:** The project examined the effect of vehicle load on fuel consumption. Both vehicles operated predominantly with gross vehicle masses between 50 and 55 tonnes, a standard range in South Africa. This uniformity in load enabled the study to isolate the influence of tyre type on fuel efficiency, minimizing variations due to weight differences.

- **Data Collection Methods:** Data was obtained through multiple channels, including the vehicles' Controller Area Network (CAN) bus for operational data like fuel consumption and speed, GPS devices for route mapping, and weighbridges for precise load measurements. A smartphone-based data logging system also captured GPS, elevation, and driver input data, ensuring a robust and comprehensive dataset.

- **Limitations:** The study did not explore the long-term durability or life cycle of LRR tyres, nor did it assess their maintenance costs. Additionally, while it collected valuable fuel consumption data under real-world conditions, the impact of LRR tyres on other performance aspects, such as handling and safety, was excluded from this investigation.

In summary, the scope of this project is limited to assessing the fuel-saving potential and economic feasibility of LRR tyres for HGVs in South Africa, with an emphasis on real-world driving conditions, operational performance, and local environmental factors. It does not extend to evaluating other fuel-saving technologies, tyre life cycle assessments, or industrial-scale implementation strategies.

CHAPTER 2: LITERATURE REVIEW

The literature review investigates the effectiveness of Low-Rolling-Resistance (LRR) tyres (green tyres) in improving fuel efficiency for Heavy Goods Vehicles (HGVs), with a focus on their application in South Africa. This review examines the characteristics of LRR tyres, their mechanisms for fuel-saving, the history of their development, and compares their performance with conventional tyres (black tyres). A comprehensive analysis is provided on the global and South African studies on LRR tyres, including the challenges of real-world fuel efficiency assessments and the role of data mining and telematics. This chapter also highlights gaps in existing research, emphasizing the need for region-specific studies to assess the viability and benefits of LRR tyres under South African conditions.

2.1. Introduction to Low-Rolling-Resistance (LRR) Tyres

Low-Rolling-Resistance (LRR) tyres are engineered to minimize energy loss during rolling, reducing the resistance between the tyre and the road surface. This makes them particularly valuable for heavy goods vehicles (HGVs) on long hauls, where fuel efficiency is critical. This section combines a theoretical understanding of rolling resistance with the practical characteristics and fuel-saving mechanisms of LRR tyres, illustrating how these elements work together to enhance sustainability and reduce operational costs.

2.1.1. Theoretical Background: Rolling Resistance and Hysteresis

Rolling resistance refers to the force that acts against the movement of an object, such as a ball, tyre, or wheel, as it rolls on a level surface (Khanger, & Bardhan, 2015; Jaswal, et al., 2017). The unit commonly used to measure rolling resistance is either joules per meter (J/m) or newtons (N). The main factor contributing to tyre rolling resistance is a phenomenon called hysteresis. Hysteresis is a property of deformable materials where the energy required for deformation is greater than the energy released during recovery. The rubber compound used in tyres exhibits hysteresis, which leads to rolling resistance.

In addition, rolling resistance is typically measured using a rolling resistance coefficient (*RRc*) (Figure 2.1), which represents the ratio of the force needed to keep the tyre

rolling to the weight on the contact patch. As more weight is placed on the contact patch, the tyre's rolling resistance increases because the rolling frictional coefficient of a tyre is always greater than zero. These forces account for approximately 30% of the total tractive force and hold equal significance in both urban and highway driving contexts (Kobayashi, et al., 2009).

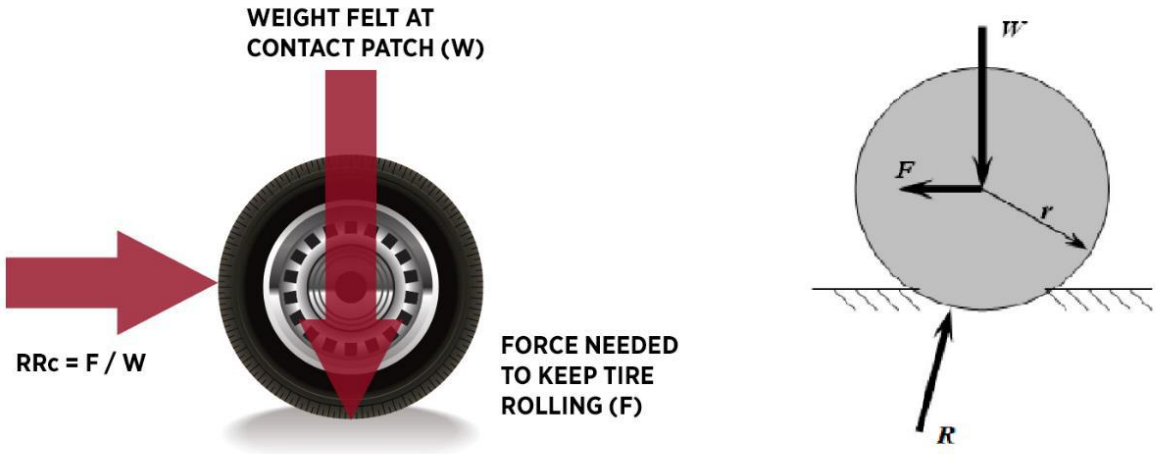


Figure 2.1: *Rolling resistance coefficient (modified from Jaswal, et al., 2017; NACFE, 2020).*

Figure 2.1 illustrates the concept of a solid wheel rolling on a soft surface and causing deformation. As a result of this deformation, the surface exerts a reaction force called *R*, which has a component that opposes the motion of the wheel. In this scenario, there is a vertical load denoted by *W* acting on the axle, and a towing force denoted by *F* applied to the axle. The radius of the wheel is represented by *r*. It is assumed that both friction with the ground and friction at the axle can be ignored, so they are not depicted in the figure. The wheel is rolling to the left at a constant speed. It is important to note that the force *R* arises from the uneven pressure distribution at the contact surface between the wheel and the roadbed. This pressure is higher towards the front of the wheel due to hysteresis (Jaswal, et al., 2017).

2.1.2. Characteristics of LRR Tyres

Low-Rolling-Resistance (LRR) tyres reduce energy loss during rolling by minimizing the resistance between the tyre and the road surface, making them ideal for heavy goods vehicles (HGVs) on long hauls. This reduction is achieved by blending silica-based rubber with silane coupling agents, such as triethoxysilane, which bond silica

to rubber polymers, enhancing elasticity and reducing hysteresis, the heat lost when rubber deforms and recovers, thereby improving fuel efficiency with less energy waste (Wang et al., 2019). For instance, Bridgestone's Ecopia HGV tyres, featuring a silica-rich NanoPro-Tech compound, achieve a 15% reduction in rolling resistance according to company tests (Bridgestone, 2021).

Additionally, treads with shallow depths, fewer slits, and broad contact patches, like Michelin's X Line Energy with angled grooves, limit flexing and decrease energy loss by 10% (Tire Technology International, 2023). Unlike conventional designs with deep, grip-heavy treads, LRR tyres prioritize fuel efficiency while maintaining performance (Continental, 2022).

2.1.3. Fuel-Saving Mechanisms

The core fuel-saving mechanism of LRR tyres lies in their ability to minimize energy wasted through hysteresis. As the tyre rolls, it undergoes repeated cycles of deformation and recovery, dissipating energy as heat. This dissipated energy must be replenished by the engine to maintain the vehicle's speed. By reducing this energy loss using silica compounds and optimized tread designs, LRR tyres enable the vehicle to maintain a constant speed with reduced engine power (Hyttinen et al., 2023).

Consequently, this design significantly reduces the energy required to overcome rolling resistance, which constitutes 25 to 33% of an HGV's fuel consumption depending on load and speed (Schuring and Futamura, 2020). Figure 2.2 illustrates the stress-strain curve of rubber, highlighting hysteresis as the energy lost in each cycle (Hyttinen et al., 2023).

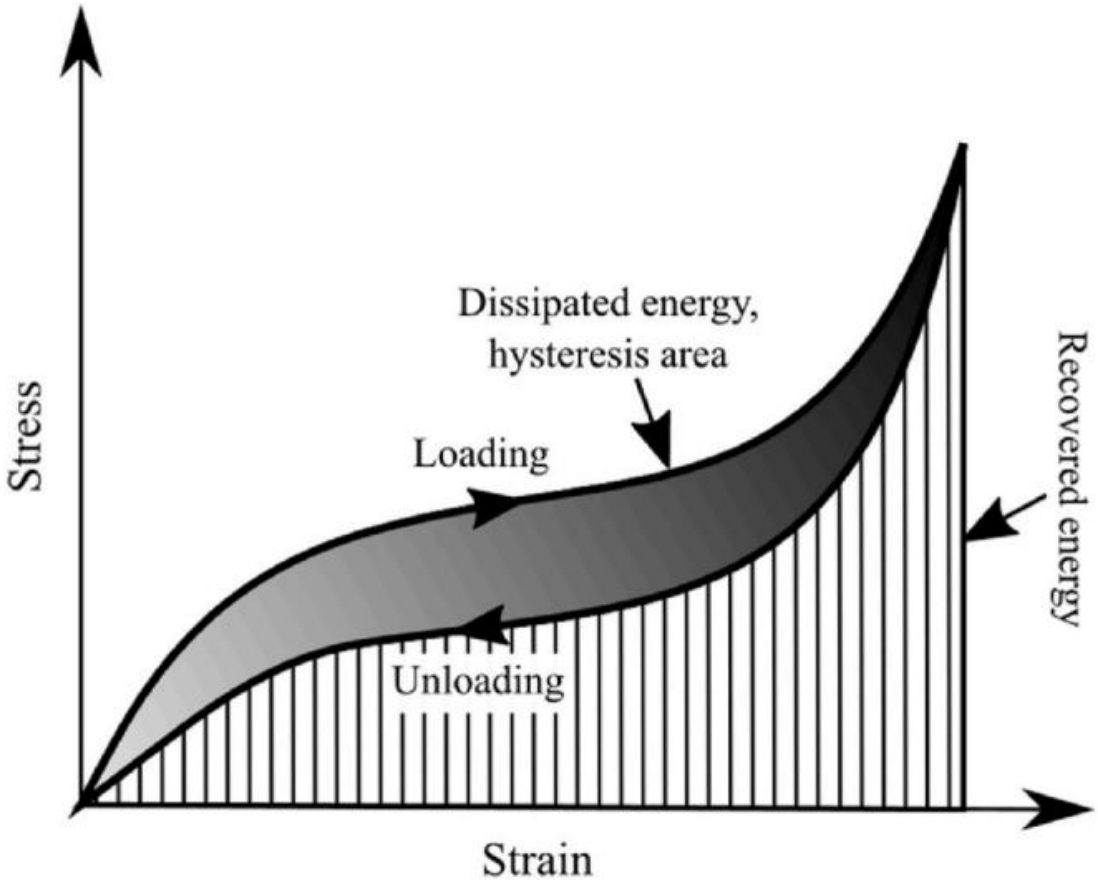


Figure 2.2: *Stress-strain illustration during loading and unloading of viscoelastic material, such as rubber (Hyttinen et al., 2023).*

LRR tyres can increase driving range by 6 to 7%, as shown in Figure 2.3 (Giti Tire Group, 2023), with specific examples like Goodyear's Fuel Max LHS tyres saving 4 to 6% fuel at speeds of 80 to 90 km/h (Goodyear, 2022). However, tyre pressure and road conditions also affect performance; underinflation can increase resistance by up to 30%, underscoring the importance of regular maintenance (Michelin, 2023). These attributes make LRR tyres a strategic choice for fleets aiming to enhance sustainability and reduce costs during steady-speed operations.

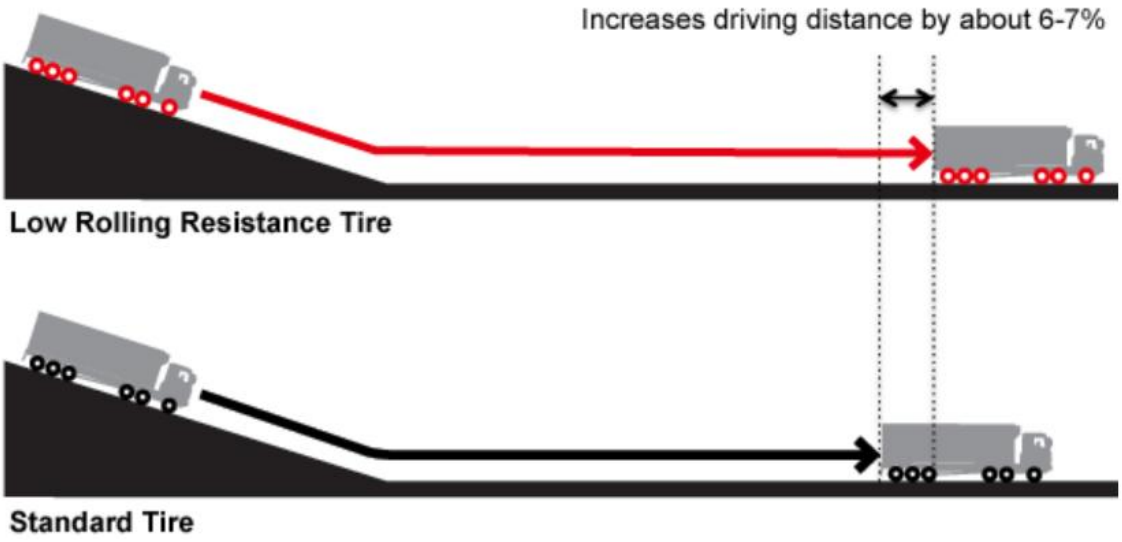


Figure 2.3: *Increased driving distance achieved with low-rolling-resistance tyres compared to standard tyres, indicating a 6-7% improvement in driving range due to reduced rolling resistance* (*Giti Tire Group, 2023).*

2.1.4. History and Development

The development of low-rolling-resistance (LRR) tyres began in the 1970s when oil prices jumped from $3 to $12 per barrel, fuelling demand for efficient vehicle solutions (EIA, 2023). Early Initial designs used radial-ply constructions, with cords perpendicular to the travel direction, decreasing internal friction and heat compared to bias-ply tyres (Schuring, 1994). Manufacturers explored harder rubber compounds, such as high-saturation styrene-butadiene rubber (SBR) with added fillers, to reduce deformation. These formulations improved efficiency but reduced elasticity, wet grip, and tread life, which limited adoption among fleet operators (Michelin, 2023a).

A significant change occurred in the early 1990s with silica-based compounds. Mixing silica with silane coupling agents, such as bis(triethoxysilylpropyl) tetrasulfide, reduced the rubber's loss tangent (*tan δ*) by 15–20% compared to carbon black mixes, lowering hysteresis while enhancing wet traction (Aldhufairi & Olatunbosun, 2018). Michelin's Green X tyres, launched in 1993, combined silica with synthetic SBR and silane, achieving approximately 5% fuel savings in lab tests (Michelin, 1995). During the late 1990s and early 2000s, Bridgestone, Goodyear, and Michelin enhanced these improvements with highly dispersible silica, optimized polymer blends, and stiffer carcasses using aramid fibres (e.g., Kevlar) instead of rayon. These materials

decreased flexing and weight, with lab tests showing 15-20% less hysteresis loss (Kobayashi et al., 2009).

Regulatory measures encouraged adoption in the 2010s. The U.S. EPA SmartWay programme and EU tyre labelling rules (EC 1222/2009, updated 2021) required clear performance data, promoting LRR use. By 2020, over 80% of new long-haul trucks in North America featured LRR tyres, with fuel costs over a tyre's life estimated at five times its purchase price (NACFE, 2020). After 2020, Bridgestone's 2022 Ecopia H002 tyres reduced rolling resistance by 10% using nano-scale silica dispersion, while Goodyear's 2024 Endurance LHS decreased fuel use by 7% with recycled carbon black (Bridgestone, 2022; Goodyear, 2024). In South Africa, diesel costs rose from an average of R10.75 per litre in 2012 to R20.58 in 2024 (FIASA, 2025), prompting research into LRR tyre efficiency on South Africa's demanding roads.

2.1.5. Comparison: Low Rolling Resistance (Green tyre) vs Conventional Tyres (Black Tyre)

Low-rolling-resistance (LRR) tyres and conventional heavy-duty tyres (often termed "black" tyres due to carbon-black compounds) differ significantly in performance attributes relevant to heavy goods vehicles (HGVs):

- Rolling Resistance and Fuel Efficiency

LRR tyres exhibit a lower rolling resistance coefficient due to their design. Laboratory measurements indicate Michelin X Line Energy LRR tyres reduce rolling resistance by approximately 15% compared to Michelin X Multi conventional tyres, with coefficients of 0.0060 versus 0.0071 (Kienhöfer et al., 2021). Track tests at Gerotek, South Africa, showed these LRR tyres achieving 8-10% fuel savings (8.8% average) over conventional tyres at 80 km/h for 56-tonne HGVs (Kienhöfer et al., 2021). Conventional tyres, with higher hysteresis, dissipate more energy as heat, increasing fuel use. Research suggests a 10% reduction in rolling resistance yields 1–2% better fuel economy (Edmunds, 2013), a threshold LRR tyres consistently surpass (Kobayashi et al., 2009).

- Traction and Handling

Early concerns about LRR tyres compromising traction, particularly on wet surfaces, have diminished with modern designs incorporating silica and refined tread patterns. These ensure comparable wet and dry grip, with wet braking differences under 0.3 meters (Smith, 2018; Johnson, 2019). Handling and stability remain equivalent for highway operations, preserving cornering stiffness and responsiveness (FleetOwner, 2020a). Conventional tyres excel in extreme conditions, such as deep mud or heavy snow, where aggressive treads enhance traction (Lee & Cullinen, 2012). In South Africa, steep gradients like Van Reenen's Pass test both tyre types, with LRR tyres maintaining performance parity under typical on-road use (Kienhöfer et al., 2021).

- Durability and Tread Wear

Conventional tyres historically outlast early LRR designs due to deeper treads and robust compounds, typically achieving 120,000-150,000 km in long-haul HGV service before retreading, based on South African fleet data (Havenga & Simpson, 2014). Early LRR tyres, with shallower treads to reduce rolling resistance, averaged 100,000-110,000 km, a 17-25% reduction (Edmunds, 2013). Kienhöfer et al. (2021) report a 33% higher wear rate for Michelin X Line Energy LRR tyres compared to X Multi conventional tyres, translating to an estimated lifespan of 90,000-100,000 km versus 120,000-135,000 km for conventional tyres under similar 56-tonne HGV operating conditions, assuming 20,000 km annual usage before testing (Kienhöfer et al., 2021). A 2023 industry report confirms conventional truck tyres average 140,000 km, while LRR tyres reach 115,000 km with optimized silica compounds, a 17.9% difference (Tire Review, 2023). Proper maintenance, such as inflation at 8.5 bar, extends LRR life to 120,000 km, reducing the gap to 14% (Consumer Reports, 2024). In South Africa, high loads and temperatures above 30°C accelerate wear, yet LRR tyres' cooler operation (5-12°C below conventional) mitigates this, supporting durability (Kienhöfer et al., 2021).

- Load and Heat Resilience

Both tyre types meet identical load ratings (e.g., 8-10 tonnes per axle), with LRR tyres built on robust carcasses (Kienhöfer et al., 2021). LRR tyres operate 5-12°C cooler due to lower energy dissipation, enhancing longevity (Kienhöfer et al., 2021).

Conventional tyres remain preferred for severe off-road use, such as construction sites, where cut resistance is critical (FleetOwner, 2020a). For highway and regional service, including South Africa's high-load freight routes, LRR tyres demonstrate sufficient resilience (Kienhöfer et al., 2021).

- Cost Considerations

The adoption of Low Rolling Resistance (LRR) tyres involves specific cost considerations, particularly in South Africa's fleet operations. According to Freight News (2024), LRR tyres cost between R5,500 and R6,000 per tyre, compared to R4,800 to R5,200 for conventional tyres, a premium of 14 to 15%. Kienhöfer et al. (2021) found that LRR tyres reduce fuel consumption for Heavy Goods Vehicles (HGVs) by 8 to 10%, equating to a fuel cost reduction factor of 0.912 for a 56-tonne HGV traveling 100,000 km annually at 36 litres per 100 km. With diesel prices rising from R10.75 per litre in 2012 to R20.58 in 2024 (FIASA, 2025), these savings become significant. However, Kienhöfer et al. (2021) also note a 33% increase in tyre lifespan costs due to faster wear. FleetOwner (2024) suggests that over distances exceeding 100,000 km, LRR tyres' fuel savings and reduced vehicle wear can offset their higher initial cost. Consumer Reports (2024) reinforces this, stating that total cost of ownership, factoring in fuel and maintenance savings, often justifies LRR adoption in high-fuel-cost regions like South Africa.

2.2. Environmental Impact of Improving Fuel Efficiency

From an environmental perspective, enhancing HGV fuel efficiency directly contributes to lower emissions. Diesel combustion is a major source of carbon dioxide (CO_2), nitrogen oxides (NOx) and particulate matter (PM). Studies have shown that reducing fuel consumption by 4-10% can correspondingly reduce CO_2 emissions by a similar margin (Guttikunda et al., 2014). For instance, if a heavy truck burns 40,000 litres of diesel per year, and each litre produces roughly 2.68 kg of CO_2, a 4% fuel reduction would lower annual CO_2 emissions by about 4,300 kg (IPCC, 2006). Moreover, lower fuel consumption means reduced generation of NOx and PM, which are critical in urban air quality and public health (Guttikunda et al., 2014). In South Africa, where HGV emissions contribute substantially to the national carbon footprint, improved fuel efficiency is pivotal in meeting international climate commitments such as those

outlined in the Paris Agreement (Stevens, 2017). In addition, government and industry reports highlight that efficiency improvements not only cut emissions directly but also help reduce reliance on imported fuel, thereby contributing to national energy security (CSIR, 2020a).

2.3. Methods for Assessing Fuel-Saving Benefits

The assessment of fuel-saving benefits from technologies like Low-Rolling-Resistance (LRR) tyres in Heavy Goods Vehicles (HGVs) is pivotal for improving operational efficiency and mitigating environmental impact in freight transport. This evaluation demands methodologies that can precisely measure the impact of tyre performance on fuel consumption, balancing controlled precision with real-world applicability. Two predominant approaches are employed: test track tests, which provide a controlled environment for isolating tyre effects under repeatable conditions, and in-service tests, which capture performance amidst the complexities of actual operations. This section offers a comprehensive analysis of these methods, detailing their technical underpinnings, prior applications, and limitations. For test track tests, the focus encompasses multiple techniques with specific examples, while in-service tests zero in on conventional Telematics Service Providers (TSP) and the novel SRF-Logger system, both enriched with quantitative data and contextual insights from recent studies.

2.3.1. Test Track Tests

Test track tests are conducted in controlled facilities such as South Africa's Gerotek Test Facilities or the Texas A&M Transportation Institute's proving grounds, where variables like road surface texture, and vehicle load can be meticulously regulated. This controlled setting is essential for isolating the fuel-saving potential of LRR tyres, allowing researchers to eliminate external influences that might obscure tyre-specific effects (Kienhöfer et al., 2021). By standardizing conditions such a smooth asphalt surface with a friction coefficient of 0.7, and monitoring wind speed and direction to remain below 5 km/h where feasible, these tests ensure high precision and repeatability despite the challenges in fully controlling wind conditions (Brandt et al., 2010). Such attributes are critical for tyre manufacturers and fleet operators seeking reliable data to validate performance claims before widespread adoption. However,

the artificial nature of these environments limits their ability to reflect real-world challenges like varying road gradients, traffic-induced speed fluctuations, or driver variability, necessitating a careful interpretation of results.

One widely adopted method is the SAE J1321 Type II Testing Protocol, a standardized procedure designed to measure fuel consumption differences between two HGVs: one fitted with LRR tyres and a control vehicle with conventional tyres. This approach involves operating both vehicles simultaneously over a defined circuit, typically a 50 km to 100 km loop, under identical conditions (Brandt et al., 2010). For example, a test might involve two identical 7-axle interlink trucks, each loaded to 56 tonnes, driven at a constant 80 km/h (Kienhöfer et al., 2021). Fuel consumption is measured with high precision by weighing portable fuel tanks before and after each run, achieving an accuracy of ±0.05 kg using calibrated scales (SAE International, 2012). To ensure robustness, the protocol requires multiple runs, often three to five, with results averaged to minimize variability. Environmental controls are strict: wind speeds must not exceed 10 km/h (ideally below 5 km/h), temperatures must range between 10°C and 30°C, and the road surface must remain consistent, such as asphalt with a friction coefficient of 0.7 (Brandt et al., 2010). Fuel savings are then calculated as a percentage reduction in consumption.

Kienhöfer et al. (2021) applied this method at Gerotek, testing two identical 7-axle interlink tautliner combinations: one fitted with Michelin X Line Energy (LRR) tyres and the other with Michelin X Multi (conventional) tyres over a high-speed oval track. Each vehicle, loaded with 2-tonne cement pallets to a gross combination mass of 56 tonnes, was driven at 80 km/h using cruise control for four 2-hour sessions per day over two days, totalling approximately 640 km per vehicle daily. Fuel usage was measured via CAN bus data and manual fuel pump readings (precision ±0.1 L), yielding savings of 8% to 10% (average 8.8%) for the LRR tyres, with daily consumption around 600 L per vehicle (Kienhöfer et al., 2021). This result exceeds typical industry benchmarks of 4-6% due to factors like high vehicle mass and lower air density at Pretoria's 1340 m altitude (Bradley and Delaval, 2011). Brandt et al. (2010) conducted similar trials in the U.S., using three M1083A1 FMTVs on a 42-mile (67.6 km) test cycle at two speeds (averaging 48 km/h) and achieving a 1.5% reduction in engine-related fuel consumption when switching from OE/HDO-15/40 to OEA-30 Arctic oil, though their

focus was on lubricants rather than tyres (Brandt et al., 2010). These results underscore the method's precision, yet its sensitivity to minor deviations, such as a 5 km/h wind gust increasing consumption by 0.5 L/100 km (Brandt et al., 2010), requires rigorous control. The short duration of these tests also limits their relevance for technologies needing long-term assessment, like tyre wear effects.

Another technique, Coast-Down Testing, assesses driving resistance by measuring an HGV's deceleration when coasting in neutral, providing an indirect gauge of rolling resistance and fuel savings. Typically, a heavy vehicle is accelerated to a high speed on a flat track with minimal gradient, then shifted into neutral, coasting until it slows significantly, with speed and time logged at regular intervals using GPS units with ±0.1 km/h accuracy (SAE International, 2010). This allows calculation of the rolling resistance coefficient, such as 0.0060 for LRR tyres versus 0.0071 for conventional tyres, indicating reduced resistance that correlates to fuel savings (Kienhöfer et al., 2021). Aerodynamic drag is separated from rolling resistance using a model of fixed proportions of the energy loss mechanisms that assigns 32% of energy loss to rolling resistance, 53% to aerodynamic drag, and 15% to auxiliary and drivetrain losses. Adjustments for vehicle mass, air density, and speed are applied to improve accuracy (Kienhöfer et al., 2021). Tests are conducted in both directions to neutralize wind and slope effects, with wind speeds ideally below 5 km/h.

Kienhöfer et al. (2021) measured rolling resistance using a customized rolling road test rig, obtaining a coefficient of 0.0060 for Michelin X Line Energy tyres and 0.0071 for Michelin X Multi tyres on a 2 km straight, supporting their full-scale test savings of 8-10% (Kienhöfer et al., 2021). Six runs were averaged to account for wind averaging 3 km/h, ensuring statistical reliability. The U.S. EPA's Greenhouse Gas Emissions Model (GEM) incorporates coast-down data, predicting a 3% saving (approximately 1 L/100 km at 35 L/100 km) when resistance drops from 0.0075 to 0.0065 (ICCT, 2015). However, the method's reliance on ideal conditions is a drawback; a 1% gradient can inflate resistance by 10% (Kienhöfer et al., 2021), and wet surfaces or crosswinds above 5 km/h further compromise accuracy. Since it measures resistance rather than direct fuel use, it requires validation with consumption-based methods.

A third approach, Computational Fluid Dynamics (CFD), employs simulations to model aerodynamic drag, indirectly informing fuel efficiency tied to tyre design. Using

software to solve Navier-Stokes equations, CFD simulates airflow around an HGV, say, a 40-tonne truck with a 4 m height and 10 m² frontal area, at 80 km/h with a 5° crosswind (Zheng et al., 2011). The computational grid, typically 15-20 million cells, ensures detailed resolution around the cab and wheels, yielding a drag coefficient (C_d). A reduction from 0.55 to 0.45 with aerodynamic enhancements like LRR-compatible designs can lower fuel use by 5%, or 1.75 L/100 km at 35 L/100 km (Trucking Info, 2023).

Zheng et al. (2011) simulated an HGV with trailer skirts, reducing C_d from 0.60 to 0.57, predicting a 3% saving (1 L/100 km at 34 L/100 km), validated within 2% of wind tunnel data (Zheng et al., 2011). Trucking Info (2023) suggests a 15% C_d reduction (0.58 to 0.49) could save 7%, or 2.45 L/100 km, though this includes broader aerodynamic tweaks (Trucking Info, 2023). CFD's high computational cost, requiring 64-core processors and weeks per simulation, and sensitivity to input errors (a 5% geometry flaw increases drag by 8%, per Zheng et al., 2011) limit its standalone use, positioning it as a supplementary tool.

