RELATIVE INFLUENCE OF HIGH CAPACITY VEHICLE DESIGN PARAMETERS

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Declaration

I declare that this dissertation is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other university.

Signed this 20th day of October 2019

Jarryd Andre Deiss

Executive Summary

A Performance-based Standards (PBS) framework legislates the dynamic performance and road-width usage of heavy vehicles, allowing the length and mass of a vehicle to exceed prescriptive legislation. The PBS framework defines the safe performance envelope of vehicles but does not optimise their safety and productivity. The design process to achieve the optimal productivity of PBS vehicles is highly iterative. An initial design is evaluated using multi-body dynamics simulation. If the required PBS performance is not achieved, design iterations are made until the required PBS performance is achieved. The process is costly, time-consuming and computationally expensive. The objective of this research is to quantify the relative effect of each Vehicle Design Parameter (VDP) of a multi-body vehicle dynamics model on the vehicle safety as measured within the PBS framework to assist in the PBS assessment process. To achieve this, three representative baseline PBS vehicles were developed (a quad semi-trailer, tridem interlink and rigid drawbar combination) from PBS assessments conducted in South Africa. A set of ranges within which each VDP could be varied was developed by considering Original Equipment Manufacturer (OEM) data, legal restrictions, physical constraints and South African PBS assessments. Each VDP for each baseline combination was varied in isolation to evaluate its influence on the vehicles performance within the PBS framework. A comparative matrix was developed for each baseline vehicle comparing the relative influence of each VDP on each of the PBS performance measures. The matrices yield insight into which VDPs have the most influence on each performance measure for each of the baseline vehicles. Furthermore VDPs that have a negligible influence on the performance of all baseline vehicles can be conservatively estimated in the absence of OEM data while still predicting representative vehicle performance. These insights will guide designers to focus on VDPs with a high influence on vehicle performance, allow PBS assessors to determine which design parameters can be modelled with generic approximate data in the absence of OEM data, and speed up the process of assessing vehicles within the PBS framework.

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I am truly grateful to my mom, dad, and brother who were there for me regardless of the hour providing love, support and guidance.

I am eternally thankful to Jesus Christ my Lord and saviour whose love, grace and mercy is with me always.

Contents

List of Figures

List of Tables

List of Symbols

The units of quantities defined by a symbol are indicated in parenthesis following the description of the symbol. Quantities with no indicated units may be assumed to be dimensionless.

CG_x	Longitudinal centre of gravity (mm)
CG_y	Lateral centre of gravity (mm)
CG_z	Vertical centre of gravity (mm)
CV	Coefficient of variation (%)
CV_n	Normalised coefficient of variation (%)
C_c	Cornering stiffness coefficient ($^{\circ -1}$)
C_α	Cornering stiffness (N/°)
I	Moment of inertia (kg·m^2)
I_{xx}	Roll moment of inertia (kg·m^2)
I_{yy}	Pitch moment of inertia (kg·m^2)
I_{zz}	Yaw moment of inertia (kg·m^2)
L_x	L for F_x - longitudinal tyre lag (mm)
$L_{y,z}$	L for F_y & M_z - lateral tyre lag (mm)
r	Radius of gyration (m)
r_x	Roll radius of gyration (m)
r_y	Pitch radius of gyration (m)
r_z	Yaw radius of gyration (m)
F_z	Vertical tyre load (N)
R_{sa}	Ratio of vehicle unit sprung mass to axle spacing (kg/m)
R_{sw}	Ratio of vehicle unit sprung mass to wheelbase (kg/m)
Δx	Tyre deflection (mm)
d_{axle}	Axle spacing (mm)
d_{wb}	Wheelbase (mm)
k_{tyre}	Tyre spring rate (N/mm)
m_{sprung}	Sprung mass (kg)

List of Abbreviations

ACC	Acceleration Capability
ADR	Automated Design Routine
CAD	Computer-aided Design
CG	centre of gravity
CSIR	Council for Scientific and Industrial Research
DoM	Difference of Maximum
FS	Frontal Swing
GA	General Arrangement
GCM	Gross Combination Mass
GRAa	Gradeability A
GRAb	Gradeability B
HCV	High-capacity Vehicle
HSTO	High-speed Transient Offtracking
LPG	Liquefied Petroleum Gas
LSMM	Low-speed Mathematical Model
LSSP	Low-speed Swept Path
MoD	Maximum of Difference
NCHRP	National Cooperative Highway Research Program
NDA	Non-disclosure Agreement
NDoT	National Department of Transport
NHVR	National Heavy Vehicle Regulator
NRTA	National Road Traffic Act
NTC	National Transport Commission
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PBS	Performance-based Standards
PS	Powertrain Standards
RA	Rearward Amplification
RH	Ride Handling
SRT	Static Rollover Threshold

SRT_{rrcu}	Static Rollover Threshold Rearward Roll-coupled Unit
SS	Stability Standards
STA	Startability
STFD	Steer-tyre Friction Demand
TASP	Tracking Ability on a Straight Path
TDP	Trailer Dynamic Performance
TS	Tail Swing
UMTRI	The University of Michigan Transportation Research Institute
VDP	Vehicle Design Parameter
VM	Vehicle Manoeuvrability
Wits	The University of the Witwatersrand, Johannesburg
YDC	Yaw Damping Coefficient

1 Introduction

The Performance-based Standards (PBS) framework is an alternative methodology of regulating the operation of heavy vehicles on a road network. Traditionally, heavy vehicles are regulated through prescriptive legislation (localised in each country due to differences in road infrastructure and environmental factors) which governs a vehicles maximum mass and dimensions. This type of legislation does not consider critical vehicle design parameters such as centre-of-gravity height thus cannot guarantee that a vehicle conforming to the legislation is safe for road operation.

PBS vehicles are required to be evaluated against a set of 16 performance measures which consider account real-world performance of the vehicle. The