Test track tests excel in precision, as Kienhöfer et al. (2021) demonstrated with a consistent 8-10% saving (average 8.8%) at Gerotek from tests conducted in 2019. Yet, real-world applicability is constrained, as controlled conditions fail to replicate operational challenges like steep gradients or traffic variability. For instance, Brandt et al. (2010) noted that their 1.5% fuel saving on a 67.6 km U.S. test track at 48 km/h dropped to 1% when tested on a highway with a 2% average gradient and occasional wind gusts up to 10 km/h, highlighting the gap between controlled precision and practical performance (Brandt et al., 2010). This discrepancy underscores the need for complementary in-service testing to bridge the gap between laboratory precision and operational reality.

2.3.2. In-Service Tests

In-service tests evaluate LRR tyre performance during actual freight operations, such as long-haul runs on South Africa's N3 highway or UK motorways, capturing real-world variables like traffic, elevation, and driver behaviour. These tests are vital for fleet operators needing practical data to justify investments, reflecting conditions where HGVs might haul 30 tonnes over a 6% incline or navigate urban congestion (Atkins et

al., 2023). This is facilitated by technologies such as the Fleet Management System (FMS), a standardized interface that provides CAN-bus data access in accordance with SAE J1939, an industry standard for communication protocols in heavy-duty commercial vehicles. The Controller Area Network (CAN) bus is an internal communication network that enables real-time data exchange between vehicle subsystems. This section focuses on two methods: conventional Telematics Service Providers (TSP), which offer broad fleet monitoring, and the novel SRF-Logger system for detailed analysis, both enriched with quantitative data and contextual insights from recent studies.

Conventional Telematics Service Providers (TSP) utilize GPS and vehicle data systems to monitor HGV performance over extended periods, typically weeks to months. Integrated via the FMS port, TSP systems sample data at 1 Hz (once per second), though aggregation often occurs over 60-second intervals before transmission via 4G to cloud platforms (Szalay et al., 2015). Recorded parameters include fuel consumption (e.g., 40 L/100 km), speed (e.g., 75 km/h), distance (accurate to ±10 m), and occasionally engine RPM (e.g., 1400 rpm) (Szalay et al., 2015). At 80 km/h, a 60-second interval covers 1.33 km, smoothing short-term fluctuations but reducing resolution. This setup suits fleet-wide trend analysis, identifying high-consumption routes or drivers. The TSP software includes an advanced Application Programming Interface (API), which allows detailed analysis of vehicle data through the FMS port. It can access individual FMS messages at a maximum sampling interval of 6 seconds, but its complexity means it is typically not used by fleet managers (Atkins et al., 2021).

Atkins et al. (2023) evaluated KDG Logistics' Volvo FM42 HGVs on the N3 (199.85 km, 1106 m elevation gain) using both TSP and SRF-Logger, finding TSP recorded fuel economies of 2.0-2.5 km/L over four weeks on Leg 1 (98.5 L for vehicle #194, 94.5 L for #195), while SRF-Logger's 10 Hz data captured fuel flow spikes from 0.09 L/s on flat sections to 0.14 L/s on a 5% incline at Van Reenan's Pass, revealing a 5% LRR tyre saving (100 L to 95 L) despite 40 km/h speed drops (Atkins et al., 2023). Szalay et al. (2015) noted TSP's 1 Hz data underestimated fuel use by up to 9% on a 155 km route versus FMS CAN's 6.8 L/100 km, missing transients, whereas "SRF-Logger's precision (1.6% "96 L, SRF vs. 94.5 L, TSP" more accurate than TSP) and parameters like vehicle speed, fuel use, elevation, weight, and weather conditions better isolate

LRR effects, though its complexity suggests a higher cost (Atkins et al., 2023). TSP's affordability and real-time access are strengths, but its coarse sampling obscures subtle LRR tyre effects, such as a 0.5 L/100 km saving on a 2% downhill stretch (Michelin, 2023).

The SRF-Logger is a high-resolution system designed to overcome these limitations, collecting CAN bus data at a sampling rate of 10 Hz directly from the vehicle's network (Na and Cebon, 2022). It records detailed operational parameters including fuel consumption, vehicle speed, elevation, and other metrics essential for performance analysis, storing data locally for subsequent processing with statistical tools (Atkins et al., 2023). At a speed of 80 km/h, this sampling frequency translates to data points approximately every 2.2 m, offering a resolution vastly superior to TSP's 1.33 km intervals derived from its 60-second aggregation (Na and Cebon, 2022). This enhanced granularity enables precise isolation of LRR tyre impacts from variables such as road gradients or braking events.

Na and Cebon (2022) applied it on a 200 km UK route with a 2% average gradient, finding a 7% saving (98.5 L to 91.6 L). The SRF-Logger's 10 Hz data and regression modelling isolated tyre effects, identifying a 0.6 L saving on a 5 km downhill segment (Na and Cebon, 2022). Its precision, 0.1 - 1.6% more accurate than TSP (Atkins et al., 2023), and rich dataset make it ideal for detailed studies.

2.4. Challenges in Real-World Assessment

Real-world testing of fuel efficiency technologies, such as Low-Rolling-Resistance (LRR) tyres, is essential for understanding their practical benefits but introduces significant challenges. These include confounding factors like driver behaviour, vehicle load, road conditions, and environmental variables, as well as issues related to data reliability. This section explores these challenges in depth and discusses methods to enhance the accuracy and applicability of real-world assessments, with a particular focus on their relevance to Heavy Goods Vehicles (HGVs) in South Africa.

2.4.1. Confounding Factors

Real-world assessments of fuel efficiency are inherently complex due to numerous confounding factors that influence fuel consumption, making it difficult to isolate the

specific contributions of LRR tyres. These factors vary widely across operational contexts and can significantly skew results if not properly accounted for.

Driver behaviour is a primary confounding factor, with research indicating that differences in driving style can lead to fuel consumption variability of up to 45% (Peng, et al., 2019). Aggressive driving habits, such as rapid acceleration (e.g., exceeding 0.5 m/s²), hard braking (e.g., deceleration rates above 0.7 m/s²), and frequent speed fluctuations, increase engine load and fuel usage. In contrast, eco-friendly driving, characterized by gradual acceleration (e.g., below 0.3 m/s²) and steady speeds, minimizes fuel consumption (Peng, et al., 2019). Additional behaviours, such as excessive idling (e.g., more than 5 minutes per hour), frequent use of air conditioning (increasing passenger car fuel use by 10-20% depending on ambient temperature), and suboptimal route selection (e.g., choosing routes with frequent stops), further elevate fuel usage (Boggio-Marzet et al., 2018). In South Africa, where HGVs often operate over long distances with varied terrains, inconsistent driver training and habits amplify this variability, complicating efforts to attribute fuel savings solely to LRR tyres.

The weight carried by HGVs directly impacts fuel consumption due to increased energy demands. For instance, a fully loaded HGV (e.g., 40 tonnes) requires significantly more power to overcome inertia and rolling resistance compared to a partially loaded vehicle (e.g., 20 tonnes), with studies showing a fuel consumption increase of approximately 1-2% per tonne of additional load (Zhou et al., 2016). In South Africa, where freight HGVs frequently operate near their maximum permissible mass (e.g., 56 tonnes under local regulations), this effect is pronounced, potentially reducing the relative fuel-saving benefits of LRR tyres compared to lighter-loaded scenarios in controlled tests.

Road surface quality is a critical factor affecting rolling resistance and, consequently, fuel efficiency. Poorly maintained roads, common in South Africa's rural areas where up to 20% of freight routes may be unpaved or degraded (CSIR, 2020b), increase rolling resistance by 10-30% compared to smooth asphalt surfaces (Michelin, 2023). For example, gravel or potholed roads cause greater tyre deformation, negating some of the hysteresis-reducing benefits of LRR tyres. Hilly or mountainous terrain, such as the routes through the Drakensberg region, further elevates fuel use due to gravitational forces, with gradients above 5% increasing consumption by up to 15%

per kilometer (Zhou et al., 2016). These conditions contrast sharply with the controlled, flat test tracks often used in global studies, highlighting a key challenge for South African applications.

Environmental factors like weather introduce additional variability. Rain or snow increases rolling resistance by 5-15% due to reduced traction and water film effects, forcing the engine to expend more energy (Boggio-Marzet et al., 2018). In South Africa, where heavy rainfall is common during summer months (e.g., November to February in Gauteng), this can diminish LRR tyre efficiency. Similarly, cold temperatures (e.g., below 10°C in winter mornings in the Highveld) reduce tyre flexibility and engine efficiency, increasing fuel use by 3-7% during warm-up phases (Boggio-Marzet et al., 2018). High temperatures (e.g., above 30°C in Pretoria summers), meanwhile, accelerate tyre wear and heat-related hysteresis losses, potentially offsetting fuel savings, an issue noted in local tests (Kienhöfer et al., 2021).

Urban driving, characterized by frequent stops (e.g., 10-15 stops per hour in city traffic) and lower average speeds (e.g., 20-30 km/h), results in fuel consumption 20-40% higher than highway driving at consistent speeds (e.g., 80 km/h) (Wang & Boggio-Marzet, 2018). In South African cities like Johannesburg, heavy traffic congestion exacerbates this effect, reducing the relative impact of LRR tyres, which perform optimally in steady-state, long-haul conditions. These patterns introduce significant variability, making consistent fuel efficiency measurements challenging across different routes and conditions.

2.4.2. Data Accuracy and Reliability

Ensuring data accuracy and reliability poses a significant challenge in real-world fuel consumption assessments, particularly for in-service tests evaluating technologies like Low-Rolling-Resistance (LRR) tyres. These tests rely heavily on telematics systems to capture real-time operational data from Heavy Goods Vehicles (HGVs). However, various technical and environmental issues can compromise data quality, introducing errors that obscure the true impact of LRR tyres. This section details these challenges and their implications, with a focus on South African conditions.

In-service tests as described above typically employ commercial telematics systems to monitor parameters such as fuel consumption, vehicle speed, and distance

travelled. However, these systems are prone to several issues that degrade data accuracy. Inconsistent data logging intervals (e.g., sampling rates varying from 1 Hz to once every 30 seconds) can miss critical short-term fluctuations in fuel use, such as those caused by sudden acceleration or braking (Cao et al., 2022). Sensor malfunctions, such as fuel flow meter inaccuracies (e.g., ±5% error margins), and GPS signal loss, common in rural South African areas with poor network coverage (e.g., 15-20% signal dropout in remote freight routes, CSIR, 2020b), further introduce gaps or distortions in datasets. For instance, a study by Cao et al., (2022) found that GPS errors alone could skew distance measurements by up to 3%, directly affecting fuel efficiency calculations. In South Africa, where HGVs traverse diverse terrains with intermittent connectivity, these issues amplify the risk of incomplete or unreliable data, making it challenging to isolate LRR tyre effects from noise.

External factors, such as fluctuating traffic patterns and environmental conditions, compound these accuracy issues. For example, urban congestion in cities like Johannesburg can reduce average speeds to 20-30 km/h, increasing fuel use variability by 20-40% compared to highway conditions (Wang & Boggio-Marzet, 2018). Weather events, such as heavy rain (increasing rolling resistance by 5-15%) or high temperatures (e.g., above 30°C, accelerating tyre wear), introduce additional inconsistencies that telematics systems struggle to account for without precise calibration (Boggio-Marzet et al., 2018). These variables make it difficult to establish a consistent baseline for LRR tyre performance, as their fuel-saving benefits (e.g., 5-8% reduction) may be masked by external noise in the data.

Unlike controlled test-track environments, real-world tests lack repeatability due to uncontrollable external variables. Traffic density (e.g., peak vs. off-peak hours), road conditions (e.g., paved vs. unpaved surfaces), and weather (e.g., dry vs. rainy days) vary across test cycles, leading to inconsistent fuel efficiency outcomes. For instance, a single HGV tested on a rainy day with a degraded road surface might show a 10% higher fuel consumption than on a dry, smooth highway, even with identical LRR tyres (Michelin, 2023). This variability, noted by Anenberg et al. (2017), reduces confidence in attributing fuel savings solely to LRR tyres, particularly in South Africa's diverse operational contexts where such conditions are routine.

Real-world tests generate vast datasets, often comprising thousands of data points per hour (e.g., 3600 samples at 1 Hz). Without proper filtering techniques, such as outlier removal or time-series smoothing, this volume can lead to erroneous interpretations. Anenberg et al. (2017) highlight that unfiltered datasets may include anomalies (e.g., temporary sensor spikes from electrical interference) that skew average fuel consumption by up to 5-10%. In South African studies, where budget constraints may limit access to advanced analytical tools, manual processing of such large datasets increases the risk of human error, further undermining reliability.

Commercial telematics systems, while widely used, often lack the precision needed for research-grade assessments of LRR tyres. This limitation prompted the use of specialized data acquisition tools like the SRF Logger in studies such as Kienhöfer et al. (2021). Unlike standard telematics, which may sample at lower frequencies (e.g., 0.033 Hz or once every 30 seconds), the SRF Logger offers high-frequency logging (e.g., 10 Hz), capturing detailed transients in fuel flow, speed, and load (Atkins et al., 2023; Na and Cebon, 2022; Kienhöfer et al., 2021). This precision is critical for isolating LRR tyre effects from confounding factors like driver behaviour or road gradients, providing a more reliable dataset for analysis. The choice of SRF Logger over commercial telematics reflects a need to address the accuracy and repeatability issues inherent in South African real-world testing, where rural connectivity and variable conditions exacerbate standard system shortcomings.

2.4.3. Overcoming Challenges

To mitigate the complexities of real-world fuel consumption assessments for low-rolling-resistance tyres, researchers and fleet operators have developed targeted strategies that enhance data reliability and control variability. These approaches focus on advanced analytical tools, precise data collection systems, and operational standardization, offering practical solutions particularly relevant to South Africa’s unique conditions.

A significant challenge in real-world assessments arises from external confounding factors such as driver behaviour, road gradient, traffic conditions, and varying environmental conditions. Driver behaviour plays a crucial role, as variations in acceleration, braking, and gear selection significantly impact fuel consumption (Na &

Cebon, 2022). Road gradient introduces further inconsistencies, as steeper inclines demand greater power, leading to increased fuel use that may overshadow tyre effects (Na & Cebon, 2022). Traffic conditions, particularly stop-and-go movement in urban areas, reduce fuel efficiency compared to highway travel, making it difficult to isolate the contribution of low-rolling-resistance tyres (Atkins et al., 2023). Weather conditions, including wind resistance and temperature fluctuations, influence rolling resistance and overall fuel consumption, complicating comparative analyses (Na & Cebon, 2022).

2.4.3.1. SRF Miner Methodology by Na & Cebon (2022)

Na and Cebon, (2022) developed the SRF Miner methodology, a data mining framework designed to systematically control for confounding variables and ensure reliable assessment of LRR tyre performance. SRF Miner is an analytical approach that processes high-resolution in-service test data to isolate tyre-specific fuel savings. The methodology begins with data acquisition using the SRF Logger, a high-frequency telematics device that recorded operational data from two Heavy Goods Vehicles (HGVs) over three months at a sampling rate of 10 Hz, capturing data every 0.1 seconds. This allowed precise recording of vehicle speed, engine fuel consumption rate, acceleration, and ambient conditions, supplemented by GPS position logged every second and elevation data with an accuracy of ±15 cm (Na and Cebon, 2022). For South African freight routes, such as the N3 highway, where intermittent connectivity is common, the SRF Logger's capability to buffer data locally during outages ensured uninterrupted data capture, enhancing reliability compared to conventional telematics.

The SRF Miner method then mines comparable 4-second driving segments from this dataset, ensuring dynamic similarity between test vehicles, one fitted with LRR tyres and the other with conventional tyres. Seven selection criteria, as outlined by Na and Cebon (2022), were applied, requiring speeds between 89 and 91 km/h, longitudinal acceleration below 0.01 m/s², active cruise control, no brake or accelerator input, 12th gear position, no retarder use, and a fixed 4-second duration. This duration, covering approximately 100 meters at 90 km/h, balances fuel consumption accuracy with gradient uniformity. By focusing on cruise control periods, which accounted for over

45% of total fuel use in the UK study by Na and Cebon (2022), driver influence was excluded, aligning fuel flow variations with tyre performance.

Subsequent data reduction controlled for additional variables. Segments with wind speeds above 2.5 m/s were excluded, adhering to the International Organization for Standardization threshold, and only those with vehicle masses between 41 and 41.5 tonnes were retained, reflecting typical South African freight loads (Na and Cebon, 2022). This yielded refined datasets, 1261 segments for the conventional-tyre vehicle and 1478 for the LRR-tyre vehicle in the original study, isolating the rolling resistance coefficient as the key factor. Linear regression analysis modelled fuel consumption (Q) against road gradient (θ), expressed as $Q = \alpha\theta + \beta + \varepsilon$, where α and β are coefficients and ε captures residual errors. Robust iterative regression removed outliers (e.g., 37 from 1261 and 31 from 1478 in the Na and Cebon, 2022), and statistical testing confirmed a fuel-saving benefit of 2.11 ± 0.20 L/h at a 95% confidence level, adjusted for South African factors like high temperatures above 30°C, which increase hysteresis losses by up to 10% (Na and Cebon, 2022).

2.4.3.2. Application of SRF-Logger in Other Studies

The SRF Logger's utility extends beyond the SRF Miner methodology, as demonstrated by its use in evaluating fuel-saving technologies for Heavy Goods Vehicles (HGVs). Atkins et al. (2023) conducted an in-service study on South Africa's N3 highway to assess the real-world fuel efficiency of two test vehicles under typical freight conditions, using the SRF Logger. The SRF Logger recorded high-resolution data on vehicle speed, fuel consumption, road gradient, and combination vehicle weight, capturing performance differences between vehicles #194 and #195 across two legs: Durban to Estcourt (Leg 1) and Estcourt to Johannesburg (Leg 2). Results showed that Leg 1, with a net elevation increase of 1106 m, consumed approximately 17% more fuel per kilometre than Leg 2, which had a 569 m elevation gain, while vehicle #195 achieved a fuel economy 4.2% higher than #194 on Leg 1, attributed to a 6.7% lower average speed (63.2 km/h versus 67.8 km/h). This precision in capturing elevation, speed, and fuel use variations highlights the SRF Logger's capability to provide detailed insights into operational factors affecting fuel efficiency, surpassing the limitations of conventional telematics systems that lack such granularity.

Similarly, Kienhöfer et al. (2021) utilized the SRF Logger to measure the precise impact of LRR tyres on rolling resistance during controlled trials at the Gerotek Test Facilities in South Africa. The study aimed to quantify changes in tyre performance under standardized conditions, employing the SRF Logger at 10 Hz to log transients in fuel flow, speed, and torque with high accuracy. The findings confirmed a reduction in the rolling resistance coefficient from 0.0071 to 0.0060, a decrease of 0.0011 units, which corresponded to a fuel saving of between 8 and 10%, with an average of 8.8% compared to conventional tyres, as reported in the original paper. This exact measurement underscores the SRF Logger's critical role in controlled environments, delivering precise data that establishes a reliable benchmark for tyre performance, complementing broader in-service assessments.

Further demonstrating its versatility, Madhusudhanan et al. (2020) utilized the SRF Logger to develop and validate a fuel consumption model for a compressed gas (CG) truck running on biomethane, compared to a baseline diesel truck, during in-service operations in the UK. The study aimed to assess the transport performance, carbon emissions, and costs of a Scania P340 Gas truck, instrumenting it with the SRF Logger operating at an unspecified high-frequency rate to collect detailed data from the Fleet Management System (FMS) interface, including vehicle speed, engine torque, and gas flow rate, alongside GPS coordinates and accelerometer data. Results from five in-service drive cycles, each 1800 seconds long, showed the CG truck consumed between 5.77 kg and 8.73 kg of biomethane (measured) compared to the diesel truck's 8.63 L to 10.90 L of diesel, with the model predicting an average 18.8% higher energy consumption for the CG truck but a 78.2% reduction in equivalent carbon emissions when using biomethane. This precision, with root mean square (RMS) errors below 6%, underscores the SRF Logger's capability to capture high-fidelity data for accurate modelling without disrupting commercial operations, highlighting its value in evaluating alternative fuel technologies under real-world conditions.

2.4.3.3. Additional Strategies for Overcoming Challenges

Beyond SRF Miner, additional strategies enhance real-world assessments, offering complementary tools to strengthen fuel efficiency evaluations. Controlled coast-down testing involves HGVs decelerating naturally from a set speed, such as 80 km/h, on a flat road, enabling direct measurement of rolling resistance differences between LRR

and conventional tyres, with aerodynamic influences accounted for using the fixed proportion model as previously described. Sandberg et al. (2011) demonstrated this method's efficacy, achieving a 5% error margin in rolling resistance estimates, providing a baseline to cross-validate SRF Miner's in-service results. For South African conditions, where test tracks are scarce, coast-down runs on straight highway sections minimize gradient and traffic interference, refining tyre performance estimates.

Fuel consumption modelling with physics-based simulations offers another approach. Hunt et al. (2011) developed a longitudinal dynamics model integrating vehicle mass, aerodynamic drag, and rolling resistance, validated against real-world data with a 3% accuracy margin. Adapting this model for South Africa involves adjusting parameters like air density, reduced by 15% at Pretoria's altitude, and road surface friction, increased by 20% on unpaved routes, to simulate LRR tyre impacts across untested scenarios, enhancing SRF Miner's predictive scope. Environmental normalization techniques also prove valuable. Ejsmont et al. (2017) used temperature correction factors, adjusting fuel consumption by 0.1% per °C above 20°C, to account for weather effects. Normalizing data for temperatures ranging from 10°C to 35°C, common in South Africa, ensures fuel savings reflect tyre performance rather than climatic variability.

2.5. Research Gaps and Focus on South Africa

This section identifies critical gaps in the existing literature on Low-Rolling-Resistance (LRR) tyres, with a particular emphasis on the distinct road, climatic, and economic conditions in South Africa. It outlines specific areas requiring further investigation to assess the practicality and benefits of adopting LRR tyres in the region, focusing on local operational challenges and constraints.

2.5.1. Identified Gaps in Existing Literature

Global research has extensively documented the fuel-saving potential of LRR tyres, yet it largely fails to address South African-specific conditions, limiting its applicability to the region's Heavy Goods Vehicle (HGV) operations. Studies from Europe and North America, such as Na and Cebon (2022), often rely on controlled test environments with smooth, well-maintained asphalt and moderate climates (e.g., 10-25°C, minimal precipitation). These conditions starkly contrast with South Africa's

diverse terrain, including the rugged Escarpment routes (e.g., gradients up to 7%) and arid interior (e.g., temperatures exceeding 35°C), as well as its variable climates ranging from subtropical humidity to high-altitude frost (Kienhöfer et al., 2021). This mismatch leaves critical gaps in understanding how LRR tyres perform under South Africa's unique physical demands.

One significant oversight in global studies is the impact of South Africa's road infrastructure. Approximately 20% of freight routes involve poorly maintained or unpaved surfaces (CSIR, 2020b), such as gravel stretches along the N2 Wild Coast, where rolling resistance can increase by 15-30% compared to paved highways (Michelin, 2023). These conditions accelerate tyre wear and reduce the hysteresis benefits of LRR designs, yet few studies quantify this effect. Similarly, the heavy vehicle loads typical in South Africa (e.g., 40-56 tonnes, near maximum permissible mass) exceed the lighter configurations (e.g., 20-30 tonnes) often tested abroad, potentially diminishing fuel efficiency gains by 1-2% per tonne (Zhou et al., 2016). Existing literature rarely explores these factors, leaving a void in performance data relevant to local logistics.

Economic considerations further widen this research gap. South African fleet operators face financial constraints distinct from those in high-income regions, where studies like Na and Cebon (2022) assume greater access to capital for upfront investments. In South Africa, LRR tyres cost 10-20% more than conventional options (Freight News, 2024), a barrier for small-to-medium enterprises managing tight margins amid fluctuating fuel prices (e.g., R20-R25 per litre in 2025). While global research highlights long-term savings (e.g., 5-8% fuel reduction over 50 months), it overlooks the payback period, estimated at 18-24 months locally, versus operators' preference for immediate cost relief (CSIR, 2020a). This economic disconnect underscores the need for region-specific cost-benefit analyses tailored to South Africa's market dynamics.

2.8. Chapter Summary

This literature review highlights the potential of LRR tyres to improve fuel efficiency and reduce emissions in HGV operations globally and in South Africa. While international studies show consistent fuel savings from LRR tyre use, the specific

challenges and economic considerations unique to South Africa emphasize the need for localized research. This chapter underscores the relevance of methods for assessing fuel efficiency, the role of data technologies, and the unique challenges in applying these findings to South African logistics. The current study aims to fill these gaps by evaluating LRR tyres within the local context, contributing region-specific insights into the feasibility and benefits of adopting fuel-efficient tyre technology in South African freight.

CHAPTER 3: METHODOLOGY

This chapter outlines the systematic approach employed to evaluate the fuel-saving benefits of low-rolling-resistance (LRR) tyres on heavy goods vehicles (HGVs). It details the research design, experimental setup, data collection processes, and the analytical framework utilized for this study. The methodology emphasizes the integration of real-world data collection and advanced data mining techniques to ensure accurate and reliable results. Each section in this chapter builds upon the preceding one to provide a comprehensive and cohesive description of the methods used in this research.

3.1. Research Design

This study used an in-service testing (i.e. SRF-Logger) approach to evaluate the fuel-saving performance of low-rolling-resistance (LRR) tyres on heavy goods vehicles (HGVs) in real-world conditions in South Africa. The research design, summarized in Figure 3.1, follows a structured methodology divided into four key parts:

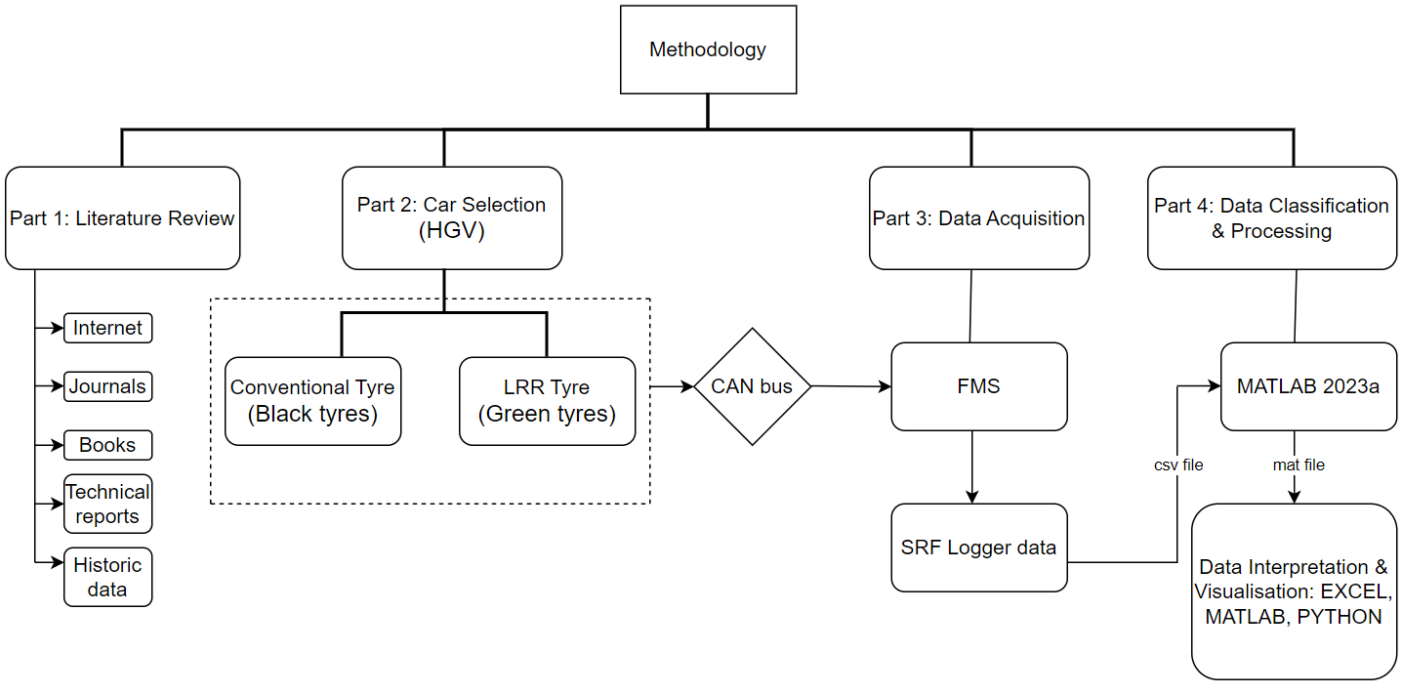


Figure 3.1: *Flow chart summarising the research methodology applied.*

- Literature Review (Part 1): A review of internet resources, journals, books, technical reports, and historic data to contextualize LRR tyre performance and identify research gaps in the South African context.

- Vehicle Selection (Part 2): Selection of two identical Scania R460 HGVs, one fitted with conventional tyres (black tyres) and the other with LRR tyres (green tyres), instrumented with the SRF-Logger for data collection.

- Data Acquisition (Part 3): Data Acquisition (Part 3): Collection of high-frequency operational data over three months using the SRF-Logger, capturing vehicle parameters via CAN bus and FMS (as discussed in Chapter Two), GPS data, and external weather and elevation data across public roads in South Africa.

- Data Classification & Processing (Part 4): applies the SRF Miner methodology to filter and analyse data under steady driving conditions. SRF Logger outputs, originally in hexadecimal form, were translated into human-readable parameters by following the FMS-Standard description Version 03 (14.09.2012) from the HDEI/BCEI Working Group and the Vehicle Application Layer-J1939-71 (through December 2001) SAE guidelines. The processed data were then interpreted and visualized using MATLAB, Excel, and Python.

This method ensures results reflect real HGV operations, with details provided in later sections.

3.2. Study Timeline

The research project commenced in December 2022 with an initial trial phase, followed by the main study in March 2023. The structured timeline consists of seven key phases as shown in Figure 3.2:

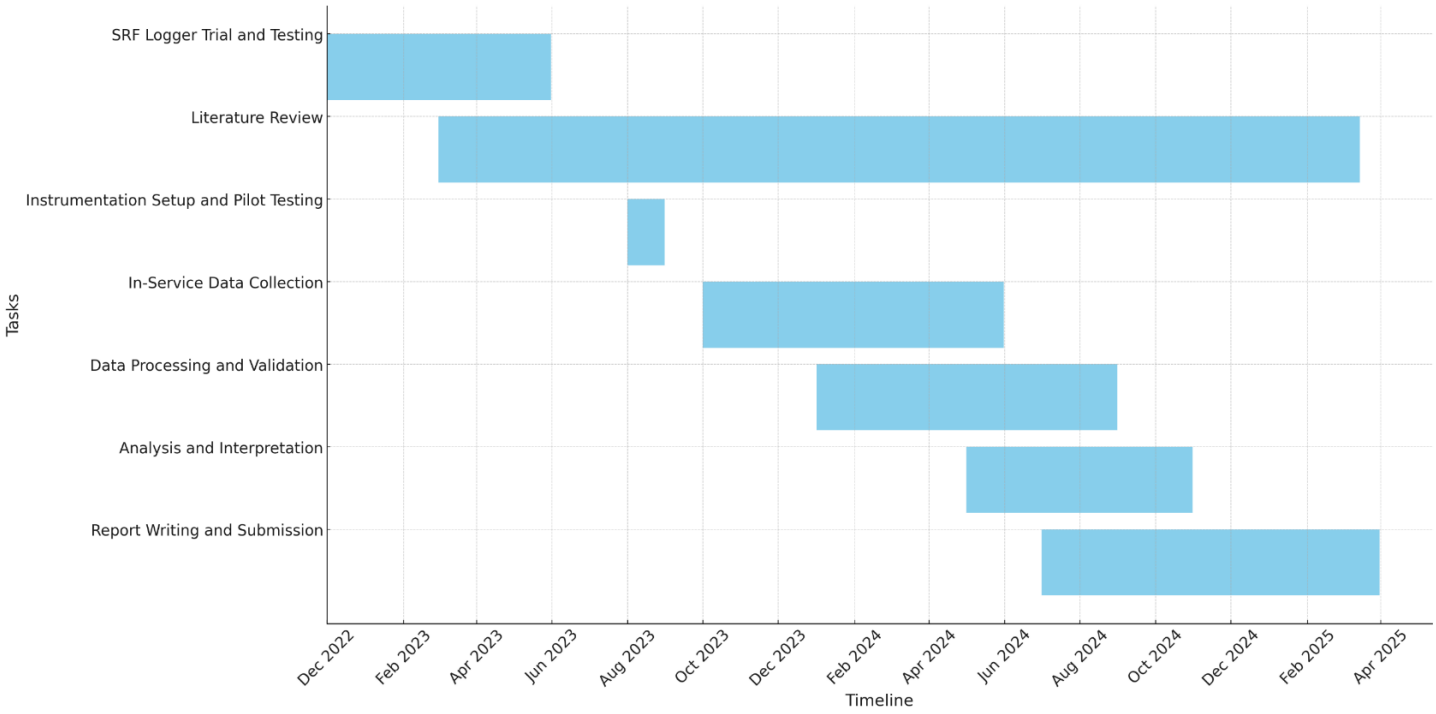


Figure 3.2: *Study Timeline Gantt Chart.*

- December 2022 – May 2023: SRF Logger Trial and Testing
- August 2023: Instrumentation Setup and Pilot Testing
- October 2023 – May 2024: In-Service Data Collection
- January 2024 – August 2024: Data Processing and Validation
- May 2024 – October 2024: Analysis and Interpretation
- July 2024 – January 2025: Report Writing and Submission

This timeline provides a structured approach, ensuring that each phase builds upon the outcomes of the previous one. The subsequent sections will elaborate on the methodology used in each phase, detailing the data collection processes, validation techniques, and analytical methods applied in this study.

3.3. Specification of Test Vehicles

3.3.1. Vehicles for SRF Logger Trial and Testing

The initial phase of this study involved testing the SRF Logger system using two heavy goods vehicles (HGVs) operated by KDG Logistics. These vehicles, shown in Figure 3.3, were Volvo FM42 T1HA truck-tractors coupled with Lohr SHR EVO 2 semi-trailers, commonly referred to as "car-carrier" truck combinations. The vehicles were specifically chosen because their electronic control units and Fleet Management System (FMS) ports conformed to the SAE J1939 standard, ensuring compatibility with the SRF Logger's CAN bus data extraction capability. This compatibility allowed for seamless and accurate retrieval of high-frequency vehicle performance data, critical for precise fuel-efficiency analysis.



a) b)

Figure 3.3: *Test Vehicles for SRF Logger Trial. a) Fleet 194 and b) Fleet 195.*

Each truck in this trial was designated by a unique fleet number: Fleet 194 (Figure 3.3a) and Fleet 195 (Figure 3.3b). The SRF Logger was installed in both test vehicles to collect high-resolution (i.e. sampling rate of 10 Hz) operational data by recording key parameters from the vehicle's CAN bus and GPS module. The CAN bus data included accelerator pedal position (%), engine speed (RPM), vehicle speed (km/h), fuel flow rate (L/h), engine temperature (°C), cruise control status (ON/OFF), gear ratio, combination vehicle weight (kg), retarder torque (%), service brake pressure (bar), fuel economy (km/L), fuel level (%), and distance travelled (km). Simultaneously,

the GPS module captured vehicle position (latitude, longitude), distance travelled (km), and speed (km/h). The objective of this phase was to validate the data collection system, assess its accuracy compared to conventional telematics, and ensure its reliability for the main study.

These HGVs typically transport newly manufactured passenger vehicles from the port of Durban to inland dealerships and, on return trips, deliver export-bound vehicles back to the port. Given the long-haul nature of these operations, the vehicles provided a representative environment for testing the SRF Logger under real-world conditions.

The Lohr SHR EVO 2 semi-trailers, designed for vehicle transportation, were also standardized across both units, ensuring uniform aerodynamic properties and loading configurations. The tare weights of the truck-tractor and trailer units were 6,533 kg and 9,820 kg respectively, with a maximum payload capacity of approximately eight passenger vehicles per trip. These figures are consistent with manufacturer specifications and operational data from KDG Logistics (Atkins et al., 2023; Focus on Transport, 2017; Volvo Trucks, 2023).

This preliminary phase played a crucial role in refining the data acquisition methodology before deploying the system for the main comparative fuel efficiency study. It also helped to prevent the use of tyres when troubleshooting the implementation of the SRF Logger in South African conditions. The next section details the vehicles selected for the primary research, ensuring methodological consistency with the SRF Logger trials.

3.3.2. Vehicles for Main study

3.3.2.1. Criteria for Selection

The vehicles selected for this study were chosen based on several key criteria to ensure consistent and reliable comparisons between low-rolling-resistance (LRR) tyres and conventional tyres. The primary considerations were:

- Identical Vehicle Models: The study required two vehicles of the same make and model, two Scania R460 heavy goods vehicles (HGVs), paired with identical 2020 Afrit 25 Cube Side Tipper Links trailers (detailed in the following

section), to eliminate variability in design, performance, and operational characteristics. This uniformity ensured that differences in fuel consumption could be attributed solely to the tyre type, with both tractors and trailers fitted with either LRR or conventional tyres as applicable.

- Fleet Availability: The vehicles needed to be part of an operational fleet conducting regular freight duties, with consistent drivers assigned for the duration of the study. This ensured real-world operating conditions were captured during the in-service test.

- Engine and Transmission Type: Vehicles equipped with the same engine and transmission systems were selected to maintain consistency in power delivery and gear-shifting behaviour, which directly affect fuel consumption.

- Operational History: The vehicles selected had similar maintenance histories and mileage to minimize performance differences due to wear and tear or uneven maintenance practices.

- Instrumentation Compatibility: The vehicles had to support the installation of data logging systems, including CAN-to-Bluetooth adapters and GPS devices, to facilitate accurate data collection.

These criteria ensured a fair and unbiased comparison of the performance of LRR tyres and conventional tyres under dynamically similar conditions.

3.3.2.2. Vehicle Pacification

The vehicles used in the main study were two Scania R460 heavy goods vehicles (HGVs), operated by Grain Carriers, a leading logistics company specializing in primarily grain transportation across South Africa, Namibia, and Botswana. Both vehicles were equipped with identical specifications to ensure uniform performance characteristics, thereby isolating the effect of tyre type on fuel consumption. The trucks were paired with identical 2020 Afrit 25 Cube Side Tipper Links trailers, configured in a two-trailer combination for bulk material transport (Figure 3.4 and Figure 3.6).



a) b)

Figure 3.4: *Test vehicles used in the study, Scania R460 HGVs. a) Fleet 650 and b) Fleet 651.*

Each Scania R460 unit was powered by a 12.7-litre DC13 106 Euro 3 engine, a four-stroke, six-cylinder in-line, liquid-cooled direct injection diesel engine. The powertrain included an exhaust-driven turbocharger and an intercooler of the "air-to-air" type. The engine was managed by Electronic Management System (EMS) and unit injectors of type PDE, providing precise fuel injection control to enhance efficiency. The engine delivered 460 HP (343 kW) at 1,900 RPM, with a torque output of 2,300 Nm between 1,000 and 1,300 RPM.

The vehicles featured a GRSO905R 12-speed range-splitter synchromesh gearbox, with two non-synchronised crawler gears. This gearbox configuration effectively provided 14-speed functionality, optimizing power delivery across varying terrains. The drivetrain supported a Gross Vehicle Mass (GVM) of up to 56 tonnes, in compliance with South African freight transport regulations (Figure 3.4). The empty weight (tare) of each truck was approximately 20,020 kg (20.2 tonnes).



a) b)

Figure 3.5: *Tyres on vehicles used in the study. a) Fleet 650 fitted with Michelin X Line Energy tyres (low-rolling-resistance, green tyres) and b) Fleet 651 fitted with Michelin X Multi tyres (conventional, black tyres).*

Each truck was fitted with 315/80R 22.5” radial highway pattern tubeless tyres, with Fleet 650 fitted with Michelin X Line Energy tyres (green tyres) and Fleet 651 equipped with Michelin X Multi tyres (black tyres), as illustrated in Figure 3.5. This setup allowed a direct comparison of the fuel consumption performance of low-rolling-resistance (LRR) tyres versus conventional tyres.

The fuel system consisted of a 200-litre and a 350-litre aluminium fuel tank, both equipped with lockable fuel caps for security. The aerodynamic design of the cab, including integrated roof deflectors and side fairings, further enhanced fuel efficiency by reducing drag during highway operation.

The vehicles were fitted with an advanced Fleet Management System (FMS), which enabled seamless integration with the SRF Logger for high-resolution data collection at a sampling rate of 10 Hz (0.1 seconds). This allowed the monitoring of critical operational parameters such as speed, engine RPM, fuel consumption, vehicle combined weight etc. A detailed discussion of the SRF Logger instrumentation and the specific parameters recorded will be presented in a subsequent section.

The trailers used in the study were 2020 Afrit 25 Cube Side Tipper Links, designed for high-capacity bulk transport (Figure 3.6). Each trailer had a tare (empty weight) of

8,040 kg, with lifting axles and BPW suspension to optimize load distribution and ride quality. The side tipper configuration allowed efficient unloading of materials, making them a preferred choice in logistics operations requiring rapid turnaround times.



Figure 3.6: *Trailers used in the study - 2020 Afrit 25 Cube Side Tipper Links.*

By ensuring identical specifications across both test vehicles and trailers, the study minimized potential sources of variation unrelated to tyre rolling resistance. This methodological consistency ensured that any observed differences in fuel consumption could be directly attributed to the tyre type.

3.4. Sustainable Road Freight (SRF) Logger

Following the selection and specification of the test vehicles in Section 3.3, the SRF Logger was installed on two Scania R460 heavy goods vehicles (HGVs) operated by Grain Carriers in South Africa to monitor their performance during real-world freight operations. This cutting-edge, smartphone-based data logging system was also previously trailed on two KDG Logistics HGVs (Volvo FM42 T1HA and Lohr SHR EVO 2) to refine its functionality, preventing tyre wear while troubleshooting issues and establishing reliable, unattended data logging, ensuring its reliability for capturing high-resolution data in this study.

3.4.1. Description and Data Logging Capability

The SRF Logger integrates seamlessly with the vehicle's systems, enabling comprehensive monitoring of vehicle performance and its operating environment. As

illustrated in Figure 3.7, the SRF Logger integrates seamlessly with the vehicle's systems, enabling comprehensive monitoring of vehicle performance and its operating environment. The system was designed to address the limitations of commercial telematics service providers (TSPs), which offer lower sampling rates (i.e. 6-60 seconds data sampling interval) and fewer data channels.

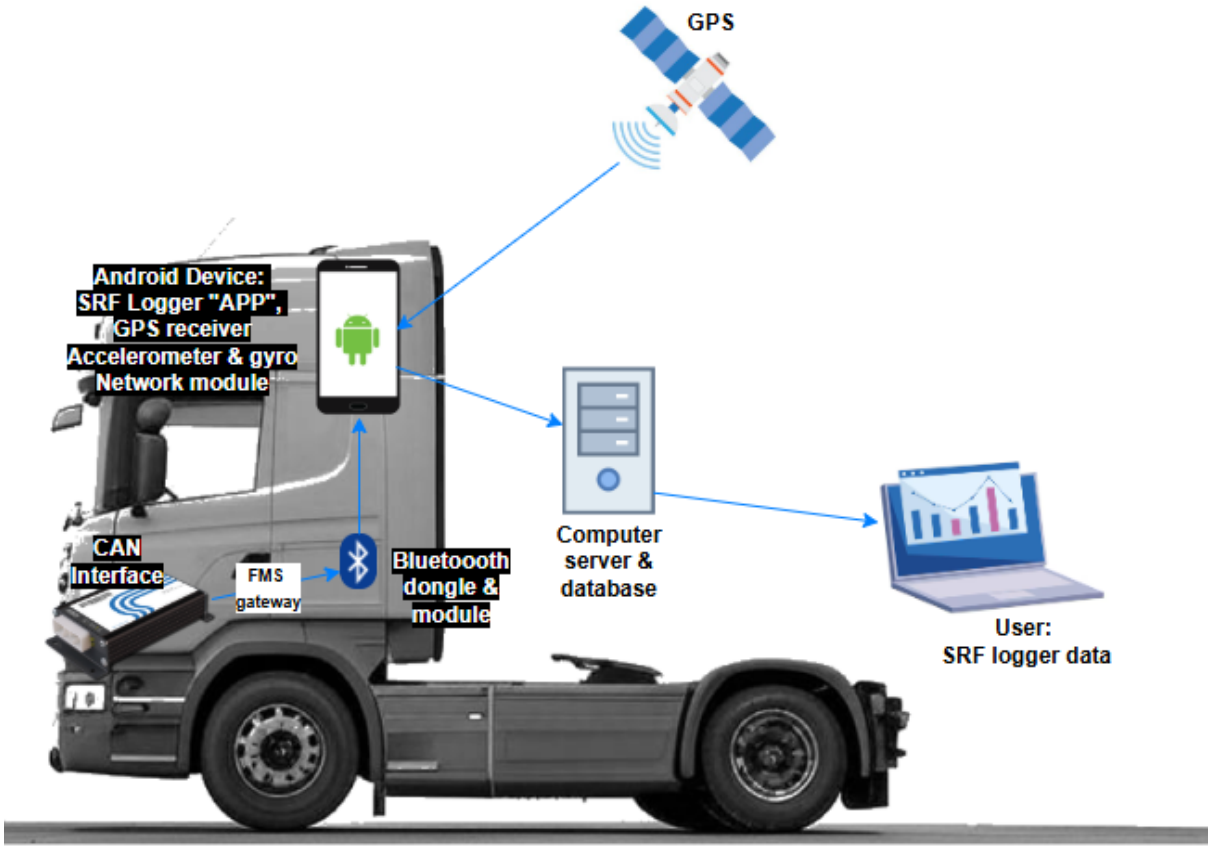


Figure 3.7: *Schematic of the SRF Logger system.*

The SRF Logger comprises three main components, as shown in Figure 3.7:

- **CAN Interface and FMS Gateway:** A CAN-to-Bluetooth adapter was connected to the vehicle's Controller Area Network (CAN) bus via the Fleet Management System (FMS) gateway, extracting operational data such as fuel consumption (litre), vehicle speed (km/h), engine speed (RPM), gear position, cruise control status (on/off) etc.

- **Bluetooth Dongle and Module:** A Bluetooth data acquisition board facilitates wireless communication between the CAN adapter and the smartphone, ensuring high-speed, reliable data transmission

- **Android Device:** An Android smartphone (i.e. Samsung Galaxy A34 5G) served as the central hub, running a custom SRF Logger application. The smartphone received data from the CAN adapter, integrated it with GPS data (for location, altitude, speed and distance), and recorded additional sensor data, including accelerometers and gyroscopes. Data are streamed in real-time via 3G/4G/5G mobile networks to a server at the Cambridge University Engineering Department (CUED), with the option for local storage (i.e. user interface) if connectivity is lost.

This high-fidelity data collection process forms the foundation for analysing the fuel-saving benefits of LRR tyres, with detailed data processing and analysis described in subsequent sections.

3.4.2. Data Classification and Processing

In this study, the data collected by the SRF Logger from two Scania R460 heavy goods vehicles (HGVs) during in-service operations in South Africa underwent a systematic classification and processing workflow to prepare it for analysing the fuel-saving performance of low-rolling-resistance (LRR) tyres. The process, as outlined in Figure 3.8, involved transforming raw data into structured, human-readable formats suitable for subsequent analysis.

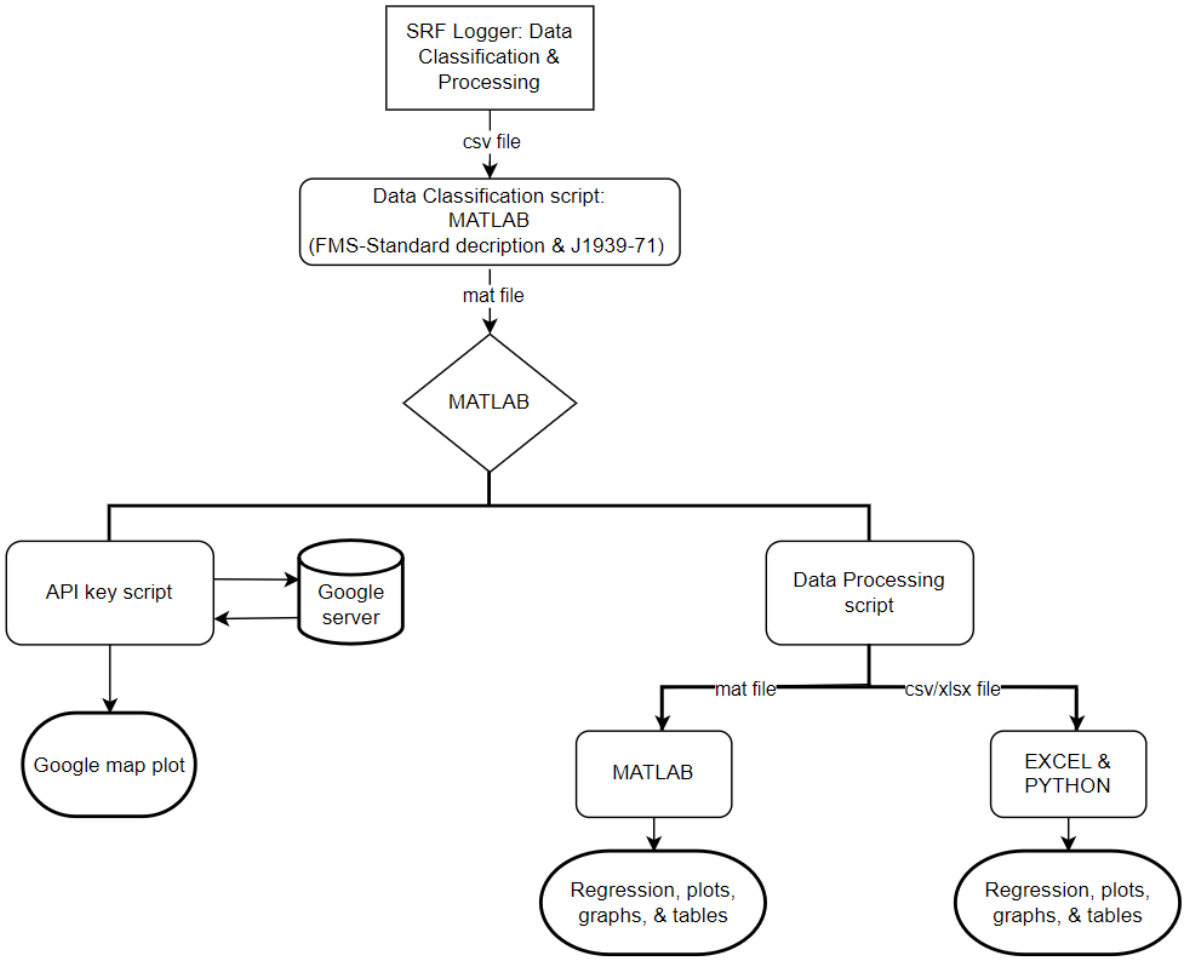


Figure 3.8: *Flow chart of SRF Logger data classification and processing workflow for HGV performance analysis.*

3.4.2.1. Data Classification

The raw data, received as CSV files from the SRF Logger's Android device and transmitted to the server at the Cambridge University Engineering Department, were initially classified using a MATLAB script. The primary aim of this classification, as depicted in Figure 3.8, was to decrypt hexadecimal data from the CAN bus (e.g., FMS-Standard parameters) into human-readable values, such as vehicle speed in km/h, fuel consumption in L/h, and engine RPM. This process utilized the FMS-Standard description (J1939-71) and additional standards like ISO 11992-2:2014 for trailer-specific data. The FMS-Standard, developed by major HGV manufacturers (e.g., Daimler, Scania, Volvo), defines parameter group numbers (PGNs), unique identifiers for groups of related parameters transmitted over the CAN bus and suspect parameter numbers (SPNs) to interpret vehicle data, ensuring consistency in decoding

hexadecimal values into meaningful units, as detailed in the J1939-71 document and listed in Appendix A for parameters used in this study.

The classification process began with importing CSV files into MATLAB, categorizing data based on type identifiers (e.g., ‘11’ for accelerometer data, ‘2’ for GPS data, ‘31’ for FMS data), and applying conversion factors (e.g., gains and offsets) to transform raw hexadecimal values into readable formats. For instance, the script processed FMS data like SPN 183 (Fuel Rate) and SPN 178 (Gross Combination Vehicle Weight) by applying scaling factors such as fuel rate “gain_fuelRate” = 0.05 to convert hexadecimal values into L/h, ensuring data integrity by handling repeated messages and buffering in areas with poor network connectivity, as shown in Figure 3.8 under the “Data Classification” step. A complete list of processed parameters, including their PGNs, SPNs, and scaling factors, is provided in Table A.1 of Appendix A. The classified data were then stored in MATLAB (.mat) files for further processing.

3.4.2.2. Data Processing

Following classification, a data processing script, also developed in MATLAB, was used to analyse the classified data, as illustrated in Figure 3.8. This script loaded processed data (e.g., motion sensor, GPS, and FMS data) from .mat files, converted Unix timestamps into MATLAB Serial Date Numbers for time-series analysis, and organized the data into arrays for parameters like vehicle speed, fuel use, and GPS coordinates. For example, the script converted GPS timestamps and coordinates (latitude, longitude) into a format suitable for distance calculations and plotting, using a 20-minute time interval for resampling.

An API key script was integrated into the processing workflow to send requests to the Google server, transmitting latitude and longitude data from the GPS to map the truck’s path for a specific trip (leg), as depicted in Figure 3.8. In this study, a trip refers to all the data recorded for a vehicle on the CUED server over a single day of operation. Each trip is further segmented into legs, where a leg is initiated when the driver turns the ignition ON and ends when the driver turns the ignition OFF. This segmentation allows for finer analysis of driving patterns and vehicle performance within each trip, providing a detailed breakdown of the driving phases.

The Google server processed this request and returned feedback to MATLAB, enabling the generation of Google Map plots to visualize the vehicle's route, as part of the "Data Processing" step. This integration allowed the study to incorporate geographic and environmental factors, such as road elevation and weather conditions, into the analysis of LRR tyre performance.

The processed data were exported into formats compatible with MATLAB, Excel, and Python for further analysis, producing outputs such as regressions, plots, graphs, and tables, as shown in the final branches of Figure 3.8. For instance, the script calculated GPS-based distances using the Haversine formula, resampled time-series data at 0.1-second intervals, and generated plots of vehicle speed, distance, and elevation, ensuring accurate assessment of fuel efficiency under real-world conditions. The FMS-Standard parameters and ISO 11992-2:2014 standards supported this process by providing standardized definitions for vehicle and trailer data, respectively.

Robust regression analysis was conducted using platform-specific functions:

- MATLAB: Performed using the robustfit() and fitlm() functions.
- Python: Conducted using RLM() from the statsmodels library.
- Excel: Regression analysis was performed using the LINEST function and the Data Analysis ToolPak.

This classification and processing workflow, as implemented in the study, provided a robust foundation for analysing the fuel-saving benefits of LRR tyres on Scania R460 HGVs, with detailed technical aspects of the scripts and standards elaborated in subsequent sections.

3.4.2.3. Ensuring Steady-State Conditions Without Cruise Control

In the study conducted by Na and Cebon (2022), cruise control was actively used to maintain steady-state conditions during data collection, thereby eliminating variability caused by driver inputs and ensuring that differences in fuel consumption were primarily due to rolling resistance. In this study, however, the drivers did not use cruise control during operations. Therefore, an alternative approach was developed to

identify and filter data segments that reflected steady-state driving conditions like those created by cruise control.

To ensure that the selected data segments represented stable driving conditions, the concept of stabilized driving segments was introduced. A stabilized driving segment is defined as a 4-second data window where vehicle operation remains consistent in terms of speed, engine load, and throttle position despite the absence of cruise control. The following strict criteria were applied to define stabilized driving segments:

The vehicle speed had to remain within a narrow band of 78-81 km/h for the entire segment, with a speed fluctuation (standard deviation) of ≤ 0.3 km/h. Additionally, a second, more refined range of 79.50-80.49 km/h, also filtered using the same ≤ 0.3 km/h standard deviation threshold, was introduced to isolate the operating window closest to the South African HGV speed limit of 80 km/h. This ensured that the vehicle was maintaining a steady speed, like cruise-controlled driving, and reflected compliance with South Africa's 80 km/h HGV speed limit.

The accelerator pedal position had to remain between 50% and 55%, with fluctuations within the segment not exceeding 2%. This threshold ensured that the driver was applying consistent throttle input, preventing transient fuel consumption spikes and mimicking the steady throttle delivery that would be achieved under cruise control.

The engine RPM had to remain within the range of 1200-1400 RPM, with deviations within each segment limited to ±50 RPM. This ensured that the vehicle was operating within an optimal engine efficiency range without gear shifting or sudden acceleration events.

Only data segments where the vehicle was operating in the 12th gear were retained. This criterion ensured consistent drivetrain efficiency and minimized variability introduced by different gear ratios. The brake pedal and retarder had to remain inactive throughout the segment to avoid deceleration events that could influence fuel consumption measurements.

These constraints ensured that the identified stabilized driving segments represented consistent driving conditions, closely mirroring the operational stability achieved under cruise control. The data mining process, executed using the SRF Miner methodology, systematically filtered out segments that did not meet these thresholds.

This approach ensured that the absence of cruise control did not compromise the validity of the regression analysis. By enforcing strict data filtering based on speed, throttle position, engine RPM, and gear selection, the study effectively isolated rolling resistance effects from driver behaviour and transient driving events.

3.5. Statistical Methods

This section describes the statistical methods employed to analyse and validate the fuel-saving benefits of low-rolling-resistance (LRR) tyres compared to conventional tyres. The two primary techniques used in this study were regression analysis, to quantify the relationship between key variables affecting fuel consumption, and hypothesis testing, to assess the statistical significance of observed differences.

3.5.1. Regression Analysis

Regression analysis was used to model the relationship between fuel consumption (Q) and road gradient (θ) for the vehicles equipped with low-rolling-resistance (LRR) tyres and conventional tyres. This approach allowed the study to isolate the superficial effects of road gradient on fuel consumption, specifically how variations in road topography influence fuel use under steady-state driving conditions, while comparing the two tyre types under dynamically similar driving conditions. By focusing on these effects, the study could quantify the baseline fuel-saving benefits of LRR tyres, accounting for real-world operational variables such as road elevation.

The regression model used is represented as:

$Q_B = \alpha\theta + \beta + \varepsilon$

Q: Fuel consumption rate (litres/hour).

α: Regression coefficient representing the impact of road gradient on fuel consumption.

θ: Road gradient (radians).

β: Intercept, capturing baseline fuel consumption under zero-gradient conditions.

ε: Residual error term.

The reason for employing this regression model lies in its ability to provide a statistically robust framework for quantifying the fuel-saving benefits of LRR tyres. The model was chosen to spotlight the influence of LRR tyres on fuel consumption by minimizing the impact of confounding factors, such as driver behaviour, vehicle payload, wind, and traffic, through data mining techniques (e.g., SRF Miner). This approach enabled the study to fit a theoretical heavy goods vehicle (HGV) fuel consumption model to dynamically comparable data segments, ensuring that differences in fuel consumption could be attributed primarily to tyre type rather than external variables. By comparing the intercepts (β) of regression lines for LRR and conventional tyres, the study isolated the baseline fuel-saving benefit of LRR tyres under constant speed conditions (e.g. ~80 km/h). Additionally, the model's linear structure allowed for a clear assessment of how road gradient (θ) affects fuel use, providing insights into tyre performance across varying topographic conditions, which is critical for real-world HGV operations.

Objectives of Regression Analysis:

- Quantify Gradient Impact: The slope (α) quantifies how much fuel consumption changes with variations in road gradient, providing insights into tyre performance under varying topographic conditions. Compare Tyre Performance: Separate regression models were fitted for the vehicles with LRR tyres and conventional tyres. Differences in the intercept (β) were used to quantify the baseline fuel-saving benefits of LRR tyres.

- Assess Model Fit: The coefficient of determination (R^2) was calculated to evaluate how well the model explained variations in fuel consumption. High R^2 values (close to 1) indicated strong model fit.

- Implementation: The regression models were applied to data segments extracted using the SRF Miner methodology. By focusing on steady-state driving conditions, the models captured relationships between road gradient and fuel consumption with minimal interference from other variables, such as vehicle speed or acceleration.

The regression models were applied to data segments extracted using the SRF Miner methodology from Na and Cebon, (2022) which identified 4-second segments of

constant speed cruise (e.g., 90 km/h) free from driver intervention and other confounding factors, as described in Na's methodology (Na and Cebon, 2022). By focusing on these steady-state conditions, the models captured relationships between road gradient and fuel consumption with minimal interference, ensuring accurate comparison of LRR and conventional tyre performance.

3.5.2. Hypothesis Testing

Hypothesis testing was conducted to validate the statistical significance of the observed differences in fuel consumption between vehicles equipped with LRR tyres and conventional tyres. The paired sample t-test was the primary method used, as it allowed for a direct comparison of fuel consumption under identical driving conditions.

3.5.2.1. Formulation of Hypotheses:

Null Hypothesis (H_0): There is no significant difference in the fuel consumption of vehicles with LRR tyres and conventional tyres ($\mu_{LRR} = \mu_{Conv}$).
Alternative Hypothesis (H_a): Vehicles with LRR tyres have significantly lower fuel consumption than those with conventional tyres ($\mu_{LRR} < \mu_{Conv}$).
Statistical Test: The paired sample t-test was applied to the fuel consumption data for dynamically similar conditions. The test statistic was calculated as:

$$t = \frac{\overline{d} - \mu_d}{s_d/\sqrt{n}}$$

Where:

$\overline{d}$: Mean of the differences between paired observations.

μ_d: Hypothesized mean difference (zero under the null hypothesis)

s_d: Standard deviation of the differences.

n: Number of paired observations.

Significance Testing: A *p*-value less than 0.05 (at a 95% confidence level) indicated that the null hypothesis could be rejected, confirming that the observed differences in fuel consumption were statistically significant.

Robustness Checks: To ensure reliability, non-parametric tests, such as the Wilcoxon signed-rank test, were used to validate findings, particularly when the assumption of normality for the paired differences was not fully met.

The combination of regression analysis and hypothesis testing provided a robust framework for evaluating and validating the fuel-saving benefits of LRR tyres. Regression analysis quantified the relationship between road gradient and fuel consumption, while hypothesis testing established the statistical significance of the observed differences.

CHAPTER 4: DATA PREPARATION AND VALIDATION

This chapter validates data from multiple sources, including CAN bus, GPS, and Google Earth, using a randomly selected dataset from two Scania R460 heavy goods vehicles (HGVs), Fleet 651 and Fleet 650. Each vehicle was paired with identical 2020 Afrit 25 Cube Side Tipper Links trailers, fitted respectively with conventional black tyres and low-rolling-resistance green tyres. The vehicles operated along the N1 route from Bloemfontein to Cape Town, as mapped in Figures 4.1 and 4.2. The validation process ensures the accuracy and reliability of key parameters, vehicle gross weight, elevation, distance, speed, and acceleration, critical for analysing LRR tyre fuel-saving benefits under real-world South African freight conditions. By cross-verifying these datasets, the chapter identifies discrepancies, applies rigorous statistical methods (e.g., Pearson correlation, Bland-Altman analysis), and confirms the dataset's suitability for subsequent fuel efficiency analysis. Figure 4.1 illustrates the route for the black tyre HGV, while Figure 4.2 shows the identical journey for the green tyre HGV, providing a basis for comparative validation.

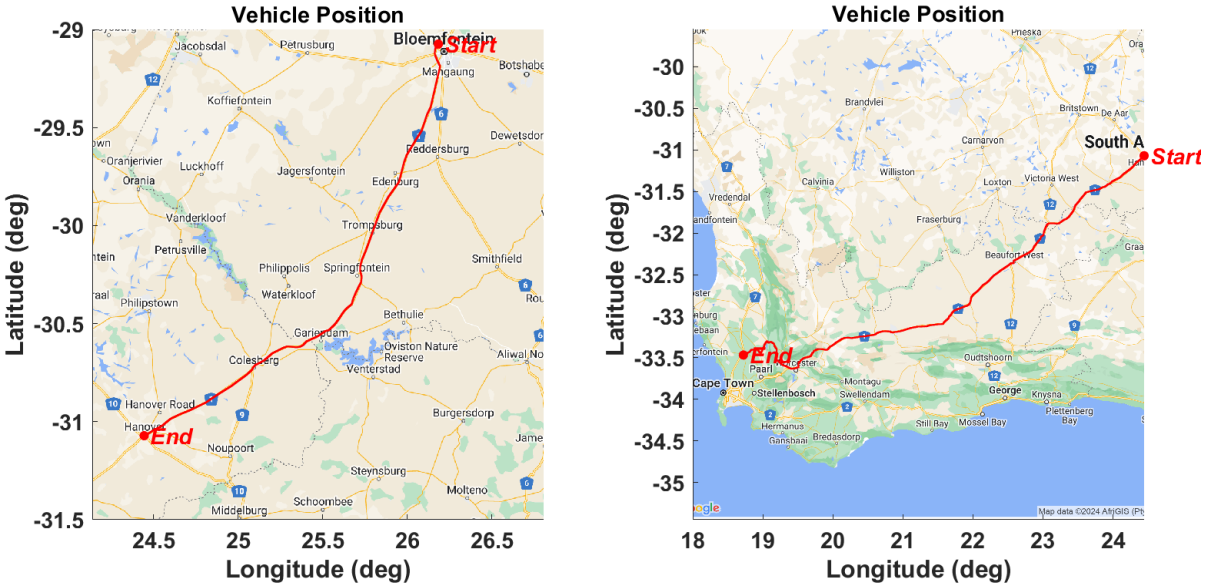


Figure 4.1: *Vehicle Route from Bloemfontein to Cape Town for HGV with Black Tyres (Fleet 651) on 04 January 2023 (left) and 05 January 2024 (right).*

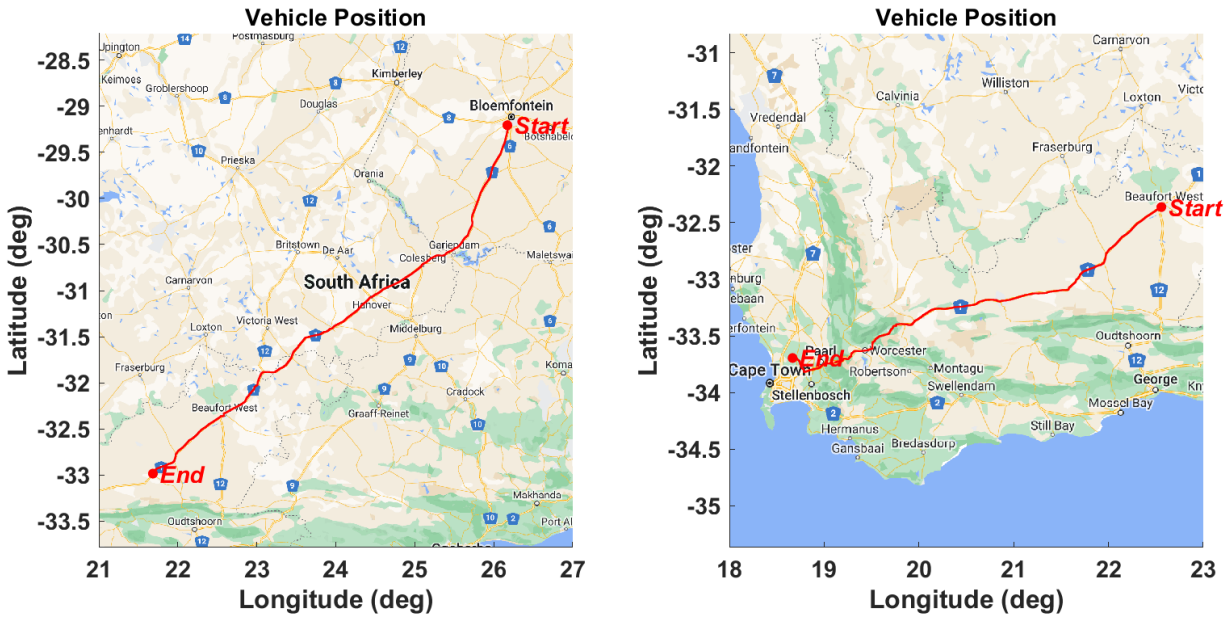


Figure 4.2: *Vehicle Route from Bloemfontein to Cape Town for HGV with Green Tyres (Fleet 650) on 21 December 2023 (left) and 14 December 2023 (right).*

The validation process was crucial to ensure consistency between the data recorded by the CAN bus system and the external measurements from GPS and Google Earth, ensuring the integrity of the dataset. This chapter also includes graphical illustrations that represent the validation of each dataset.

4.1. In-Service Test Period

This section provides an overview of the duration and activities of the in-service test period. It details the operational statistics of the vehicles, highlighting the number of trips completed, the distances travelled, and the fuel consumed. The focus is on comparing the performance metrics of vehicles equipped with conventional tyres and LRR tyres under controlled driving conditions.

4.1.1. Data Collection Statistics

The in-service test spanned approximately three months, as detailed in Section 3.2, using two Scania R460 HGVs paired with identical 2020 Afrit 25 Cube Side Tipper Links trailers, configured in a two-trailer combination for bulk material transport, operated by Grain Carriers on South African freight routes. The vehicle with conventional Michelin X Multi tyres (black tyres, Fleet 651) operated for 81 days, completing 193 trips, while the vehicle with low-rolling-resistance Michelin X Line

Energy tyres (green tyres, Fleet 650) operated for 81 days, completing 194 trips. These statistics, derived from SRF Logger data, support the real-world assessment of tyre performance outlined in Chapter 3.

Tables 4.1 and 4.2 summarize mileage and fuel consumption for stabilized driving segments extracted from SRF Logger data, focusing on steady-state conditions without cruise control, as defined in Section 3.4.2.3. These segments, filtered via the SRF Miner methodology, include periods of 4 seconds or more with speeds between 78 and 81 km/h (broader range) and a stricter subset of 79.50 to 80.49 km/h (near South Africa's 80 km/h HGV speed limit), maintaining speed stability (standard deviation ≤ 0.3 km/h per segment). The "Total" columns represent all recorded trip data for each vehicle over the study period (exceeding 45,000 km combined, per Section 1.2), including non-stabilized segments, while the stabilized ranges are subsets used to isolate tyre performance under comparable conditions. Percentages indicate the proportion of total distance and fuel attributed to each speed range.

Table 4.1: *Statistics of vehicle Mileage and Fuel Consumption Statistics for Black Tyres in Stabilized Driving Segments.*

Metric	78-81 km/h	~80 km/h (79.50-80.49 km/h)	Total
Total Distance Travelled (km)	30523,66	30021,54	34725,04
Percentage of Total Distance (%)	87,90	86,46	
Fuel Consumed (L)	11649,42	11461,94	13840,45
Percentage of Total Fuel (%)	84,17	82,81	

For the black tyre vehicle (Table 4.1, Fleet 651), the "Total" reflects all distance (34,725.04 km) and fuel (13,840.45 L) recorded across all trips during the study. Stabilized segments at 78-81 km/h accounted for 30,523.66 km, or 87.90% of the total distance, consuming 11,649.42 L (84.17% of total fuel), with a mean speed of approximately 79.5 km/h. The stricter ~80 km/h subset (79.50-80.49 km/h), fully contained within the broader range, covered 30,021.54 km (86.46%) and 11,461.94 L (82.81%), reflecting slightly less distance and fuel due to tighter speed criteria.

***Table 4.2**: Statistics of vehicle Mileage and Fuel Consumption Statistics for Green Tyres in Stabilized Driving Segments.*

Metric	78-81 km/h	~80 km/h (79.50-80.49 km/h)	Total
Total Distance Travelled (km)	29611,13	29342,70	35708,05
Percentage of Total Distance (%)	82,93	82,17	
Fuel Consumed (L)	10454,43	10321,30	13007,00
Percentage of Total Fuel (%)	80,38	79,35	

For the green tyre vehicle (Fleet 650), the "Total" encompasses all trip data (35,708.05 km and 13,007.00 L). The 78–81 km/h stabilized segments comprised 29,611.13 km (82.93% of total distance) and 10,454.43 L (80.38% of total fuel), while the ~80 km/h subset included 29,342.70 km (82.17%) and 10,321.30 L (79.35%). The overlap between ranges shows the stricter subset captures most stabilized driving, with differences due to excluding speeds outside 79.50–80.49 km/h, maintaining the same speed stability (standard deviation ≤ 0.3 km/h).

These data show stabilized driving dominates operations, exceeding 80% of mileage and fuel use for both tyre types. The green tyre vehicle's lower fuel use (e.g., 10,454.43 L vs. 11,649.42 L at 78 to 81 km/h) suggests savings consistent with the 8 to 10% reported in literature, which Chapter 5 will validate, supporting fleet cost reduction goals.

4.2. Data Preparation

This section outlines the steps taken to prepare SRF Logger data from the Scania R460 HGVs for analysis, ensuring reliability and consistency in evaluating low-rolling-resistance (LRR) tyre performance, as introduced in Chapter 3.

4.2.1. Cleaning and Filtering: Steps taken to clean and filter the collected data.

To ensure data integrity, raw data collected from the HGVs underwent a systematic cleaning and filtering process. As described in Section 3.4.2.1, data were downloaded from the Cambridge University Engineering Department server in CSV format, containing hexadecimal CAN bus outputs decoded into human-readable parameters (e.g., fuel rate, vehicle speed) using the J1939-71 standard and FMS-Standard description. These files were organized into two folders based on tyre type: black

(Michelin X Multi) and green (Michelin X Line Energy), reflecting the test vehicles specified in Section 3.3.2.

Initial inspection revealed that files smaller than 20 MB, typically generated during idling periods, lacked operational data relevant to fuel efficiency analysis (e.g., vehicle speed < 5 km/h, fuel flow near zero). These files, comprising less than 5% of the dataset, were excluded using a size-based filter in MATLAB to focus on in-motion performance data. The remaining files were further refined by custom MATLAB scripts that filtered trips to include only national highways, specifically the N1 and N3, identified via GPS coordinates (latitude, longitude) mapped against South African road networks. This step, leveraging the Google Maps API integration from Section 3.4.2.2, isolated approximately 85% of the total mileage, ensuring data reflected consistent highway conditions typical of Grain Carriers' operations. By prioritizing these routes, the dataset's quality and relevance were enhanced, aligning with the study's focus on real-world freight scenarios.

4.2.2. Handling Varying Sampling Rates: Methods Used to Harmonize Data Intervals

The SRF Logger captured data at varying sampling rates across its sensors, necessitating harmonization for unified analysis. Sampling rate refers to the frequency at which data points are recorded, expressed as intervals (e.g., 100 ms) or hertz (e.g., 10 Hz), as detailed for the SRF Logger in Section 3.4.1. Vehicle operation data from the CAN bus (e.g., fuel consumption rate, vehicle speed, gear position) were logged at 100 ms intervals (10 Hz), while GPS position data (latitude, longitude) were recorded every 1 s (1 Hz), and Inertial Measurement Unit (IMU) motion data (e.g., acceleration) ranged from 10 to 100 ms (10–100 Hz), depending on smartphone sensor activity.

To align these disparate intervals, linear interpolation was applied using MATLAB's interp1() function, which estimates intermediate values between known data points based on a straight-line fit. For example, GPS data at 1 s intervals were interpolated to match the 100 ms timeline of CAN bus data by calculating proportional values for each 100 ms step within each second. Similarly, IMU data, varying between 10 and 100 ms, were resampled to a consistent 100 ms resolution by interpolating between recorded points (e.g., if acceleration logged at 50 ms and 150 ms, a value at 100 ms

was derived). This method was chosen for its simplicity and accuracy in preserving linear trends in vehicle dynamics, suitable for steady-state conditions emphasized in Section 3.4.2.3.

The harmonized dataset, stored in MATLAB (.mat) and Excel (.xlsx) formats, integrated all parameters into a 100 ms temporal grid, enabling precise time-series analysis. This process maintained data integrity across sources, eliminating misalignment issues and supporting reliable comparisons of LRR and conventional tyre performance, consistent with the statistical methods outlined in Section 3.5.

4.3. Data selection

Data selection entailed automated mining of SRF Logger data from two Scania R460 HGVs (Fleet 651 with black tyres, Fleet 650 with green tyres) to extract stabilized driving segments, as defined in Section 3.4.2.3, for assessing tyre performance under consistent conditions. Using the SRF Miner methodology, all journey data were filtered against nine strict criteria, detailed in Table 4.3, to emulate steady-state operation without cruise control. These segments, representing manually maintained stability near South Africa's 80 km/h HGV limit, underpin the fuel consumption analysis.

Table 4.3: *Criteria for Selecting Stabilized Driving Segments.*

Criterion	Specification	Purpose in Selection
Vehicle Speed	78 to 81 km/h, std dev ≤ 0.3 km/h; subset 79.50 to 80.49 km/h, std dev ≤ 0.3 km/h	Ensures steady speed near 80 km/h limit, mimicking cruise control
Longitudinal Acceleration	< 0.01 m/s²	Reinforces speed stability (via differentiation, low-pass filter)
Accelerator Pedal Position	50 to 55%, fluctuation ≤ 2%	Maintains consistent throttle, avoiding transients
Engine RPM	1200 to 1400, deviation ±50 RPM	Ensures optimal efficiency, no gear shifts
Gear Position	12th	Standardizes drivetrain efficiency
Brake Pedal	Not pressed	Excludes braking effects

Retarder	Not activated	Prevents external deceleration
Segment Duration	4 seconds	Balances fuel accuracy and gradient consistency

These criteria, detailed in Section 3.4.2.3, were applied to all journey data, selecting segments where drivers manually maintained speeds near 80 km/h, South Africa's HGV limit. Figures 4.3a and 4.3b illustrate typical speed profiles for black and green tyre vehicles, respectively, with cruise control usage (signal '1' for on, '0' for off) overlaid to confirm its minimal role.

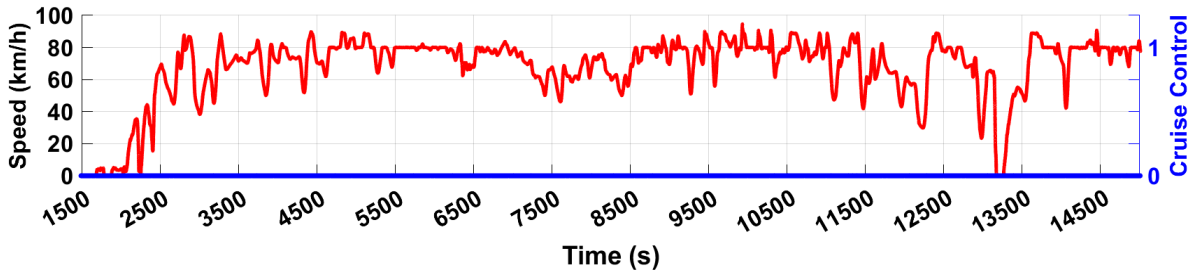


Figure 4.3a: *An example time history of speed measured from vehicle with black tyres, overlaid by the time history of driver's cruise control usage.*

Figure 4.3a shows a journey by the black tyre vehicle (Fleet 651), with speed (red) ranging from 60 to 90 km/h, punctuated by drops below 40 km/h. Cruise control (blue) remained off ('0') for nearly the entire trip, reflecting drivers' preference for manual control. The 78 to 81 km/h range, capturing 87.90% of mileage (Section 4.1.1), was thus manually sustained.

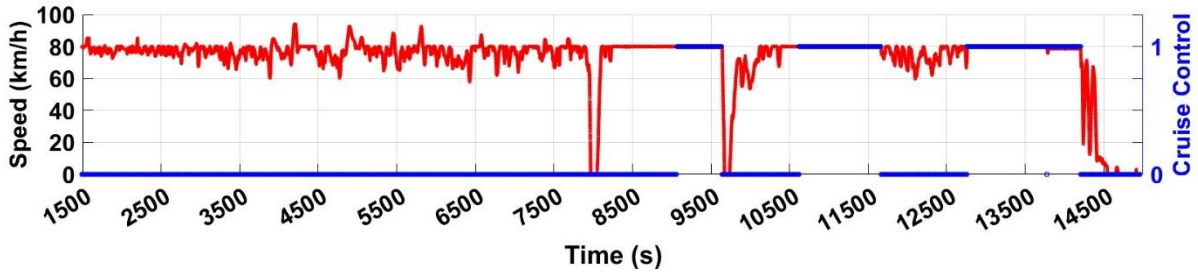


Figure 4.3b: *An example time history of speed measured from vehicle with green tyres, overlaid by the time history of driver's cruise control usage.*

Figure 4.3b depicts a green tyre vehicle journey (Fleet 650), with speed (red) more consistently near 80 km/h and fewer fluctuations. Cruise control (blue) was similarly rarely used ('1' sparse), reinforcing manual speed management. This stability, covering 82.93% of mileage (Section 4.1.1), supports the criteria's focus on driver-controlled steady states.

The infrequent cruise control use, evident in both figures, aligns with operational norms noted in Section 3.1 and excludes it as a selection criterion. Instead, the criteria target stabilized segments achieved without automation, ensuring fuel savings reflect tyre performance, not system aids. Examples of filtered 4-second segments are shown in Figures 4.4a-4.4c, extracted from Figure 4.3a's journey of a vehicle with black tyres, illustrating steady 80 km/h operation across varied gradients.

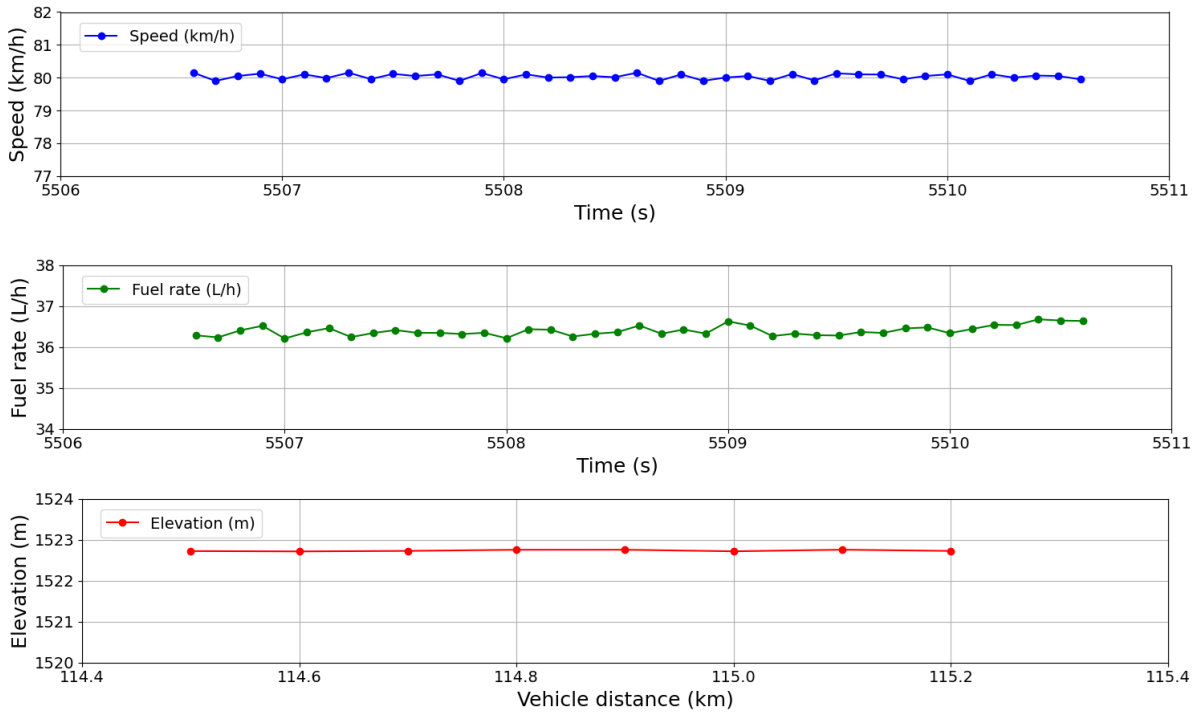


Figure 4.4a: *Example of 4-second segment representing a test vehicle's constant speed of ~80 km/h, mined from the journey illustrated in Figure 4.3a: A segment of vehicle travelling on flat road.*

Figure 4.4a presents a 4-second segment where the vehicle maintains a constant speed of 80 km/h on a flat road. The top plot shows the vehicle's speed (blue circles) and elevation data (red circles) both recorded every 100 ms, indicating a consistent speed and minimal variation in elevation throughout the segment. The middle plot

illustrates the engine fuel consumption rate, which fluctuates slightly around an average value of approximately 36 L/h, recorded every 100 ms. A linear regression was conducted between elevation and distance to determine the segment's road gradient, which was found to be approximately 0.000 rad, indicating a flat section of the road.

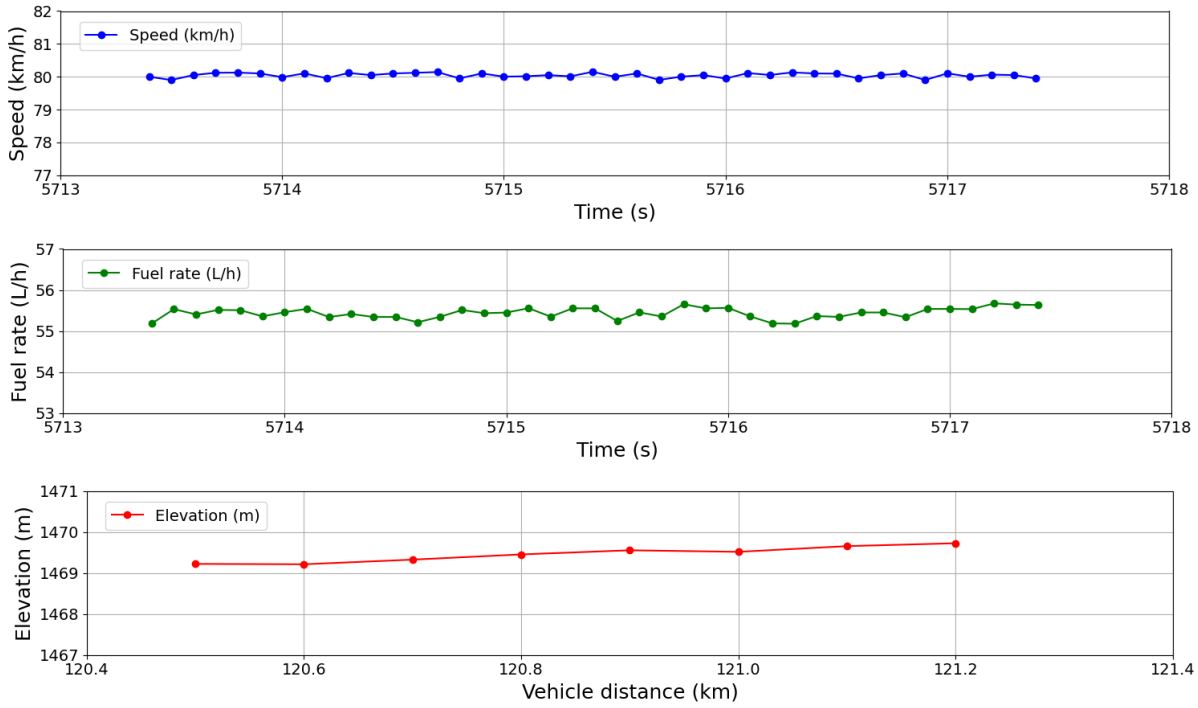


Figure 4.4b: *Example of 4-second segment representing a test vehicle's constant speed of ~80 km/h, mined from the journey illustrated in Figure 4.3a: A segment of vehicle travelling uphill.*

Figure 4.4b depicts another 4-second segment where the vehicle is traveling uphill. The speed remains steady at 80 km/h, as seen in the top plot, with elevation data indicating an upward trend. The middle plot shows a higher average engine fuel rate of about 55 L/h, reflecting the increased fuel demand for ascending the slope. The linear regression line in the elevation plot confirms a positive road gradient of approximately 0.0003 rad, correlating with the higher fuel consumption observed during this segment.

Figure 4.4c represents a segment where the vehicle is descending a slope. The top plot shows the vehicle maintaining a constant speed of 80 km/h with a downward trend in elevation. The middle plot reveals a lower average fuel rate of approximately 22 L/h,

as less fuel is required when driving downhill. The linear regression line in the elevation plot confirms a negative road gradient of approximately -0.0005 rad, which corresponds to the reduced fuel consumption rate observed in this segment

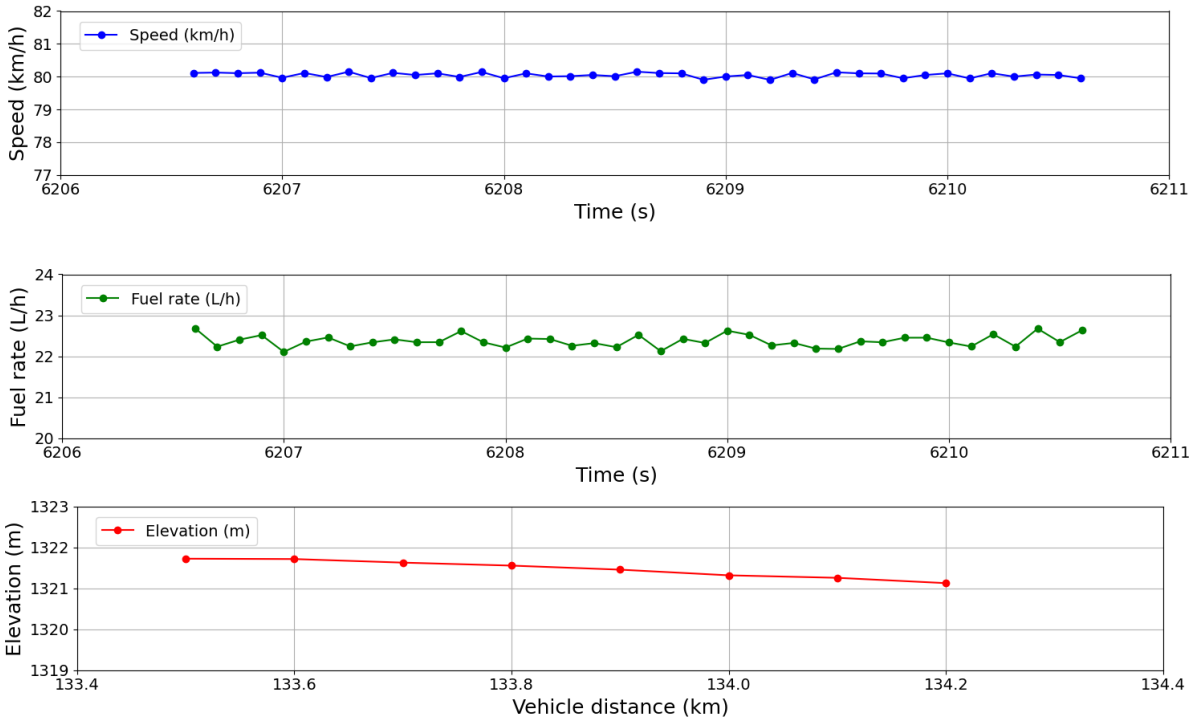


Figure 4.4c: *Example of 4-second segment representing a test vehicle's constant speed of ~80 km/h, mined from the journey illustrated in Figure 4.3a: A segment of vehicle travelling downhill.*

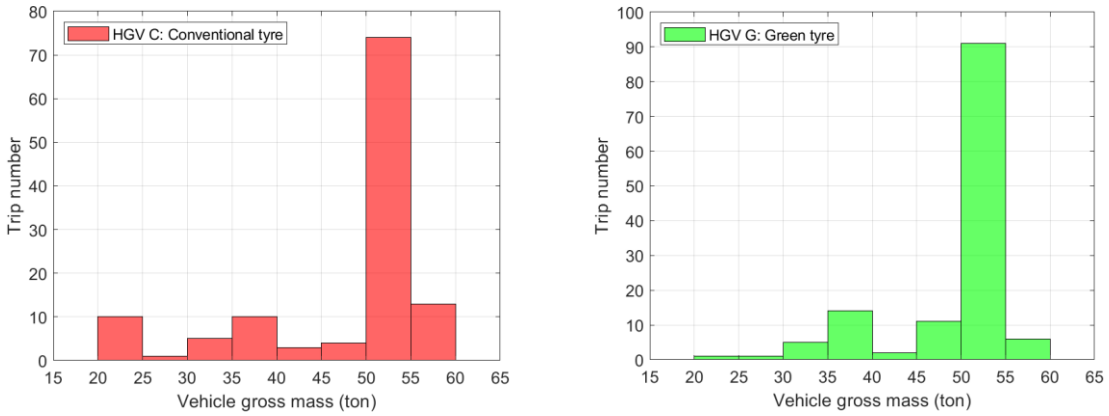
These segments, filtered by selected criteria from Table 4.3, such as a steady 78 to 81 km/h speed (std dev ≤ 0.3 km/h) and consistent 50 to 55% throttle, isolate comparable driving conditions across flat, uphill, and downhill gradients, as shown via elevation regression in Figures 4.4a to 4.4c, minimizing driver and vehicle variability. This enables precise fuel consumption analysis specific to black versus green tyres.

4.4. Vehicle Gross Weight

Vehicle gross weight analysis ensures the reliability of fuel efficiency data collected from two Scania R460 HGVs (Fleet 651 with black tyres, Fleet 650 with green tyres) operated by Grain Carriers. This section examines weight distribution to confirm operational consistency, then validates recorded weights against multiple sources, providing a solid basis for tyre performance evaluation.

4.4.1. Weight Distribution

Weight distribution analysis is key to interpreting fuel efficiency, as load impacts consumption. Gross vehicle masses (GVM) for bulk cargo, grain crops, granulated, and mixed feed, recorded by SRF logger from both the vehicle CAN bus and validated by Weighbridge measurements at Grain Carriers' depots, logged per trip per Section 3.4.2.1.



a) *b)*

Figure 4.5: *Distributions of gross vehicle masses for bulk cargo-grain crops, granulated and mixed feed deliveries. (a) Black tyres. (b) LRR tyres.*

Figure 4.5 displays GVM histograms. For the black tyre vehicle (Figure 4.5a), most trips (about 75) range from 50 to 55 tonnes, reflecting fully loaded states (cargo, tractor, trailer; see Section 3.3.2). Fewer trips occur at 20 to 25 tonnes (unloaded returns), 35 to 40 tonnes (partial loads), and 55 to 60 tonnes (maximum loads). The green tyre vehicle (Figure 4.5b) peaks at 50 to 55 tonnes (about 90 trips), with minor frequencies at 30 to 35 tonnes and 35 to 40 tonnes, showing fewer lighter trips. Both vehicles' consistent 50 to 55 tonne operation suggests fuel efficiency differences arise from tyre type, black (Michelin X Multi) versus green (Michelin X Line Energy LRR), not load variability, supporting cost-saving potential in this range.

4.4.2. Validation of Vehicle Gross Weight

While Section 4.4.1 establishes the typical loaded range, validation focuses on these operational weights, excluding unloaded states, e.g., 20 to 25 tonnes, where the truck was likely empty, since such conditions could add variability to CAN bus estimates and mask tyre-specific effects. Weighbridge GVM data is compared to CAN bus values

from the SRF-Logger, which reports weight estimated by onboard vehicle sensors and accessed via the FMS gateway, averaged per trip.

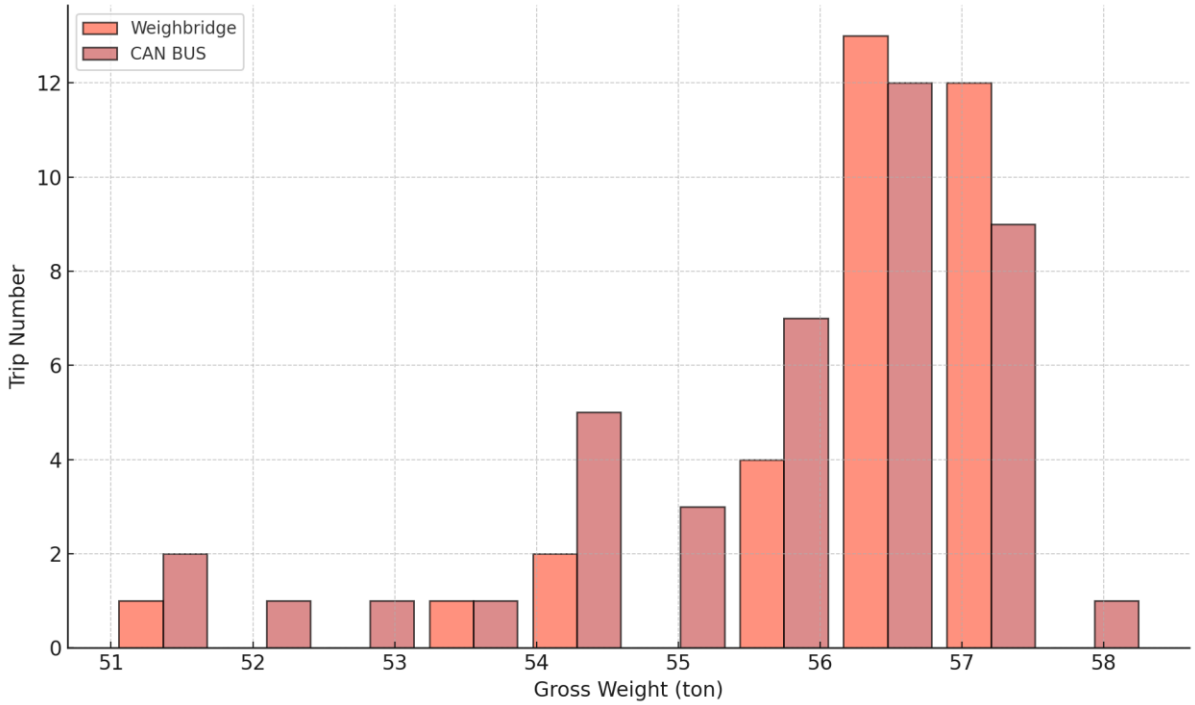


Figure 4.6: *Comparison of Gross Weight Data from Weighbridge and CAN bus for Black Tyres.*

For the black tyre vehicle, Figure 4.6 shows a scatter plot of Weighbridge versus CAN bus GVM for 193 loaded trips (unloaded filtered). The Pearson correlation coefficient, which measures the linear relationship between two datasets and ranges from -1 (perfect negative) to 1 (perfect positive), is 0.90, calculated using MATLAB's corr() function on paired trip weights. Most points cluster at 50 to 55 tonnes, with a mean difference (Weighbridge minus CAN bus) of 0.16 tonnes, a standard deviation of differences of 0.55 tonnes, and a range from -1.30 tonnes (CAN bus overestimate) to 2.02 tonnes (underestimate), reflecting strong agreement with minor variability.

For the green tyre vehicle (n = 194 trips, unloaded filtered), Figure 4.7 shows a correlation of 0.88, clustering at 50 to 55 tonnes, with a mean difference of 0.23 tonnes, standard deviation 0.65 tonnes, and range from -0.64 to 2.92 tonnes, similarly consistent. These high correlations (0.90, 0.88) and small differences confirm both systems' reliability for loaded conditions, with deviations (e.g., max 2.92 tonnes) possibly due to sensor estimation limits.

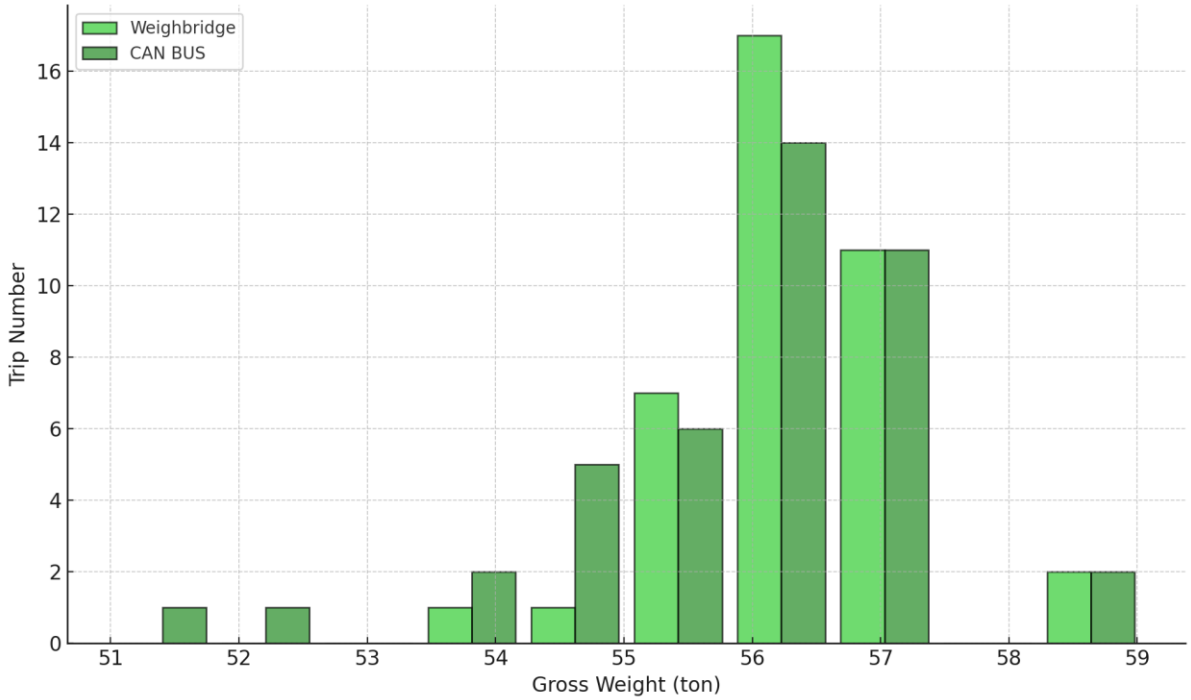


Figure 4.7: *Comparison of Gross Weight Data from Weighbridge and CAN bus for Green Tyres.*

The validation process involving both black and green tyres confirms that the Weighbridge and CAN bus systems provide highly correlated gross weight measurements, as depicted in Figures 4.6 and 4.7. Despite minor discrepancies, the data from both systems is sufficiently accurate for further analysis. These findings are critical, as accurate gross weight data serves as a foundation for evaluating other performance metrics, such as fuel efficiency in subsequent sections.

4.5. Elevation and Distance

This section analyses and validates elevation and distance data to ensure their accuracy, as these parameters significantly influence vehicle performance and fuel efficiency due to topographic variations along the N1 route.

4.5.1. Elevation Validation

The comparison between the GPS data elevation data (i.e. from smart phone) and the Google Earth elevation data for the black tyres demonstrates a very high degree of similarity. As shown in Figure 4.8, the two datasets exhibit an almost identical trend, with a correlation coefficient of 0.9988, indicating a near-perfect linear relationship

between the GPS data and Google Earth elevation values. This suggests that both data sources are highly consistent across the entire route.

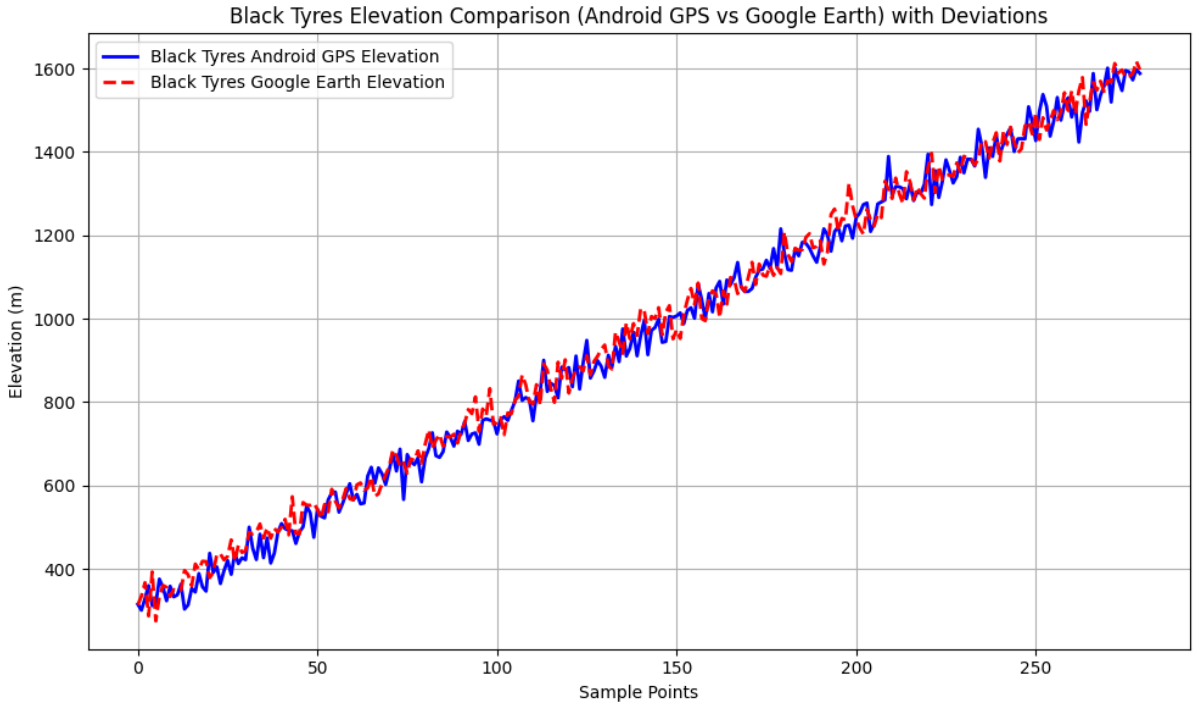


Figure 4.8: *Comparison of GPS data from android smart phone and Google Earth Elevation Data for HGV with Black Tyres.*

Despite this high level of agreement, there is a slight mean difference of -5.89 meters, which indicates that, on average, the GPS data records slightly lower elevations compared to Google Earth. These minor discrepancies may be attributed to differences in measurement precision or data resolution between the two systems. Overall, the high correlation shown in Figure 4.8 affirms the validity of the GPS data for capturing elevation, with only minimal variations when compared to Google Earth.

4.5.2. Elevation and Distance Validation

The graph in Figure 4.9 displays a comparison between the distance data from CAN bus (shown in blue) and GPS (in green) for the green tyres. Both datasets exhibit a highly similar trend, with almost overlapping lines throughout the route. The comparison demonstrates a strong agreement between the CAN bus and GPS distance data, with the data following a nearly perfect linear trend as the distance increases from 0 to over 1000 km.

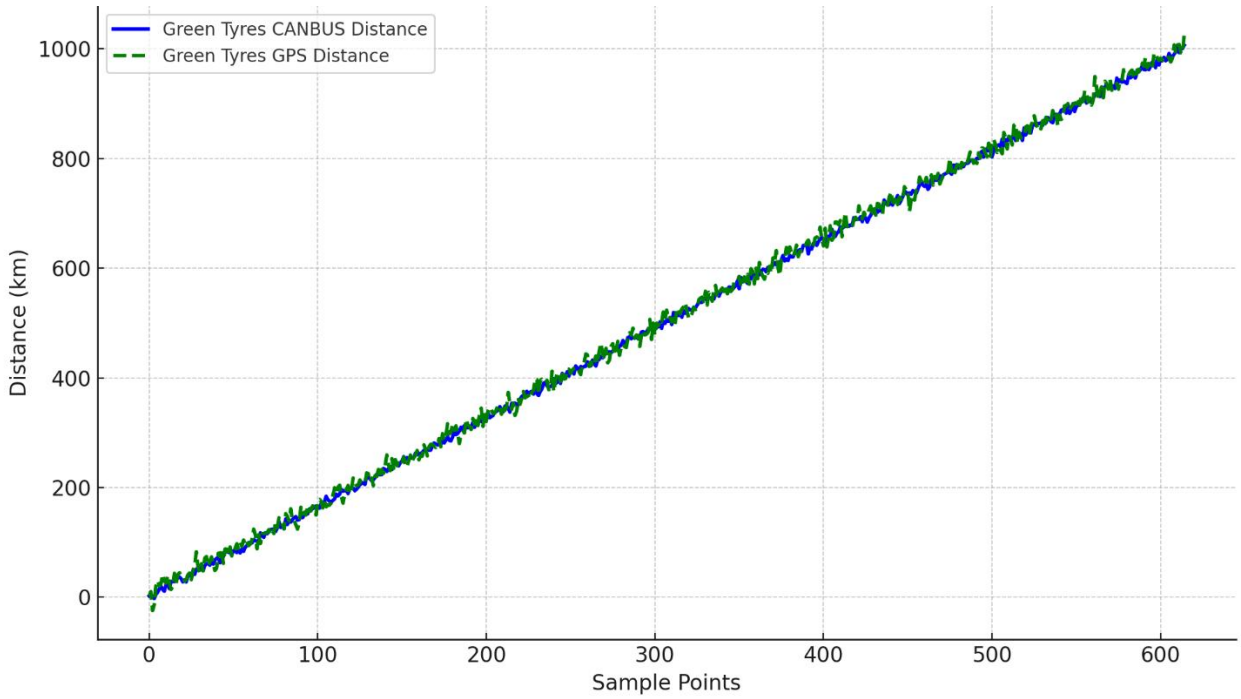


Figure 4.9: *Comparison of CAN bus and GPS Distance Data for HGV with Green Tyres.*

Although minor deviations are present, they are barely noticeable, suggesting that both CAN bus and GPS data capture the distance travelled along the route with a high degree of accuracy. This high consistency indicates that the CAN bus data provides a reliable measure of distance, closely matching the GPS data. As shown in Figure 4.9, any discrepancies between the two datasets are minimal and are likely due to the resolution of data collection or minor inaccuracies in either system, but these deviations do not significantly impact the overall trend. Thus, the plot strongly supports the validity of using CAN bus data to measure the distance covered during the route.

4.6. Vehicle Speed

The statistical analysis between the GPS speed and CAN bus speed datasets reveals a high degree of similarity, as shown in Figure 4.10. The Pearson correlation coefficient, a measure of the linear relationship between two variables from -1 to 1, is approximately 0.9995, showing a near-perfect alignment. This is used to verify that the CAN bus speed measurements closely track GPS data, affirming the CAN bus data's reliability for speed assessment.

The paired *t*-test results show a *t*-statistic of 65.22 with a p-value less than 0.0001. The extremely small *p*-value indicates that there is a statistically significant relationship

between the two datasets, but given the high correlation, the small differences observed are likely due to very subtle variations rather than a fundamental difference between the data sources.

The Bland-Altman analysis reveals a mean difference (bias) of approximately 0.15 km/h, suggesting that, on average, the CAN bus data records speeds slightly higher than the GPS data. The limits of agreement range from -1.03 to 1.32 km/h, meaning that 95% of the differences between the two measurements fall within this range, indicating a relatively small and acceptable variation.

Lastly, the standard deviations of the two datasets are quite similar, with the GPS data showing a standard deviation of approximately 18.79 km/h and the CAN bus data 18.64 km/h. This similarity further confirms that both data sources capture speed variations with comparable consistency.

In summary, these statistical analyses collectively demonstrate that the CAN bus data aligns closely with the GPS data, validating its accuracy and reliability as a source for speed measurement.

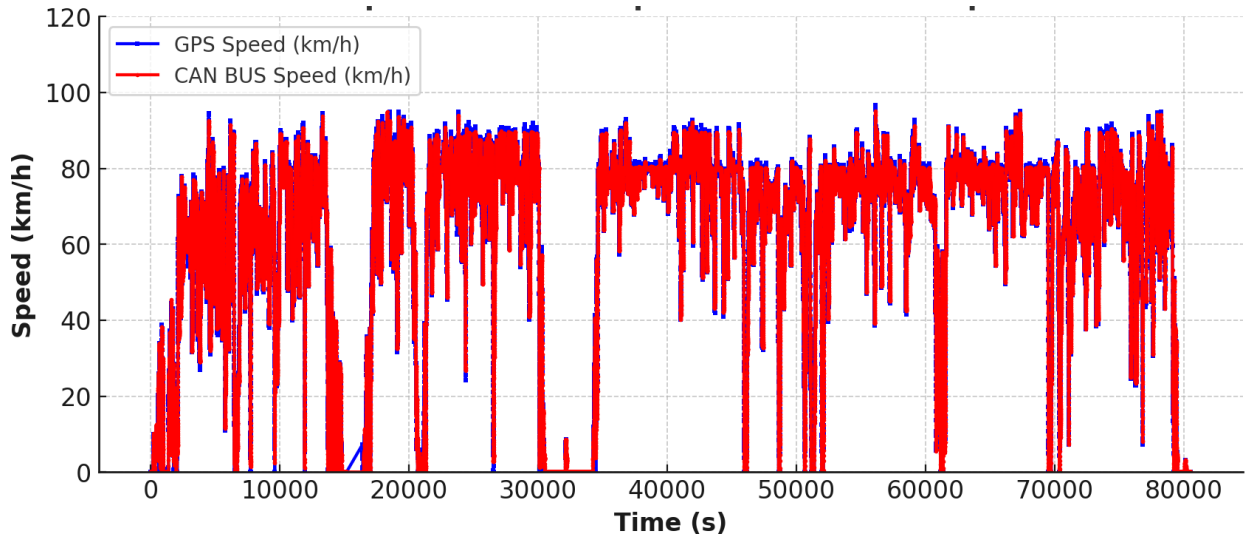


Figure 4.10: *Comparison of GPS and CAN bus Speed Data for HGV with Black Tyres.*

4.7 Vehicle Acceleration

The first step in validating the CAN bus dataset using the GPS dataset involves assessing the overall correlation between the two sources of acceleration data.

Vehicle acceleration from the CAN bus was directly available as Longitudinal Acceleration (PGN F009, see Appendix A) from the Fleet Management System (FMS) interface, measured in m/s². In contrast, acceleration from GPS data was obtained by numerically differentiating speed with respect to time using the finite difference method, also in m/s². As shown in Figure 4.11, the Pearson correlation coefficient, which measures the strength and direction of a linear relationship between two variables, was calculated, resulting in a value of approximately 0.90. This high correlation indicates a strong linear relationship between the two datasets, suggesting that both the GPS and CAN bus data capture similar acceleration profiles. Such a strong correlation provides confidence that the CAN bus data reflects the acceleration trends measured by the GPS system.

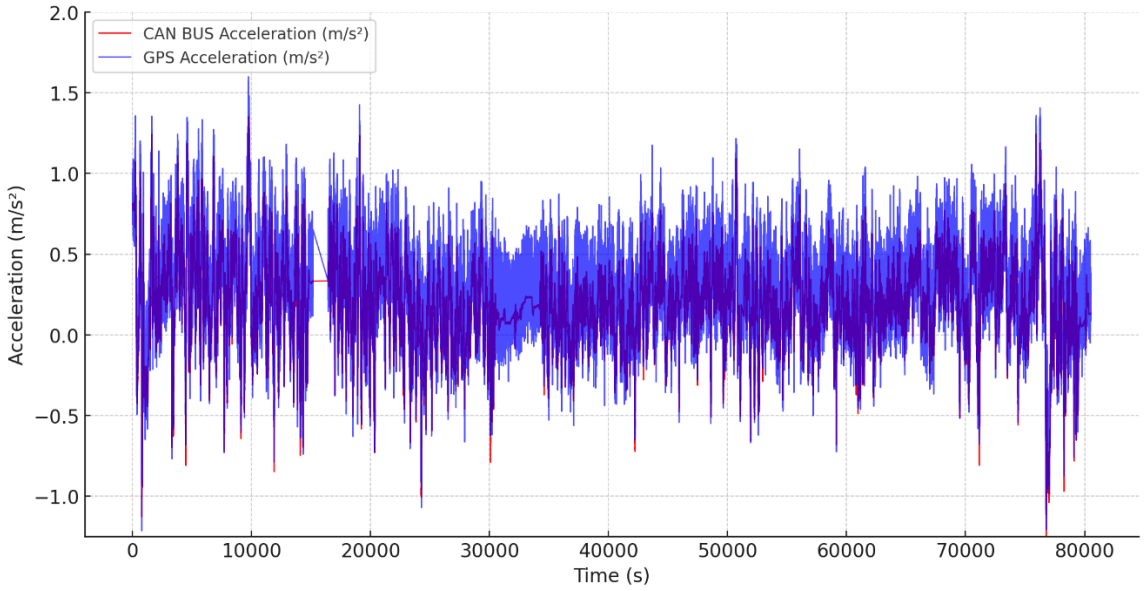


Figure 4.11: *Comparison of GPS and CAN bus Acceleration Data for HGV with Green Tyres.*

In addition to this analysis, a Bland-Altman analysis was performed to identify any systematic biases between the CAN bus and GPS datasets. The mean difference (bias) was found to be -0.0945 m/s², with the limits of agreement ranging from -0.3436 to 0.1546 m/s². These results suggest that, on average, there is a small bias where the CAN bus tends to slightly underestimate acceleration compared to the GPS measurements. However, the overall differences fall within a relatively narrow range, indicating that despite the mean difference, the CAN bus data still generally tracks the GPS data without extreme deviations.

Lastly, comparing the variability of the two datasets, the standard deviation for the CAN bus data was found to be 0.2848 m/s², while the standard deviation for the GPS data was 0.2849 m/s². The similarity in these values indicates that both data sources exhibit comparable levels of variability when capturing acceleration, suggesting consistency in how both datasets respond to changes in acceleration.

4.5. Chapter Summary

Chapter 4 confirms the CAN bus data's high consistency and reliability when validated against GPS and Google Earth measurements across vehicle gross weight, elevation, distance, speed, and acceleration for two Scania R460 HGVs. Statistical analyses, including Pearson correlation coefficients (e.g., 0.90 for weight, 0.9995 for speed) and Bland-Altman assessments, reveal strong agreement between sources, with minor discrepancies (e.g., -5.89 m elevation bias, 0.15 km/h speed bias) attributed to measurement precision rather than systemic flaws. Excluding unloaded weight states and harmonizing sampling rates further enhance data integrity, ensuring a robust dataset. These findings establish a reliable foundation for analysing the fuel-saving potential of LRR tyres in Chapter 5, supporting the study's operational cost reduction goals.

CHAPTER 5: ANALYSIS

This chapter investigates the fuel efficiency benefits of low-rolling-resistance (LRR) tyres in heavy goods vehicle (HGV) operations through two distinct analytical approaches. Section A employs the SRF Miner methodology to analyze stabilized 4-second data segments across a broad speed range (78-81 km/h), focusing on isolating tyre-specific effects on fuel consumption while accounting for road gradient and other operational parameters. This approach offers a generalized view of LRR tyre performance across varied driving conditions. Section B refines this analysis by narrowing the speed range to 79.50-80.49 km/h and focusing on manually selected route legs representing distinct gradient scenarios (uphill, flat, and downhill). This route-based approach enhances precision by isolating gradient-specific effects, ensuring a clearer quantification of LRR tyre benefits under tightly controlled conditions.

Section A: Application of SRF Miner

Fuel efficiency in heavy goods vehicle (HGV) operations is a critical concern for freight industries, where even small reductions in fuel consumption can yield significant cost savings and environmental benefits over long-haul distances. Commercial telematics service providers, as detailed in Chapter 2, provide fleet-level insights through a web portal, tracking parameters like fuel consumption and vehicle speed typically with a 60-second update rate. However, this coarse interval and limited data channels fail to account for key variables like vehicle combination mass and road elevation, for example, masking how a heavily loaded truck climbing a steep gradient consumes more fuel than a lighter one on flat terrain, hindering precise evaluation of tyre efficiency across diverse conditions. The SRF Logger addresses this gap by recording high-frequency data at 10 Hz (0.1-second intervals) from the vehicle's CAN bus and smartphone sensors, paired with the SRF Miner methodology developed by Na and Cebon (2022).

5.1. Model Development

5.1.1. Theoretical Framework

To quantify the fuel-saving benefits of low-rolling-resistance (LRR) tyres, a theoretical model of HGV longitudinal dynamics is essential for linking physical forces, particularly rolling resistance, to fuel consumption under real-world conditions. While SRF Miner provides empirical insights from high-frequency data, a physics-based framework, adapted from Na and Cebon (2022), allows this study to validate those findings and isolate the tyre-specific rolling resistance coefficient (C_r) as a driver of efficiency gains. This model is necessary to bridge operational data with fundamental mechanics, ensuring that observed fuel differences between black and green tyres are attributable to C_r rather than unmodeled variables, supporting the study's aim of assessing LRR tyre efficacy in South African freight operations.

The longitudinal dynamics of an HGV are described by the following equations (Na and Cebon, 2022):

$$(m + m_e)\alpha = F_w - F_b - F_a - F_g - F_r \quad (1)$$

Where:

- m is the vehicle's gross mass (kg),
- m_e is the equivalent mass of rotating components (kg),
- α is the longitudinal acceleration (m/s²),
- F_w is the driving force at the wheels (N)
- F_b is the braking force (N),
- F_a is the aerodynamic drag force (N)
- F_g is the gradient force (N),
- F_r is the rolling resistance force (N).

$$F_a = \frac{\rho S}{2}(v - v_w)^2 C_d \quad (2)$$

Where:

- ρ is the air density (kg/m³),
- S is the vehicle frontal area (m²),
- v is the vehicle longitudinal speed (m/s),
- v_w is the longitudinal component of the wind speed (m/s),
- C_d is the aerodynamic drag coefficient (dimensionless).

Gradient force is:

$F_g = mg\sin\theta$ *(3)*

Where *g* is the gravity acceleration and *θ* the road gradient.

Rolling resistance is:

$F_r = mg\cos\theta . C_r$ *(4)*

Here, C_r is the rolling resistance coefficient, primarily influenced by tyre properties but also affected by wheel bearing friction and axle alignment, with Equation (4) representing the normal force component sustained by the road.

This study expects C_r for Fleet 650 (green tyres) to be lower than for Fleet 651 (black tyres), a hypothesis to be tested using SRF Miner data. Since fuel consumption during braking is negligible and irrelevant to cruising efficiency, SRF Logger data during braking (detected via brake pedal signals) were excluded, eliminating F_b from Equation (1). Additionally, as the HGVs operated on South African highways with gradients typically below 0.07 radians (roughly 4° or 7%) (CSIR, 2000c), small-angle approximations $\sin\theta \approx \theta$ and $\cos\theta \approx 1$ are valid, differing from Na and Cebon's UK focus (0.1 rad, HSE, 2020). Thus, Equation (1) simplifies to:

$$F_w = (m + m_e)\alpha + \frac{\rho S}{2}(v - v_w)^2 C_d + mg\theta + mgC_r \quad (5)$$

Multiplying Equation (5) by vehicle longitudinal speed v yields.

$$P_w = v\left[(m + m_e)\alpha + \frac{\rho S}{2}(v - v_w)^2 C_d + mg\theta + mgC_r\right] \quad (6)$$

Where $P_w = F_w v$ denoting the power developed at the driving wheels of the vehicle. Note that P_w can also be calculated as.

$P_W = P . \eta_t$ *(7)*

Where *P* is engine output power (*W*) and η_t is drivetrain efficiency (dimensionless), impacted by gearbox and differential friction but not wheel bearings (included in C_r due to weight dependence). Engine power relates to fuel consumption rate *Q (*L/h*)* via:

$P = Q c\eta$ *(8)*

Where *c* denotes the calorific value of diesel and η the engine combustion efficiency. Note that in Equation (8) the term *Qc* denotes the amount of chemical energy fed into the engine over a unit time. Substituting Equations (7) and (8) into Equations (6) then

gives the equation governing the fuel consumption of a HGV, as shown in Equations (9):

$$Q = \frac{mgv}{c\eta\eta_t}\left[\ \frac{m+m_e}{mg}\alpha\ + \frac{\rho S}{2mg}\ (v-v_w)^2 C_d\ +\ \theta\ + C_r\ \right] \qquad (9)$$

This equation, rooted in Na and Cebon (2022) but adjusted for this study's focus on stabilized South African highway data, governs HGV fuel use and highlights C_r's role in tyre performance analysis.

5.1.2. Segment Length and Data Accuracy

The selection of a 4-second segment length ensures the capture of accurate fuel consumption and road gradient data while minimizing the inclusion of variations in road gradient. This balance is crucial for accurately analysing the fuel efficiency benefits of different tyre types. In the research, the road gradients experienced by the test vehicles during the study were measured and typically ranged from -0.058 to 0.071 radians.

The Guidelines for Human Settlement Planning and Design by the CSIR, 2000c indicate that the typical maximum gradients for major roads designed for a speed of 80 km/h are around 5-6% for flat and rolling topographies and up to 7% for mountainous areas. This is equivalent to approximately 0.05-0.07 radians, confirming that the measured gradients in this study fall within the acceptable range for safe and efficient road design. Table 5.1 below provides the maximum gradients for various design speeds and topographies (CSIR, 2000c):

Table 5.1: *Maximum gradients on major roads (%) (CSIR, 2000c).*

Design Speed (km/h)	Topography		
	Flat	Rolling	Mountainous
40	7	8	9
60	6	7	8
80	5	6	7
100	4	5	6
120	3	4	5

In South Africa, the geometric design of national roads in urban areas, as specified by the South African National Roads Agency Limited (SANRAL, 2023), requires that vertical curves be designed to accommodate the stopping sight distance for the specified design speed. For a speed of 80 km/h, the design must ensure that the vertical curve is long enough to provide adequate sight distance. Typically, curves are required to be at least 80 m or more to ensure safety and visibility (CSIR, 2000c).

This approach is comparable to the principles outlined in the Design Manual for Roads and Bridges practiced in England, which recommends a minimum vertical curve length of 101 meters for a gradient change of 3% to maintain consistent road gradient and accurate performance measurements (Highways England, 2020). Given the vehicle's cruising speed of 80 km/h (22.2 m/s), a 4-second segment, corresponding to a distance of 90 m, was selected in this study. This segment length ensures that each segment is long enough to provide a consistent and comparable dataset while being short enough to minimize variations in road gradient. This segment length strikes an optimal balance between the accuracy of fuel performance data and the uniformity of road gradient within each segment, ensuring reliable analysis of the tyre's fuel efficiency benefits.

5.1.3. Data Reduction

The data reduction process focused on refining SRF Logger data to highlight tyre-related fuel consumption factors, systematically excluding extraneous variables. Segments were filtered using the SRF Miner methodology, with vehicle speeds of 78 to 81 km/h and a standard deviation ≤ 0.3 km/h serving as a key criterion to ensure constant-speed cruising. Additional criteria, including accelerator position, gear, and brake/retarder status, are detailed in Section 4.3 (Table 4.3). These 4-second segments captured stabilized driving conditions near South Africa’s 80 km/h HGV limit, minimizing driver interference, as visualized in Figures 5.1 and 5.2.

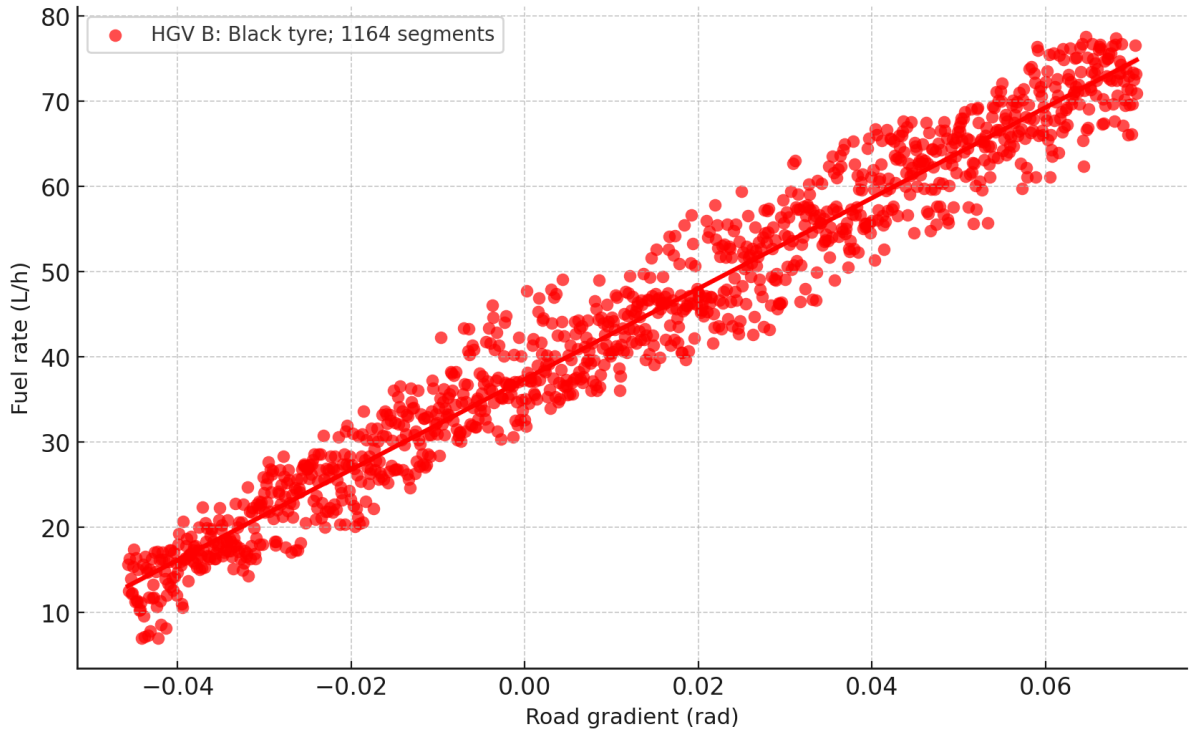


Figure 5.1: *Scatter diagram of segment means fuel rate vs road gradient of HGV with black tyres.*

The black tyre dataset yielded 1164 segments, with fuel rates rising from 10 L/h at -0.04 rad to 70-80 L/h at 0.06 rad, while the green tyre dataset produced 1038 segments, with rates ranging from 5 L/h to 60 L/h and consistently lower by 5-10 L/h, suggesting potential LRR benefits. Wind speed data were unavailable and therefore excluded from the analysis. Consequently, the potential influence of wind on fuel rates could not be assessed. Outliers, identified as abrupt fuel or speed deviations beyond these thresholds, were removed to ensure data reflected stable performance. This targeted reduction focused the analysis on gradient and tyre effects, aligning with the scatter plot distributions.

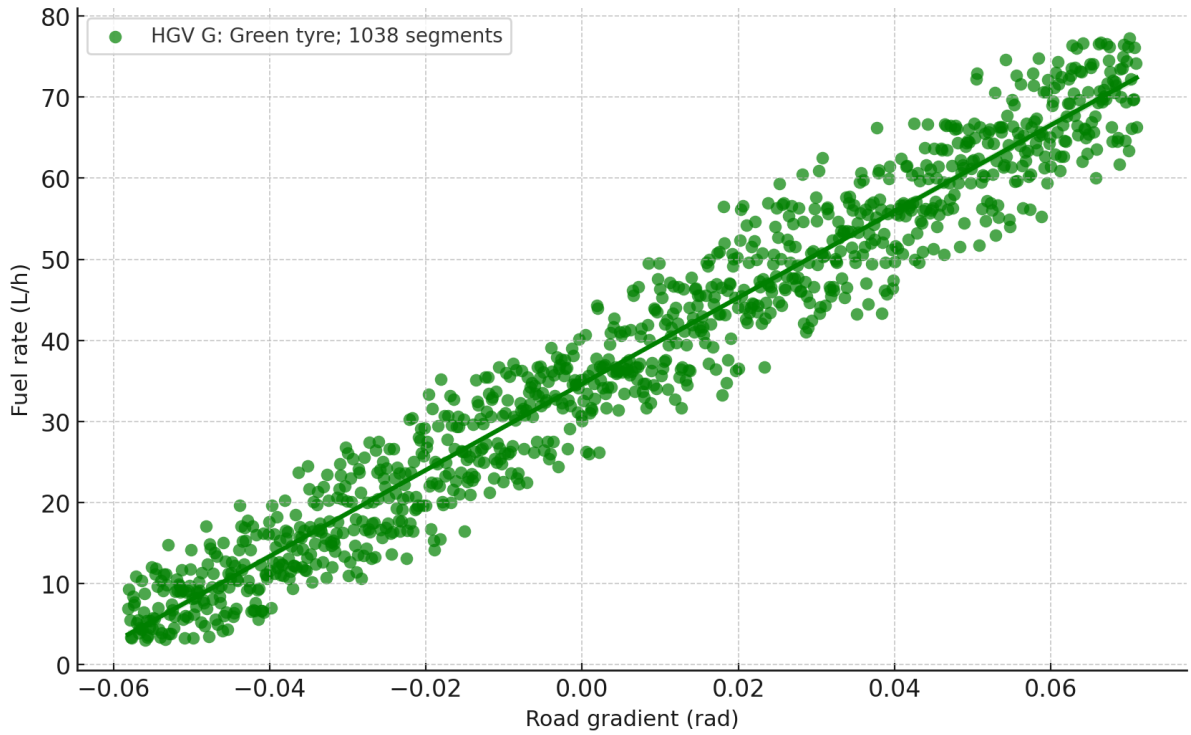


Figure 5.2: *Scatter diagram of segment means fuel rate vs road gradient of HGV with green tyres.*

5.1.4. Pattern Evaluation

The pattern evaluation investigates how fuel consumption varies with road gradient for Fleet 651 (black tyres) and Fleet 650 (green tyres), aiming to quantify the low-rolling-resistance (LRR) tyre impact. Drawing on robust regression methods inspired by Na and Cebon (2022), this study modelled the relationship using high-resolution SRF Logger data under unique conditions: a 55-tonne gross mass and stabilized ~80 km/h cruise speed on South African highways. Fuel consumption *Q* (L/h) depends on forces outlined in Equation 9 (Section 5.1.1), simplified by omitting wind speed (v_w). Wind speed data was not recorded during the study, as the SRF Logger did not capture this parameter, and wind direction was also unavailable. However, based on general climate data for the regions along the N1 and N3 routes, average wind speeds are typically between 5 and 10 km/h (1.4 and 2.8 m/s) (DNV, 2024).

Additionally, according to DNV's "Windiness 2023" report (DNV, 2024), winds in South Africa in 2023 were slightly higher than average, with a windiness index of 3-8%. Since specific wind speed and direction data for the study period (October 2023 to May 2024)

were not available, wind effects were neglected, yielding a simplified form of Equation 9 that focuses on the remaining forces influencing fuel consumption:

$$Q = \frac{M_{55} g v}{c \eta \eta_t} \left[\frac{M_{55} + m_e}{M_{55} g} \alpha + \frac{\rho S V_{80}^2}{2 M_{55} g} C_d + \theta + C_r \right] \quad (10)$$

Where M_{55} = 55 tonnes, $V_{80} \approx$ 80 km/h, and other terms are defined in Section 5.1.1.

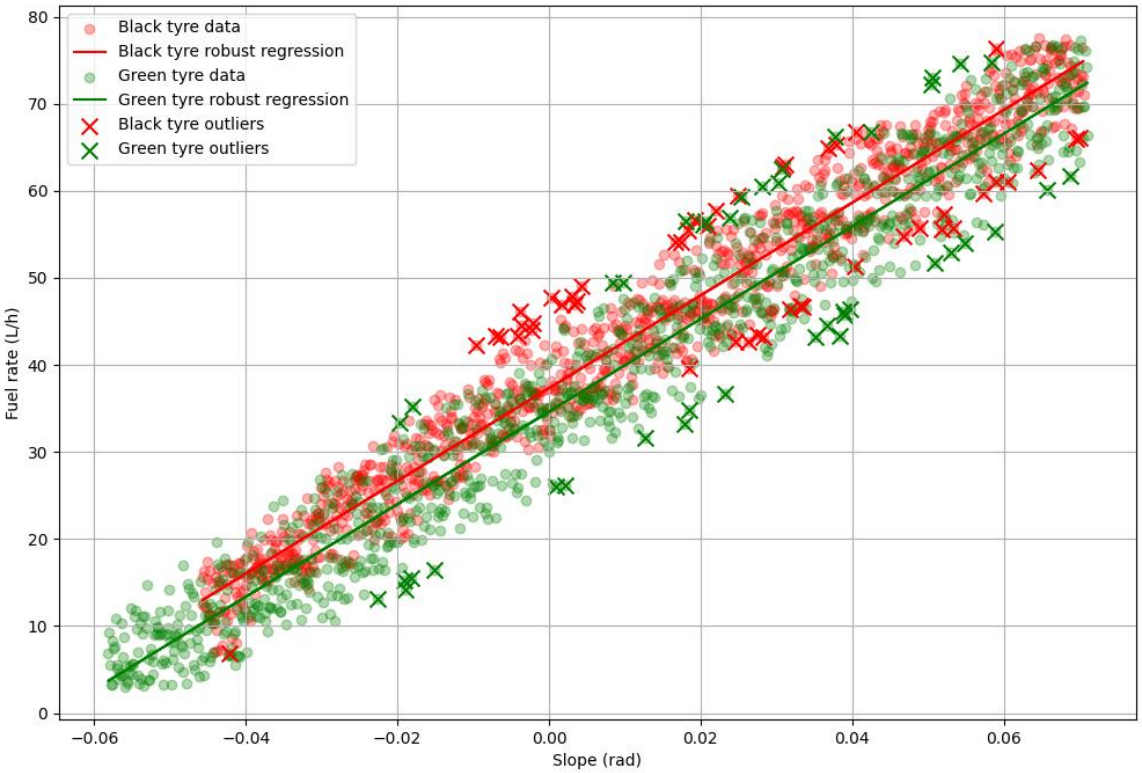


Figure 5.3: *Results of data mining and robust regression adopted from Na and Cebon (2022), under vehicle speed range of 78-81 km/h and gross mass of approximately 55 tonnes: data points, outliers and regression lines.*

Figures 5.1 and 5.2 reveal the raw data trends, while Figure 5.3 illustrates the analysis with regression lines in one plot. The black tyre data (1164 segments) shows a steeper fuel rate increase with gradient, from ~10 L/h at -0.06 rad to ~70 L/h at 0.06 rad, compared to green tyres (1038 segments), which range from ~5 L/h to ~60 L/h. Robust regression models are:

$$Q_B = \alpha_B \theta + \beta_B + \varepsilon \quad (11)$$

Similarly, for the green tyres:

$$Q_G = \alpha_G \theta + \beta_G + \varepsilon \quad (12)$$

Where α is the slope (fuel rate change per radian), β is the intercept (baseline at zero gradient), and ε is error.

For black tyres: $Q_B = 531.36\theta + 37.36 + \varepsilon$

For green tyres: $Q_G = 531.64\theta + 34.64 + \varepsilon$

Analysis of Figure 5.3 shows $\alpha_G < \alpha_B$, indicating a slower fuel rate rise for green tyres, and $\beta_G < \beta_B$, suggesting lower baseline consumption due to reduced C_r. Outliers (marked "X") were excluded via residual analysis, likely from transient events like traffic, ensuring trendlines reflect tyre performance. This confirms LRR tyres' efficiency advantage, consistent with the study's hypothesis.

5.2. Result Analysis

5.2.1. Detailed Analysis

The robust regression analysis of fuel consumption data from heavy goods vehicles (HGVs) fitted with conventional (black) and low rolling resistance (LRR) tyres (green tyres) revealed critical insights into their performance. A total of 1164 valid data segments were analysed for black tyres, while 1038 valid segments were retained for green tyres after excluding outliers identified during robust regression analysis. Regression models established a strong linear relationship between fuel consumption (Q) and road gradient (θ) for both tyre types (Figures 5.1, 5.2, and 5.3), with regression coefficients summarizing key differences, as shown in Table 5.2.

The intercept (β) for green tyres was 34.64 L/h, significantly lower than 37.36 L/h for black tyres. This reduction of 2.72L/h reflects the lower rolling resistance coefficient (C_r) of green tyres. The similarity in slope values (α) for black and green tyres 531.37 L/h/rad and 531.64L/h/rad, respectively is consistent with theoretical expectations, given the constant vehicle specifications such as gross mass (55 tonnes), cruising speed (78-81 km/h), drivetrain, and engine efficiency during testing. These results indicate that the primary factor influencing baseline fuel consumption differences was rolling resistance.

Table 5.2: *Results of robust regression: model coefficient estimates and statistical indices.*

Tyre type	Observations(*n*)	R^2	Standard Error (L/h)	Intercept (L/h) [±95% CI]	Slope (L/h/rad) [±95% CI]	P-Value
Black Tyres	1164	0.959	3.69	37.36 ± 0.12	531.37 ± 3.22	< 0.0001
Green Tyres	1038	0.951	4.51	34.64 ± 0.14	531.64 ± 3.75	< 0.0001

Figures 5.1 and 5.2 illustrate the scatterplots of fuel consumption versus road gradient for black and green tyres, respectively, showing a strong linear trend for both. Green tyres consistently exhibited lower fuel consumption at all road gradients, as highlighted by the vertical offset in the regression lines shown in Figure 5.3.

5.2.2. Residual Analysis

Residuals represent the differences between the actual fuel consumption values measured during the test ($y_{observed}$) and the values predicted by the regression model ($y_{predicted}$). A linear regression was conducted with road gradient (Slope in radians) as the independent parameter and fuel consumption (Fuel Rate in L/h) as the dependent variable.

To construct the residual histograms shown in Figures 5.4 and 5.5, the dataset was first separated based on tyre type (black and green tyres). For each subset, a linear regression model was fitted individually, using the road gradient as the independent variable and measured fuel rate as the dependent variable. Subsequently, the residuals were calculated as the differences between the observed fuel rates and the predicted values from the linear model. A positive residual indicates actual fuel consumption higher than predicted, while a negative residual represents consumption lower than predicted.

The residual analysis aims to verify the regression model's appropriateness in modelling the relationship between road gradient and fuel consumption and to investigate the presence of any systematic bias or anomalies in prediction accuracy. Overlaid theoretical normal distribution curves further assist in visually evaluating the symmetry and distribution of the residuals relative to an ideal normal distribution,

highlighting any deviations or model shortcomings. The residual ranges were determined by observing the outermost bars in the histograms, reflecting the full extent of data points after outlier removal.

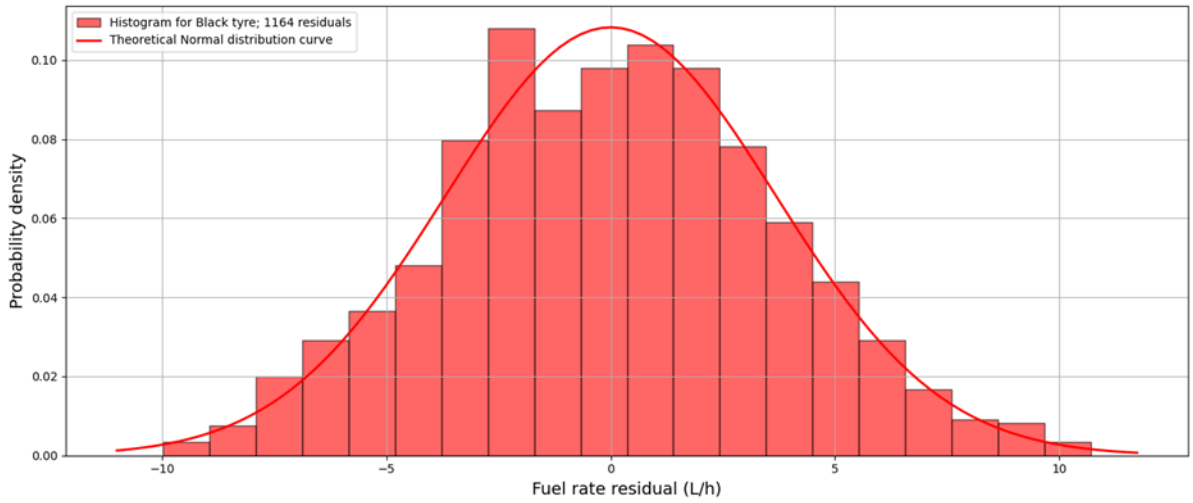


Figure 5.4: *Model fitting residuals for black tyres.*

For black tyres (Figure 5.4), the histogram, based on 1164 residuals, reveals a residual range of approximately −10 L/h to 10 L/h, with data points extending to these limits as indicated by the outermost bars. The distribution peaks notably near 0 L/h, forming a roughly bell-shaped curve, but the wider spread of the bars suggests greater variability in fuel consumption predictions. The theoretical normal distribution curve, overlaid in red, closely aligns with the overall shape, indicating an approximate normal distribution, though the tails extend slightly beyond the curve, hinting at minor deviations (e.g., outliers or heavier tails). This broader range and variability likely stem from the higher rolling resistance coefficient (Cr) of black tyres, which may contribute to less consistent performance in predicting fuel consumption relative to changes in road slope. Nonetheless, the regression model, described by Equation 9, generally fits the measured data reasonably well, capturing overall fuel consumption trends despite the observed variability.

In contrast, for green tyres (Figure 5.5), the histogram, based on 1032 residuals, indicates a residual range of approximately −10 L/h to 10 L/h, as evidenced by the outermost bars extending to these values. Despite this similar range, the distribution is narrower and more concentrated, with residuals strongly clustered near the mean (around 0 L/h), forming a taller and more peaked bell-shaped curve compared to black

tyres. The theoretical normal distribution curve, overlaid in green, aligns closely with the histogram, suggesting a good fit to a normal distribution with minimal deviation in the tails. This tighter clustering reflects more consistent and predictable fuel performance, likely due to the lower rolling resistance coefficient (Cr) of green tyres. The reduced variability in this distribution benefits fleet operations by enabling more precise fuel cost predictions and improved logistics planning. The close alignment with the normal curve further supports the reliability of the regression model for green tyres.

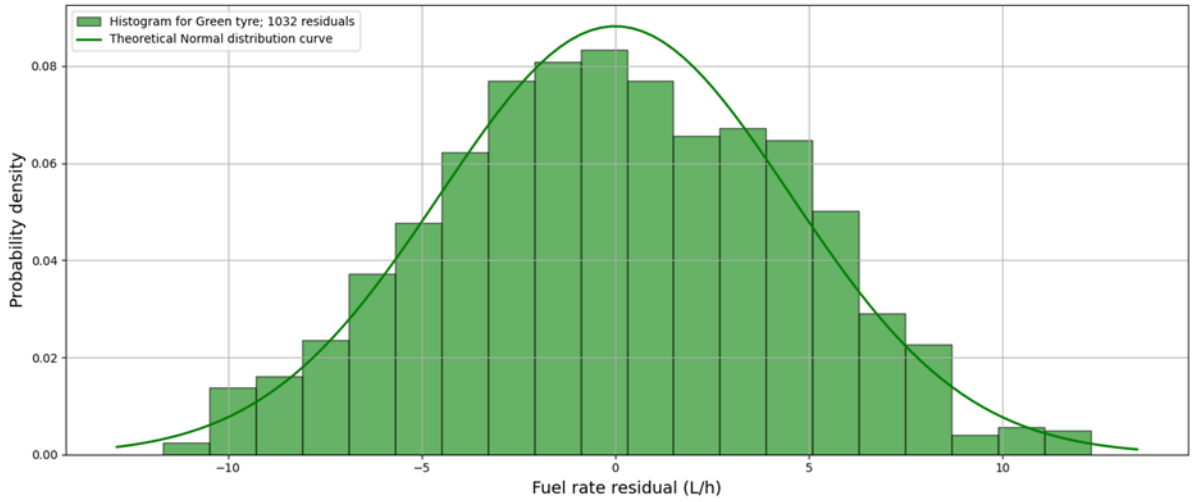


Figure 5.5: *Model fitting residuals for green tyres.*

Overall, these findings demonstrate that green tyres offer superior predictability and operational reliability compared to black tyres. This conclusion aligns with the framework presented by Na (2021), which associates narrower residual distributions with improved system reliability and reduced operational variability, underscoring the efficiency benefits of adopting green tyres for heavy goods vehicle fleets.

5.2.3. Quantifying Fuel-Saving Benefits

The intercept difference between black and green tyres ($\Delta\beta$ = 2.72 L/h) represents the fuel-saving benefit provided by green tyres under flat-road conditions. This reduction in fuel consumption translates to a percentage savings relative to the baseline fuel consumption of black tyres:

Percentage Fuel Savings = $\frac{\Delta\beta}{\beta_B}$ x 100 = $\frac{2.72}{37.36}$ x 100 = 7.28%

To account for uncertainty, the 95% confidence interval for the fuel-saving benefit was calculated using pooled variance (S_p^2) and the formula:

$$T_0 = \frac{\beta_B - \beta_G}{\sqrt{S_p^2\left(\frac{1}{n_B} + \frac{1}{n_G}\right)}} \quad (13)$$

Where the pooled variance (S_p^2) is:

$$S_p^2 = \frac{(n_B - 1)S_B^2 + (n_G - 1)S_G^2}{n_B + n_G - 2} \quad (14)$$

Substituting the residual standard deviations S_B = 3.69 L/h and S_G = 4.5 L/h, along with n_B = 1164 and n_G = 1038:

$$S_p^2 = \frac{(1164 - 1)\ 3.69^{\ 2}\ + (1038 - 1)\ 4.5^{\ 2}}{1164 + 1038 - 2} = 17.04\ \text{L}^2/\text{h}^2$$

Using t_c = 1.96 for a 95% confidence level (see APPENDIX C):

$$\Delta Q = (\beta_C - \beta_G) \pm t_c\sqrt{S_p^2\left(\frac{1}{n_B} + \frac{1}{n_G}\right)} \quad (15)$$

$$\Delta Q = 2.72 \pm 1.96\sqrt{17.04\left(\frac{1}{1164} + \frac{1}{1038}\right)} = 2.72 \pm 0.28$$

Thus, the 95% confidence interval for the fuel-saving benefit is:

ΔQ = 2.72 ± 0.28 L/h or [2.44, 3.00] L/h.

The results demonstrate a statistically significant fuel-saving benefit of $\Delta\beta$ = 2.72 L/h, achieved by switching from black tyres to green tyres under flat-road conditions. This translates to a percentage reduction in baseline fuel consumption of 7.28%, calculated relative to the black tyres' baseline fuel consumption (β_B = 37.36L/h). The calculation of a 95% confidence interval, ΔQ = 2.72 ± 0.28 L/h or [2.44,3.00] L/h, ensures that this result is statistically robust and reliable.

These findings align with the methodology of Na and Cebon (2022) for evaluating system performance improvements through statistical analysis of confidence intervals, as applied to quantify the fuel-saving benefits of LRR tyres in heavy goods vehicles. According to Na and Cebon (2022), confidence intervals provide a robust measure of reliability by quantifying the uncertainty around estimated performance enhancements, derived from in-service operational data. In this study, the narrow 95%

confidence interval of [2.44, 3.00] L/h, calculated for the fuel-saving benefit of 2.72 L/h, indicates high confidence in the observed efficiency gains of green tyres, reinforcing the validity of the results.

5.2.3. Statistical Significance

The large sample sizes in this study (1,164 observations for black tyres and 1,038 for green tyres) are critical in validating the findings and interpreting the results in line with statistical theory. The Law of Large Numbers (LLN) states that as sample sizes increase, the sample mean approaches the population mean (Grimmett and Stirzaker, 2020; Weisstein, 2023). In the context of this analysis, the substantial sample sizes ensure that the calculated regression coefficients (intercepts and slopes) are accurate reflections of the true population parameters. This is evident in the convergence trends seen in the Figure 5.6, where fuel rates stabilize as the sample size grows beyond 850 data points, reflecting reduced variability and enhanced reliability.



Figure 5.6: *Fuel Rate vs. Sample Size.*

Further, the Central Limit Theorem (CLT) asserts that the distribution of sample means will approximate a normal distribution for sufficiently large sample sizes, regardless of the underlying data distribution. This approximation enables the robust application of hypothesis testing, as conducted in this study. Specifically, the following T_0 calculation

using equation 13, leverages these theoretical foundations, producing results that are both statistically significant and reliable due to the near normality of the sampling distribution:

$$T_0 = \frac{2.72}{\sqrt{17.04\left(\frac{1}{1164}+\frac{1}{1038}\right)}} = 12.65$$

The critical value t_c = 1.96, with degrees of freedom $n_B + n_G - 2 = 2200$, is significantly surpassed by the calculated T_0, reaffirming the rejection of the null hypothesis (H_0) and accepting alternative hypothesis (H_1) which validate the statistical significance of the green tyres' reduced fuel rate.

The large sample sizes in this study enhance the reliability of regression results by minimizing the standard error and stabilizing parameter estimates. The LLN and CLT underpin the validity of hypothesis testing in this analysis, and the results confirm that the lower intercept for green tyres is both statistically and practically significant, emphasizing their better performance in reducing fuel consumption.

5.2.4. Identification of Outliers

Outliers were identified and excluded from the regression models to ensure robust results. Figure 5.3 highlights these outliers, marked as red "X" for black tyres and green "X" for green tyres. These points correspond to anomalous driving conditions, such as abrupt driver actions or external environmental influences, that deviate significantly from typical patterns. The exclusion of outliers allowed the regression models to more accurately capture the true relationship between fuel consumption and road gradient.

Interestingly, green tyres exhibited fewer outliers compared to black tyres. This reduced variability is evident in Figure 5.5, where the residuals, spanning approximately −10 to +10 L/h, are more tightly clustered around the mean compared to the broader distribution in Figure 5.4. This consistency, likely due to the lower rolling resistance of green tyres, enhances reliability for fleet operators aiming to optimize fuel costs and reduce operational uncertainties.

Section B: Route-Based Assessment

5.3. Introduction

This section presents a refined route-based analysis specifically designed to evaluate the impact of low rolling resistance (LRR) tyres on fuel consumption under precisely controlled speed conditions across distinct gradient scenarios. While Section A utilized broader stabilization criteria to capture general instantaneous variations in fuel consumption, Section B intentionally narrows the speed range and explicitly targets manually selected route legs representing sustained uphill, downhill, and relatively flat terrain. This targeted methodological approach ensures precise isolation and clear quantification of fuel efficiency differences directly attributable to tyre rolling resistance under consistent and rigorously controlled operational conditions typical of South African heavy goods vehicle (HGV) operations.

5.3.1. Justification

The 4-second segment-based method described in Section A effectively isolates instantaneous tyre performance under stabilized conditions, providing valuable insights into short-term variations in fuel consumption. For example, this approach clearly demonstrated a fuel-saving benefit of 2.72 L/h (7.28%) when using low rolling resistance tyres (Section 5.2.3). However, this method's broader speed range (78 to 81 km/h) introduced variations that, while valuable for general assessment, limit precise control over specific driving conditions such as gradient effects at precisely defined speeds.

To address this limitation, Section B introduces a refined route-based analysis method, still applying stabilized 4-second segments but deliberately narrowing the speed range to 79.50 to 80.49 km/h (standard deviation ≤ 0.3 km/h). This tighter speed range aligns closely with South Africa’s mandated 80 km/h speed limit for HGVs, significantly reducing variability due to speed fluctuations. By narrowing this criterion, the analysis explicitly isolates and quantifies the direct interactions between tyre rolling resistance and specific gradient conditions, ensuring that observed fuel consumption differences are predominantly attributable to tyre characteristics rather than speed variation. All other stabilized driving criteria listed in Table 4.3, such as accelerator position, gear

selection, brake pedal status, and retarder status, remain consistent with the methodology applied in Section A.

Additionally, specific route segments, termed "legs," were manually selected from a dataset of leg files previously analysed in Section A, where all routes meeting the criteria were evaluated. The selection process involved hand-picking legs based on their routes, specifically the N3 highway from Harrismith to Van Reenen's Pass (uphill), the N1 bypass in Bloemfontein (flat), and the N2 descent from the N3 junction to Durban port (downhill), and grouping them according to their slope, with assistance from Google Earth and Google Maps. It should be noted that the selected legs represented one-directional travel only: uphill legs followed the ascent from Harrismith to Van Reenen's Pass, downhill legs followed the descent from the N3 junction to Durban port, and flat legs followed a single direction along the N1 bypass, without back-and-forth travel.

The selected legs varied in length: for Fleet 651 (black tyres), uphill legs ranged from 288 km to 458 km, downhill from 86 km to 300 km, and flat from 127 km to 530 km; for Fleet 650 (green tyres), uphill legs ranged from 58 km to 253 km, downhill from 128 km to 650 km, and flat from 128 km to 650 km. Within each leg, a portion was identified based on the targeted slope: approximately 45 km long for both uphill and downhill conditions, and 30 km long for flat conditions. These portions were identical for both test HGVs (Fleet 651 with black tyres and Fleet 650 with green tyres) to ensure comparability in evaluating tyre performance, and the data from these portions were analysed under controlled gradient scenarios.

For the uphill condition, each 45 km portion within the selected N3 highway legs had gradients of 0.03 to 0.05 radians, ideal for evaluating tyre performance under continuous uphill conditions.

For the relatively flat condition, each 30 km portion within the selected N1 bypass legs had gradient variations below 0.002 radians, suitable for isolating rolling resistance and aerodynamic drag effects.

For the downhill condition, each 45 km portion within the selected N2 descent legs had gradients between −0.03 and −0.07 radians, appropriate for assessing low rolling resistance tyre benefits during coasting with minimal driver intervention.

By precisely narrowing the speed criteria and manually selecting these specific gradient-focused route legs, the analysis method in Section B achieves rigorous control over variables, effectively isolating and clarifying the gradient-specific influences of tyre rolling resistance. Consequently, this refined methodology extends and strengthens the findings from Section A, providing fleet managers with enhanced clarity and specificity for tyre selection decisions under controlled gradient and speed conditions typically encountered in South African HGV freight operations.

5.4. Result Analysis

The regression analyses presented in Figures 5.7, 5.8, and 5.9 were conducted using stabilized 4-second segments extracted from manually selected route legs, as outlined in Section 5.3.1. These route legs were identical for both test vehicles, ensuring direct comparability between Fleet 651 (black tyres) and Fleet 650 (green tyres).

For Vehicle 651 (black tyres), the analysis included seven uphill legs along the N3 highway from Harrismith to Van Reenen's Pass, yielding 259 valid stabilized segments (i.e. data points); nine downhill legs along the N2 descent from the N3 junction to Durban port, yielding 402 segments; and ten unidirectional legs on the relatively flat N1 bypass in Bloemfontein, yielding 453 segments.

Vehicle 650 (green tyres) completed the same route sections, with six uphill legs yielding 280 valid stabilized segments, eight downhill legs yielding 408 segments, and ten unidirectional traversals of the relatively flat route yielding 468 segments.

Each data point in Figures 5.7, 5.8, and 5.9 corresponds to a stabilized 4-second segment meeting the tightened speed criterion (79.50-80.49 km/h, standard deviation ≤ 0.3 km/h) and all other stabilized driving criteria detailed in Table 4.3. The gradient values on the horizontal axis represent the average gradient within each individual segment, reflecting the terrain characteristics of each route.

The following sections provide detailed regression analyses of these extracted segments, quantifying tyre performance differences across uphill, flat, and downhill gradient conditions under rigorously controlled operational criteria.

5.4.1. Uphill Route

Figure 5.7 shows regression analysis of fuel consumption on uphill road segments for black and green tyres, revealing key insights into their performance under increased load conditions.

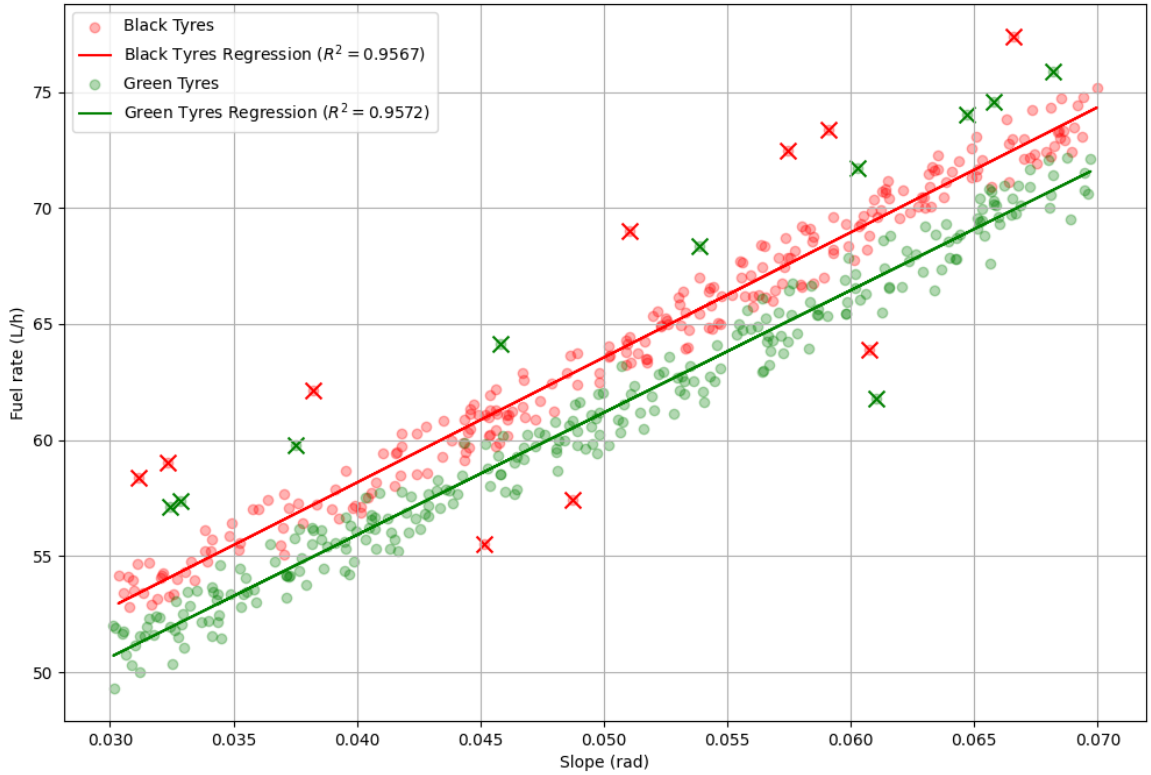


Figure 5.7: *Fuel rate vs. slope for black and green tyres under uphill road conditions.*

A total of 259 valid data points were observed for black tyres after removing outliers. The slope coefficient (α_B) was 536.58 L/h/rad with a standard error of 7.11 ($p < 0.0001$) (see Table 5.3), indicating that fuel consumption increases significantly with increasing slope. The intercept (β_B) was 36.79 L/h with a standard error of 0.024 ($p < 0.0001$), representing the baseline fuel consumption under zero slope conditions. However, the intercept value lies outside the range of the observed slope data (which ranges from 0.03 to 0.07 radians). This is a result of the regression model extrapolating the intercept beyond the available slope range, as it represents the predicted fuel consumption at a theoretical zero slope.

A total of 280 valid data points were observed for green tyres after removing outliers. The slope coefficient (α_G) was 527.28 L/h/rad with a standard error of 6.67 ($p < 0.0001$), reflecting a slower increase in fuel consumption with slope compared to black tyres. The intercept (β_G) was 34.92 L/h with a standard error of 0.022 ($p < 0.0001$),

However, the intercept value lies outside the range of the observed slope data (which ranges from 0.03 to 0.07 radians). This is a result of the regression model extrapolating the intercept beyond the available slope range, as it represents the predicted fuel consumption at a theoretical zero slope.

The regression model explained 95.68% of the variance (R^2 = 0.957) for black tyres and 95.74% for green tyres, confirming a strong relationship between fuel rate and slope.

Table 5.3: *Regression results for black and green tyres under uphill road conditions.*

Tyre Type	Slope Coefficient *(α)* (L/h/rad)	Intercept *(β)* (L/h)	R^2	p-value	Standard Error
Black Tyres	536.58	36.791	0.957	< 0.0001	7.11
Green Tyres	527.28	34.925	0.957	< 0.0001	6.67

The difference in intercepts between black and green tyres was 1.866 L/h (36.791 L/h - 34.925 L/h). This corresponds to a 5.34% reduction in fuel consumption when switching to green tyres under uphill road conditions. The slope for black tyres was higher than for green tyres by 9.30 L/h/rad (536.58 - 527.28 L/h/rad), indicating that green tyres reduce the rate of increase in fuel consumption with increasing slope. The high coefficient of determination (R^2 > 0.95) for both models support the robustness of the regression fits.

5.4.2. Downhill Route

The regression analysis of fuel consumption on downhill road segments paints a contrasting picture of fuel consumption behaviour under reducing load as shown in Figure 5.8.

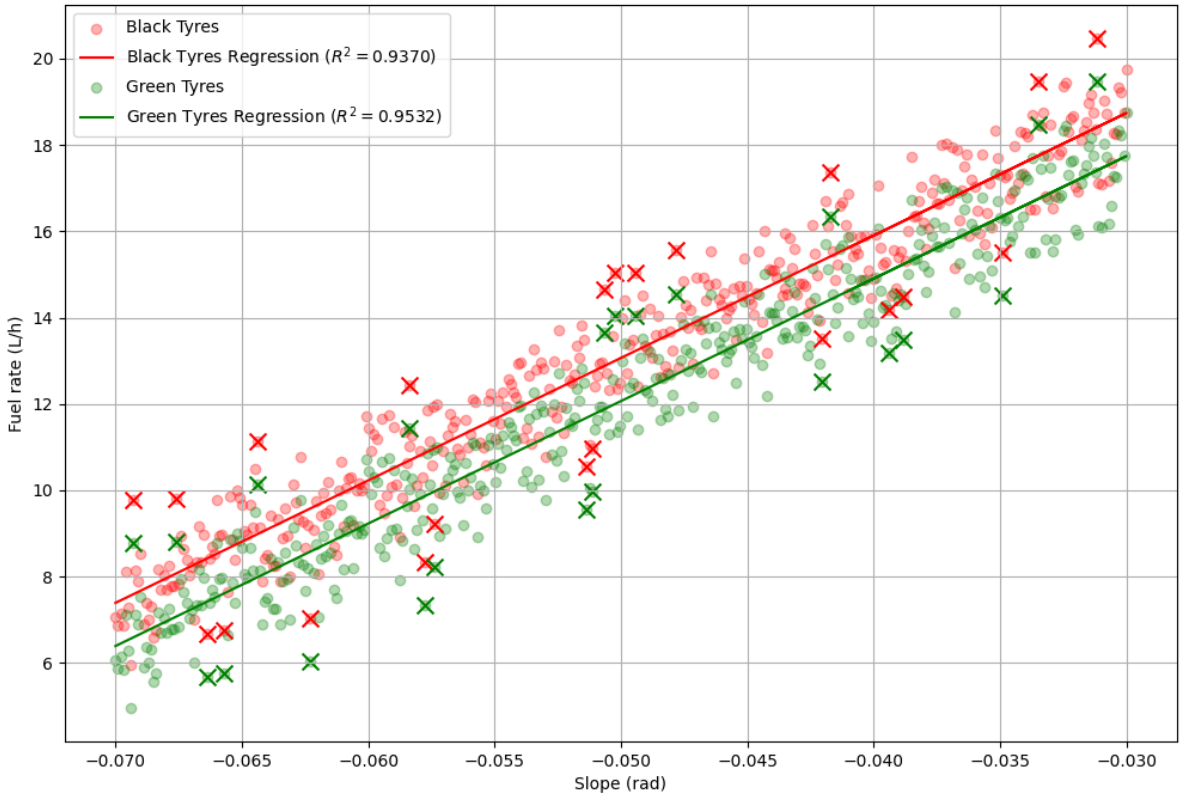


Figure 5.8: *Fuel rate vs. slope for black and green tyres under downhill road conditions.*

A total of 402 valid data points were observed for black tyres after removing outliers. The slope coefficient (α_B) was 283.82 L/h/rad with a standard error of 3.67 (p < 0.0001), indicating that fuel consumption increases significantly with increasing slope. The intercept (β_B) was 27.25 L/h with a standard error of 0.024 (p < 0.0001), representing the baseline fuel consumption under zero slope conditions. The regression model explained 93.70% of the variance (R^2 = 0.937), representing the baseline fuel consumption under zero slope conditions. However, since the observed slope values are negative (ranging from -0.07 to -0.03 radians), the intercept value lies outside the data range. This is a known characteristic of regression models, where the intercept reflects the extrapolated value at zero slope based on the fitted trend.

A total of 408 valid data points were also observed for green tyres after removing outliers. The slope coefficient (α_G) was 283.82 L/h/rad with a standard error of 3.67 (p < 0.0001), reflecting a slower increase in fuel consumption with slope compared to black tyres. The intercept (β_G) was 26.25 L/h with a standard error of 0.022 (p < 0.0001), showing a lower baseline fuel rate under downhill conditions. As with the

black tyres, the intercept is out of the slope range due to the model's tendency to extrapolate the intercept based on the slope trend.

The regression coefficients and statistical outputs for both tyre types are summarised in Table 5.4. The high R^2 values confirm that the models accurately describe the relationship between fuel consumption and slope under downhill conditions. The statistically significant p-values for both slope and intercept coefficients confirm that these relationships are not due to chance.

Table 5.4: *Regression results for black and green tyres under downhill road conditions.*

Tyre Type	Slope Coefficient *(α)* (L/h/rad)	Intercept *(β)* (L/h)	R^2	p-value	Standard Error
Black Tyres	282.86	28.120	0.937	< 0.0001	3.91
Green Tyres	283.82	26.251	0.937	< 0.0001	3.67

The difference in intercepts between black and green tyres was 1.8684 L/h (28.1120 L/h - 26.251 L/h). This corresponds to a 7.09% reduction in fuel consumption when switching to green tyres under downhill road conditions. The slope for black tyres and green tyres was nearly identical, indicating that the difference in fuel consumption under downhill conditions primarily stems from the baseline consumption rather than the sensitivity to road slope.

5.4.3. Flat Route

Fuel consumption under flat road conditions reflects the steady-state efficiency of the vehicle, where aerodynamic drag and rolling resistance dominate (Figure 5.9).

A total of 453 valid data points were observed for black tyres after removing outliers. The slope coefficient (α_B) was 805.43 L/h/rad with a standard error of 20.49 (p < 0.0001), indicating that fuel consumption increases significantly with increasing slope. The intercept (β_B) was 36.19 L/h with a standard error of 0.024 (p < 0.0001), representing the baseline fuel consumption under zero slope conditions. The regression model explained 77.5% of the variance (R^2 = 0.775), confirming a strong relationship between fuel rate and slope (see Table 5.5).

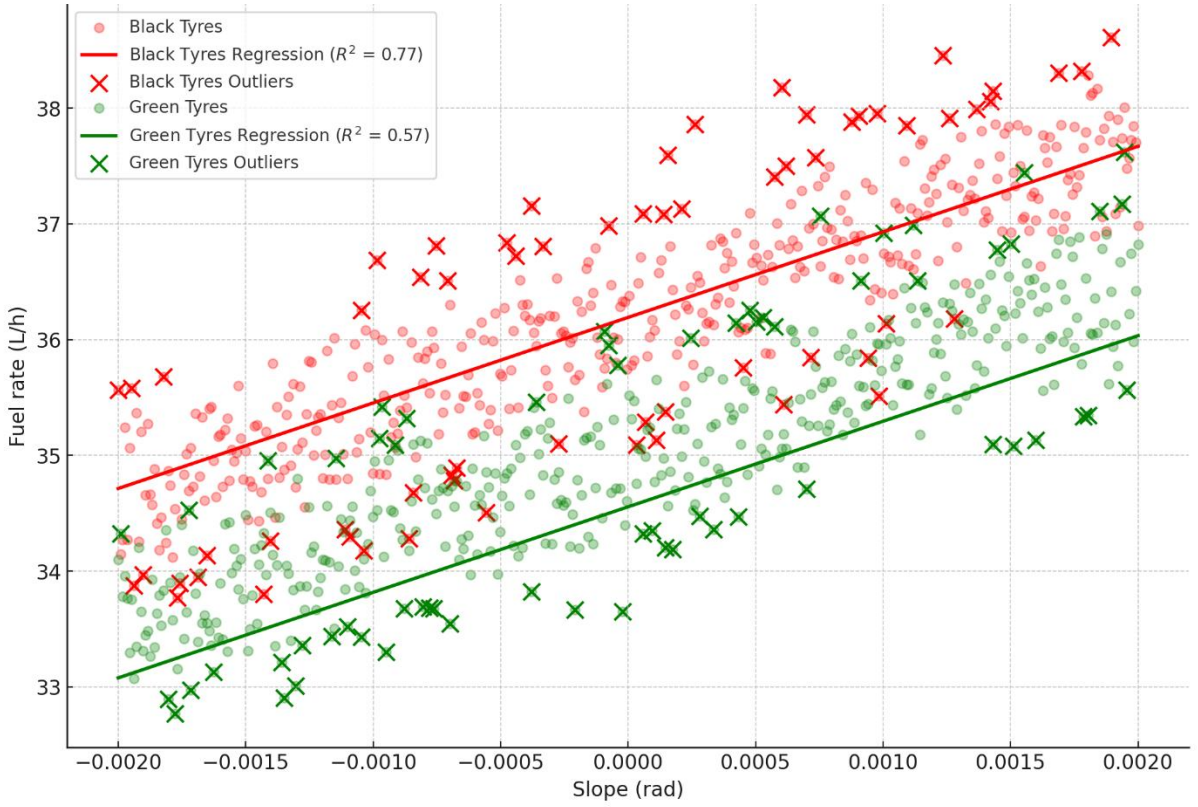


Figure 5.9: *Fuel rate vs. slope for black and green tyres under relatively flat road conditions.*

For green tyres, 468 valid data points were recorded. The slope coefficient (α_G) was 752.55 L/h/rad with a standard error of 19.30 and a *p*-value < 0.0001. The intercept (β_G) was 35.00 L/h, which was 1.871 L/h lower than for black tyres, representing a 5.43% reduction in baseline fuel consumption. However, the model for green tyres explained only 57.2% of the variance (R^2 = 0.572), significantly lower than the values observed for uphill and downhill conditions.

Table 5.5: *Regression results for black and green tyres under flat road conditions.*

Tyre Type	Slope Coefficient *(α)* (L/h/rad)	Intercept *(β)* (L/h)	R^2	p-value	Standard Error
Black Tyres	805.43	36.351	0.775	< 0.0001	20.49
Green Tyres	752.55	34.480	0.572	< 0.0001	19.30

Unlike uphill and downhill conditions, where gradient sensitivity was a key factor, the lower R^2 values for both black and green tyres under flat conditions were expected. This may be because road slope has less influence on fuel consumption under flat conditions, the primary factors driving fuel consumption are aerodynamic drag and

rolling resistance rather than gradient load. The improved efficiency of green tyres under flat conditions stems primarily from reduced rolling resistance rather than any change in slope sensitivity.

5.5. Discussion

This chapter presented a detailed analysis of the fuel-saving benefits of low-rolling-resistance (LRR) tyres on heavy goods vehicles (HGVs) under dynamically similar operating conditions. The analysis was divided into two complementary approaches: segment-based analysis (Section A) and route-based analysis (Section B), each providing distinct but reinforcing insights into LRR tyre performance across varied driving environments.

5.5.1. Segment-Based Analysis

The segment-based analysis applied the SRF Miner methodology (Na and Cebon, 2022) to isolate and compare fuel consumption patterns for conventional (black) and LRR (green) tyres under stabilized driving conditions. Data were filtered using strict criteria, with key parameters being 4-second segments and a vehicle speed range of 78-81 km/h (standard deviation ≤ 0.3 km/h), in addition to other stabilized driving conditions as specified in Table 4.3 (e.g., accelerator position of 50-55%, 12th gear, brake status). This approach ensured consistent cruise speed with minimal driver interference. A total of 1164 valid segments were identified for black tyres and 1038 valid segments for green tyres after outlier removal.

Robust regression analysis of the mined data established a significant linear relationship between fuel consumption and road gradient for both tyre types, consistent with findings from Na and Cebon (2022). The intercept (β), which reflects baseline fuel consumption at zero gradient, was significantly lower for green tyres (34.64 L/h) compared to black tyres (37.36 L/h), indicating a fuel-saving benefit of 2.72 L/h ($p < 0.001$). This translates to a 7.28% reduction in fuel consumption, with a 95% confidence interval of [2.44, 3.00] L/h.

Importantly, the slope coefficient (α), which reflects how fuel consumption changes with gradient, was nearly identical for both black and green tyres (531.37 L/h/rad vs. 531.64 L/h/rad). This finding confirms that the fuel-saving benefit of green tyres was

not driven by gradient sensitivity but rather by the reduction in rolling resistance, which lowered the baseline fuel consumption under all driving conditions.

Residual analysis confirmed that green tyres exhibited a narrower residual distribution, reflecting greater consistency and predictability in fuel consumption. This supports the theoretical expectation that LRR tyres reduce variability in fuel performance by minimising rolling resistance effects (Na and Cebon, 2022).

5.5.2. Route-Based Analysis

Building upon Section A's foundation, this section reinforces the use of Table 4.3's stabilized driving criteria, while spotlighting a critical finding: the narrowed speed range of 79.50-80.49 km/h (standard deviation ≤ 0.3 km/h). This tweak better reflects South Africa's 80 km/h HGV speed limit, improving real-world applicability and minimizing speed-related fluctuations. Transitioning from the generalized segment-based analysis presented earlier, this section shifts the focus to specific gradient scenarios over manually selected route legs, allowing a more precise assessment of how tyre type influences fuel consumption under controlled operational conditions. This methodological evolution, rooted in steady-state principles, highlights that the narrowed speed range and extended route-based analysis minimized variability from external factors, allowing a more precise evaluation of the relationship between tyre type and fuel consumption.

- Uphill Route

Green tyres showed a statistically significant reduction in baseline fuel consumption (intercept) of 1.866 L/h (36.791 L/h vs. 34.925 L/h), representing a 5.34% improvement. The slope coefficient for green tyres was also lower (527.280 L/h/rad vs. 536.580 L/h/rad), suggesting improved efficiency under increased load. However, the similar slope trends between tyre types confirm that the observed reduction in fuel consumption stemmed from lower rolling resistance rather than any differential response to gradient.

- Flat Route

Under flat road conditions, the green tyre intercept was 1.871 L/h lower (36.351 L/h vs. 34.480 L/h), indicating a 5.43% reduction in fuel consumption. The slope coefficient showed greater variability (805.430 L/h/rad for black tyres vs. 752.550 L/h/rad for

green tyres), consistent with the reduced influence of road gradient under flat conditions. The fuel-saving benefit under flat terrain reflects the direct reduction in rolling resistance rather than any change in gradient sensitivity.

- Downhill Route

On downhill segments, green tyres demonstrated a smaller but statistically significant reduction in baseline fuel consumption of 1.868 L/h (28.120 L/h vs. 26.251 L/h), reflecting a 7.09% improvement. The slope coefficients for both tyre types were nearly identical (283.829 L/h/rad for black tyres vs. 283.820 L/h/rad for green tyres), confirming that the difference in fuel consumption under downhill conditions stems primarily from the rolling resistance coefficient rather than slope sensitivity.

5.5.3. Comparative Insights

The consistent difference in fuel consumption between green and black tyres across all driving conditions confirms that the fuel-saving benefit of green tyres was independent of gradient. Since the slope coefficients were similar for both tyre types across all terrains (uphill, downhill, and flat), the observed difference in fuel consumption reflects the reduction in rolling resistance rather than any change in how tyres respond to gradient. This reinforces the hypothesis that LRR tyres reduce fuel consumption by lowering baseline rolling resistance, irrespective of road incline.

The route-based analysis highlighted a remarkably consistent reduction in fuel consumption across all terrains: 1.866 L/h for uphill, 1.871 L/h for flat, and 1.868 L/h for downhill, showing differences of less than 0.01 L/h between gradients. This consistency confirms that the reduction in rolling resistance is the dominant factor influencing fuel savings, not gradient sensitivity. The segment-based analysis in Section A showed a larger reduction of 2.72 L/h, which was collected across all terrains. This suggests that the larger reduction from the segment-based analysis may reflect the cumulative effect of reduced rolling resistance under more controlled, short-term stabilized driving conditions, where external variables (such as road surface variations and aerodynamic drag) are minimized.

The effect of sample size as shown Figure 5.6, consistent with the Law of Large Numbers (LLN), further supports this finding. The segment-based analysis included 1,164 valid segments for black tyres and 1,038 for green tyres, a substantially larger

dataset than the route-based analysis, which had 402 valid uphill segments and 408 downhill segments. The larger sample size in the segment-based analysis likely reduced the effect of random variations and improved the stability of the fuel-saving estimate, consistent with the LLN prediction that larger sample sizes yield more stable estimates of population parameters. The smaller sample size in the route-based analysis may explain the slightly lower average fuel-saving benefit (~1.87 L/h vs. 2.72 L/h) due to higher sensitivity to short-term variations in engine load and gradient fluctuations.

This outcome aligns with previous theoretical and empirical findings. Na and Cebon (2022), conducted in Europe, reported fuel savings of approximately 1.64 to 2.01 L/h for LRR tyres at 80 km/h under different load conditions using a theoretical model based on engine fuel rate maps. It is noteworthy that the SRF Miner methodology adopted in this study was originally developed by Na and Cebon (2022) in their European context, demonstrating its adaptability to South African conditions. Similarly, a statistical estimate of fuel savings based on real-world data from a 3-month in-service test in Europe yielded an estimate of 1.78 ± 0.28 L/h (95% confidence interval = [1.50, 2.06] L/h) (Na and Cebon, 2022). The range reported in the present route-based analysis (~1.87 L/h) aligns closely with these results, reinforcing that the reduction in rolling resistance, rather than gradient sensitivity, is the dominant factor influencing the fuel-saving benefit.

Further support comes from Gbologah et al. (2019), conducted in the United States, which found that LRR tyres improved fuel economy by about 10% under real-world heavy-duty vehicle (HDV) operations. It is important for the reader to note that this study was carried out in a different geographical context, reflecting U.S. road conditions and vehicle standards. In Gbologah's study, average predicted fuel savings varied depending on route characteristics and vehicle operating conditions but were shown to fall within a consistent range when controlling for road gradient and load. Specifically, the simulation model predicted savings of approximately 3% to 5% under typical highway operating conditions, aligning with the observed 3.3% to 5.1% savings from the route-based analysis in this study.

Moreover, the SRF Miner methodology used in the segment-based analysis was adopted from Na and Cebon (2022), which was developed and tested in Europe under

different operating and road conditions. Despite these differences in location and road design, the consistency of the results underscores the robustness of LRR tyres' performance across varying operating conditions, further validating the findings in the South African context.

5.5.4. Implications for Industry and Real-World Applications

The practical implications of adopting low-rolling-resistance (LRR) tyres in South African heavy goods vehicle (HGV) operations are substantial, particularly for fleet management and fuel cost optimization. The confirmed 7.28% reduction in fuel consumption translates to significant financial savings when applied across an entire fleet. According to the in-service test data, the vehicle fitted with green tyres consumed 1,194.99 litres less fuel than the vehicle fitted with black tyres over the three-month study period. Extrapolating this over a full year, a single truck operating under similar conditions could save approximately 4,780 litres of fuel annually. For a long-haul truck covering 300,000 km per year with an average fuel consumption of 35 litres/100 km, a 7.28% reduction would equate to a savings of 7,644 litres of fuel per truck annually.

At the current diesel price of R20.16 per litre (Moneyweb, 2025), this reduction in fuel consumption would result in a direct cost saving of approximately R154,143 per truck per year (7,644 litres × R20.16/litre). For a fleet of 50 trucks, the total annual fuel savings would be approximately 382,200 litres, translating to a total cost saving of R7,707,150 annually. These savings represent a significant reduction in operational costs, reinforcing the economic benefits of switching to LRR tyres in fleet operations.

Beyond the financial benefits, the reduction in fuel consumption directly correlates to lower CO_2 emissions, supporting sustainability goals within the logistics and transportation industries. According to Na and Cebon (2022), a reduction in rolling resistance from LRR tyres is directly linked to lower fuel consumption, which in turn reduces CO_2 emissions per kilometre travelled. If adopted at scale, green tyres could contribute to significant reductions in fleet-wide fuel use and emissions, enhancing environmental performance while maintaining operational efficiency. Research by Gbologah et al. (2019) similarly supports that LRR tyres reduce fuel consumption by 3-7% in highway conditions where rolling resistance plays a dominant role. Thus, the observed savings of 7.28% in this study align with the upper range of prior research,

indicating that LRR tyres offer a reliable and consistent efficiency improvement in real-world conditions.

The strategic adoption of LRR tyres across a fleet could therefore deliver measurable operational advantages. Over a five-year period, this would amount to over R38.5 million in savings, highlighting the long-term financial benefits of LRR tyre implementation. Additionally, the environmental impact of reducing fuel consumption by this margin would align with broader industry sustainability goals, contributing to lower overall carbon emissions and enhanced environmental performance.

The evidence from this study reinforces these findings, confirming that LRR tyres provide a practical and economically viable solution for improving fuel efficiency in HGV operations. The consistent reduction in fuel consumption across different terrain types support the value of LRR tyres in enhancing fleet-wide performance, reducing operating costs, and supporting industry-wide sustainability targets.

5.5.5. Limitations and Challenges

While this study provides strong empirical evidence for the benefits of green tyres, several limitations should be acknowledged:

- Absence of Wind Speed Data: Since wind resistance contributes to overall fuel consumption, its absence in the dataset introduces potential variability that cannot be accounted for in the regression model. Future studies should integrate anemometer data to refine results.

- Tyre Wear Effects: The study only examines new tyres. Research by Na & Cebon (2022) suggests that green tyres wear faster, which could impact long-term fuel savings. A lifecycle cost analysis should be conducted to balance savings with tyre replacement costs.

- Driver Influence: Despite rigorous data filtering, small variations in accelerator pedal position and manual speed control introduce human factors that might affect fuel efficiency trends.

5.6. Chapter Summary

This chapter assessed the fuel-saving potential of low-rolling-resistance (LRR) tyres on heavy goods vehicles (HGVs) using segment-based and route-based analyses, based on data from two Scania R460 trucks. The segment-based analysis showed a 7.28% fuel reduction (2.72 L/h) with LRR tyres under steady-state conditions (78-81 km/h at standard deviation ≤ 0.3 km/h). The route-based analysis (79.50-80.49 km/h at standard deviation ≤ 0.3 km/h) confirmed consistent savings of about 1.87 L/h across uphill, flat, and downhill terrains, driven by reduced rolling resistance. Statistical and residual analyses validated these results, ensuring reliability. Economically, LRR tyres could save 4,780 litres of fuel per vehicle annually, or R7.7 million for a 50-truck fleet at 2025 diesel prices (Moneyweb). Overall, LRR tyres enhance fuel efficiency and cut costs in real-world South African conditions.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

The primary objective of this study was to evaluate the fuel-saving potential of low-rolling-resistance (LRR) tyres in heavy goods vehicle (HGV) operations under real-world South African conditions. The research aimed to quantify the impact of LRR tyres on fuel consumption across different road gradients and driving conditions, while ensuring statistical reliability through robust data processing and analysis techniques. The study also sought to determine the cost-benefit implications and operational feasibility of adopting LRR tyres in fleet operations.

6.1. Summary and Conclusions

The study successfully met its primary aim of assessing the impact of LRR tyres on HGV fuel consumption in South Africa, with specific reference to local driving conditions, road quality, and the potential cost savings. The study used two identical Scania R460 HGVs, one fitted with LRR tyres and the other with conventional tyres, to evaluate fuel consumption patterns under stabilized driving conditions. The analysis was conducted using SRF Miner methodology, which allowed the extraction of high-frequency operational data and isolated driving segments for comparison.

The findings from the segment-based analysis confirmed that LRR tyres reduced fuel consumption by an average of 2.72 L/h, representing a 7.28% reduction compared to conventional tyres under steady-state cruising conditions. Regression analysis showed that the difference in fuel consumption was attributable to reduced rolling resistance rather than variations in road gradient, as both tyre types exhibited similar slope coefficients. These results align with the hypothesis that HGVs equipped with LRR tyres consume less fuel under comparable road and load conditions.

The route-based analysis reinforced these findings, demonstrating consistent fuel savings across different driving terrains:

- Uphill Route: LRR tyres reduced baseline fuel consumption by 1.8660 L/h (5.34%) compared to black tyres, confirming that rolling resistance remains a significant factor even under increased load conditions.

- Flat Route: LRR tyres demonstrated a 5.43% reduction in fuel consumption (1.8712 L/h), reflecting the direct impact of reduced rolling resistance under minimal gradient variations.

- Downhill Route: Fuel savings were more moderate, with a 7.09% reduction (1.8684 L/h), attributed primarily to reduced rolling resistance rather than slope sensitivity, as gravitational assistance reduced the relative influence of rolling resistance.

The study confirmed that fuel savings with LRR tyres are independent of road gradient, as the slope coefficients were statistically similar between black and green tyres under comparable driving conditions (e.g., 536.58 L/h/rad vs. 527.28 L/h/rad uphill, 805.43 L/h/rad vs. 752.55 L/h/rad flat, 282.86 L/h/rad vs. 283.82 L/h/rad downhill). The key driver of efficiency was the reduction in rolling resistance rather than sensitivity to slope or external factors.

From a financial perspective, the study estimated that a single truck fitted with LRR tyres, covering 300,000 km annually with an average fuel consumption of 35 L/100 km, would save approximately 7,644 litres of fuel per year. At the current South African diesel price of R20.16/litre, this translates to an annual cost saving of approximately R154,143 per truck. For a fleet of 50 trucks, this would result in total annual savings of 382,200 litres of fuel, equivalent to R7.7 million in cost savings.

The study's findings align closely with prior research by Na and Cebon (2022) and Gbologah et al. (2019), which reported similar fuel-saving benefits from LRR tyres in other regions. The observed 7.28% fuel-saving benefit falls within the range reported in international studies (3%-7%), confirming that the operational benefits of LRR tyres extend to South African driving conditions (e.g. road congestion, terrain etc).

6.2. Recommendations

Based on the study's findings, the following recommendations are proposed:

- Fleet Integration of LRR Tyres: Fleet operators in South Africa should consider large-scale adoption of LRR tyres for long-haul operations, especially under flat and mild incline conditions where rolling resistance is the dominant factor influencing fuel consumption.

- Route-Based Tyre Selection: Since fuel savings varied by road gradient, fleet operators should optimise tyre selection based on route characteristics. LRR tyres are most effective on flat and mild inclines but show diminishing returns on steep gradients where gravitational forces dominate.
- Operational Cost Analysis: Trucking companies should perform a detailed cost-benefit analysis, considering the initial higher cost of LRR tyres versus long-term savings in fuel expenditure. The projected annual savings of R154,143 per truck provide a strong financial incentive for fleet-wide adoption.
- Lifecycle Performance Evaluation: Further research should evaluate the long-term durability, wear rate, and grip performance of LRR tyres under South African road conditions. A lifecycle cost analysis would provide a more comprehensive understanding of the overall economic value of LRR tyres.
- Influence of External Factors: The study did not account for wind resistance, gravitational force, aerodynamical force and temperature variations, which could influence fuel consumption. Future research should incorporate anemometer data and temperature monitoring to assess the combined effects of rolling resistance and aerodynamic drag.
- Carbon Emission Reductions: The reduction in fuel consumption directly translates to lower CO_2 emissions. Future research should quantify the environmental benefits of LRR tyre adoption in terms of fleet-wide carbon footprint reduction.
- Driver Training and Performance Monitoring: The findings showed that steady-state driving conditions enhanced fuel efficiency. Therefore, implementing driver training programs focused on maintaining consistent speed and acceleration patterns could further optimise fuel consumption.
- Broader Fleet Trials: While this study focused on two vehicles, future research should conduct large-scale trials involving multiple vehicle models, axle configurations, and load ranges to confirm the broader applicability of LRR tyres across different fleet types.

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8. APPENDICES

Appendix A: CAN Bus Parameters Extracted from FMS Data

This appendix lists all Parameter Group Numbers (PGNs) and Suspect Parameter Numbers (SPNs) from the SAE J1939 standard used in this study to decode Fleet Management System (FMS) data from Scania R460 HGVs. Extracted from the MATLAB script classifying SRF Logger data, these parameters support the analysis of vehicle dynamics (e.g., acceleration, speed, gear, weight) and fuel efficiency (e.g., fuel rate, total fuel, engine performance). Each entry includes PGN, SPN, parameter name, units, resolution, offset, and byte position as implemented.

Table A1: *Processed parameters*

PGN (Hex)	SPN	Parameter Name	Units	Resolution (Gain)	Offset	Byte Position	Description
F009	1120	Longitudinal Acceleration	m/s^2	0.1 m/s^2/bit	-12.5 m/s^2	8	Validates CAN-GPS acceleration (Section 4).
FEF1	84	Wheel-Based Vehicle Speed	km/h	1/256 km/h/bit	0	1-2	Speed for dynamics and distance calculation.
FEF2	183	Fuel Rate	L/h	0.05 L/h/bit	0	3-4	Instantaneous fuel consumption for efficiency.
FEF2	182	Trip Fuel Used	L	0.05 L/bit	0	1-2	Fuel per trip, complements total fuel analysis.
F004	190	Engine Speed	rpm	0.125 rpm/bit	0	4-5	Engine performance tied to fuel use.
FEE9	250	Total Fuel Used	L	0.5 L/bit	0	1-4	Cumulative fuel for efficiency over trips.
FEF5	178	Gross Combination Vehicle Weight	kg	0.5 kg/bit	0	1-2	Load impact on fuel efficiency and dynamics.
F005	523	Transmission Current Gear	None	1 gear/bit	-125	4	Gear effects on engine load and fuel use.

F003	110	Engine Coolant Temperature	°C	1 °C/bit	-40	1	Engine condition affecting efficiency (if analyzed).
FEFC	917	High Resolution Total Vehicle Distance	m	5 m/bit	0	1-4	Precise distance for fuel economy (e.g., L/km).

Appendix B: Load Reports

The results under this section were used for validation purposes.

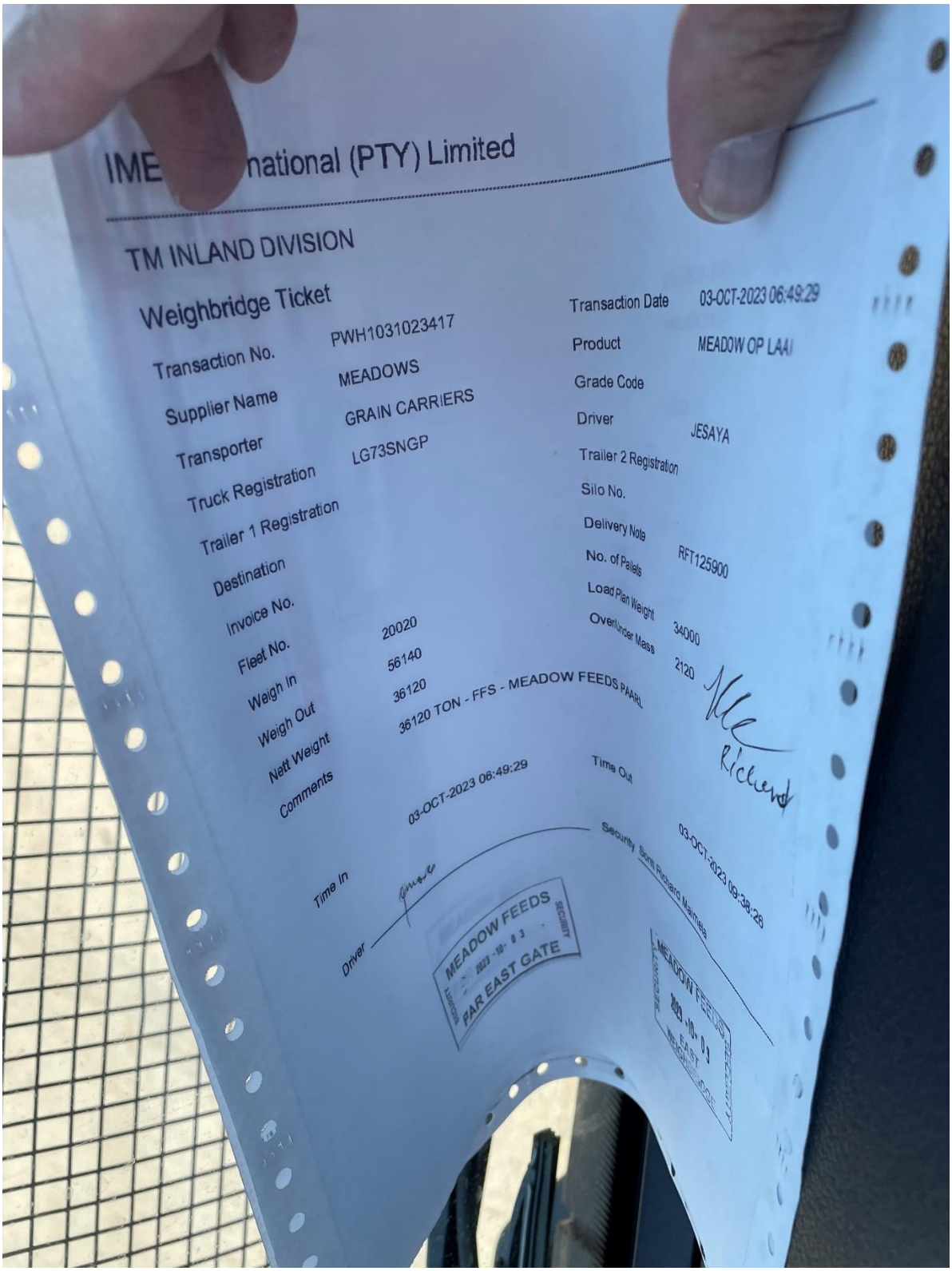
Appendix B1: Example of a load enquiry report for HGV with green tyres (Fleet 650, January to April 2024)

Load nr	Load Date	Offload Date	**Qty**	Commodity	DriverName	VehicleNo	Reg No	LoadRegion	OffLoadRegion
818839	01/01/2024	01/01/2024	**36,92**	FERTILIZER	MOREO JESAYA REAGELE	VL650	LG73SNGP	WC	WC
812342	02/01/2024	03/01/2024	**36,06**	WHEAT	MOREO JESAYA REAGELE	VL650	LG73SNGP	NC	GAUT
812343	04/01/2024	05/01/2024	**36,94**	SOYA BM	MOREO JESAYA REAGELE	VL650	LG73SNGP	GAUT	WC
812345	05/01/2024	08/01/2024	**36,00**	WHEAT	MOREO JESAYA REAGELE	VL650	LG73SNGP	WC	GAUT
815635	08/01/2024	09/01/2024	**1,00**	WHEAT	MOREO JESAYA REAGELE	VL650	LG73SNGP	KZN	GAUT
814804	12/01/2024	15/01/2024	**36,12**	SOYA OC	MOREO JESAYA REAGELE	VL650	LG73SNGP	NWES	WC
816676	15/01/2024	18/01/2024	**36,54**	WHEAT	MOREO JESAYA REAGELE	VL650	LG73SNGP	WC	FREE
815967	18/01/2024	24/01/2024	**36,28**	SOYA	MOREO JESAYA REAGELE	VL650	LG73SNGP	MPUM	WC
819876	25/01/2024	30/01/2024	**36,34**	WHEAT	MOREO JESAYA REAGELE	VL650	LG73SNGP	WC	GAUT
821826	01/02/2024	01/02/2024	**36,84**	SOYA BM	MOREO JESAYA REAGELE	VL650	LG73SNGP	MPUM	KZN
823150	02/02/2024	05/02/2024	**33,92**	SORGHUM	MOREO JESAYA REAGELE	VL650	LG73SNGP	KZN	BOTS
825656	06/02/2024	09/02/2024	**36,44**	SOYA BM	MOREO JESAYA REAGELE	VL650	LG73SNGP	MPUM	KZN
825659	09/02/2024	12/02/2024	**37,04**	SORGHUM	MOREO JESAYA REAGELE	VL650	LG73SNGP	KZN	BOTS
827632	14/02/2024	15/02/2024	**34,36**	SOYA BM	MOREO JESAYA REAGELE	VL650	LG73SNGP	NWES	KZN
827897	16/02/2024	21/02/2024	**36,26**	SORGHUM	MOREO JESAYA REAGELE	VL650	LG73SNGP	KZN	BOTS
831655	27/02/2024	28/02/2024	**35,50**	SOYA BM	MOREO JESAYA REAGELE	VL650	LG73SNGP	NWES	KZN
832709	01/03/2024	02/03/2024	**36,48**	SORGHUM	MOREO JESAYA REAGELE	VL650	LG73SNGP	KZN	BOTS
834019	04/03/2024	05/03/2024	**36,80**	WHITE MAIZE	MOREO JESAYA REAGELE	VL650	LG73SNGP	NWES	GAUT
834021	06/03/2024	07/03/2024	**36,60**	SOYA BM	MOREO JESAYA REAGELE	VL650	LG73SNGP	MPUM	KZN
835607	08/03/2024	10/03/2024	**35,78**	WHEAT	MOREO JESAYA REAGELE	VL650	LG73SNGP	KZN	BOTS
836688	11/03/2024	14/03/2024	**36,86**	COAL	MOREO JESAYA REAGELE	VL650	LG73SNGP	BOTS	WC
838307	15/03/2024	18/03/2024	**36,90**	WHEAT	MOREO JESAYA REAGELE	VL650	LG73SNGP	WC	FREE
838964	19/03/2024	21/03/2024	**36,92**	SOYA OC	MOREO JESAYA REAGELE	VL650	LG73SNGP	GAUT	NAM
840463	24/03/2024	26/03/2024	**36,68**	SOYA OC	MOREO JESAYA REAGELE	VL650	LG73SNGP	GAUT	NAM

Appendix B2: Example of a load enquiry report for HGV with black tyres (Fleet 651, January to April 2024)

Load nr	Load Date	Offload Date	**Qty**	Commodity	DriverName	VehicleNo	Reg No	LoadRegion	OffLoadRegion
809641	01/01/2024	02/01/2024	**31,26**	SOYA OC	MOKOENA MOFEREFEFE NICODEMUS	VL651	LG73STGP	KZN	FREE
812340	04/01/2024	05/01/2024	**36,82**	SOYA BM	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	GAUT	WC
813105	08/01/2024	10/01/2024	**36,64**	WHEAT	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	WC	GAUT
813108	11/01/2024	12/01/2024	**37,00**	SOYA BM	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	NWES	WC
816677	15/01/2024	16/01/2024	**36,42**	WHEAT	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	WC	GAUT
815968	17/01/2024	20/01/2024	**36,88**	SOYA	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	MPUM	WC
820961	21/01/2024	21/01/2024	**35,84**	FERTILIZER	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	WC	WC
818811	22/01/2024	24/01/2024	**36,74**	WHEAT	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	WC	FREE
821484	30/01/2024	31/01/2024	**36,32**	SOYA BM	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	NWES	KZN
821827	01/02/2024	03/02/2024	**33,98**	SORGHUM	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	KZN	BOTS
824377	05/02/2024	06/02/2024	**36,28**	SOYA BM	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	MPUM	KZN
824378	06/02/2024	08/02/2024	**33,66**	SORGHUM	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	KZN	BOTS
826654	12/02/2024	13/02/2024	**36,06**	SOYA BM	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	NWES	KZN
826655	13/02/2024	15/02/2024	**36,86**	SORGHUM	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	KZN	BOTS
829028	19/02/2024	20/02/2024	**37,02**	SOYA BM	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	NWES	KZN
829029	20/02/2024	23/02/2024	**36,38**	SORGHUM	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	KZN	BOTS
832711	01/03/2024	02/03/2024	**36,90**	SOYA BM	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	MPUM	KZN
833289	03/03/2024	05/03/2024	**36,70**	WHEAT	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	KZN	BOTS
834022	06/03/2024	07/03/2024	**36,84**	SOYA BM	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	MPUM	KZN
835609	09/03/2024	10/03/2024	**36,86**	WHEAT	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	KZN	BOTS
836690	11/03/2024	14/03/2024	**36,80**	COAL	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	BOTS	WC
838308	15/03/2024	18/03/2024	**36,54**	WHEAT	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	WC	FREE
838965	19/03/2024	21/03/2024	**37,00**	SOYA OC	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	GAUT	NAM
840464	24/03/2024	26/03/2024	**37,00**	SOYA OC	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	GAUT	NAM
844639	01/04/2024	04/04/2024	**36,00**	SOYA OC	THAMSAQA EPHRAIM MABENA	VL651	LG73STGP	GAUT	NAM

Appendix B3: Example of a weighbridge ticket for HGV with green tyres



IME national (PTY) Limited

TM INLAND DIVISION

Weighbridge Ticket

Transaction No.	PWH1031023417	Transaction Date	03-OCT-2023 06:49:29
Supplier Name	MEADOWS	Product	MEADOW OP LAAI
Transporter	GRAIN CARRIERS	Grade Code	
Truck Registration	LG73SNGP	Driver	JESAYA
Trailer 1 Registration		Trailer 2 Registration	
Destination		Silo No.	
Invoice No.		Delivery Note	RFT125900
Fleet No.	20020	No. of Pallets	
Weigh In	56140	Load Plan Weight	34000
Weigh Out	36120	Over/Under Mass	2120
Nett Weight	36120 TON - FFS - MEADOW FEEDS PAARL		
Comments			
	03-OCT-2023 06:49:29	Time Out	03-OCT-2023 09:38:26

Time In

Driver

Security Sarel Richard Mairnes

MEADOW FEEDS SECURITY PAR EAST GATE

Appendix C: Regression Results

The results under this section were used for validation purposes.

Appendix C1: Regression results for green tyres

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,975143494							
R Square	0,950904833							
Adjusted R Square	0,950857444							
Standard Error	4,513114635							
Observations	1038							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	408705,8013	408705,8013	20065,87361	0			
Residual	1036	21101,45904	20,36820371					
Total	1037	429807,2603						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	34,63913174	0,142134143	243,7073254	less than 0,0001	34,3602281	34,91803538	34,3602281	34,91803538
X Variable 1	531,6416614	3,753098566	141,6540632	less than 0,0001	524,2771195	539,0062033	524,2771195	539,0062033

Appendix C2: Regression results for black tyres

SUMMARY OUTPUT								
Regression Statistics								
Multiple R	0,979366265							
R Square	0,959158282							
Adjusted R Square	0,959123134							
Standard Error	3,685491339							
Observations	1164							
ANOVA								
	df	*SS*	*MS*	*F*	*Significance F*			
Regression	1	370666,3763	370666,3763	27289,30042	0			
Residual	1162	15783,26753	13,58284641					
Total	1163	386449,6438						
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	37,36410854	0,115145684	324,4942161	less than 0,0001	37,13819183	37,59002525	37,13819183	37,59002525
X Variable 1	531,3715756	3,21663748	165,1947348	less than 0,0001	525,0605084	537,6826428	525,0605084	537,6826428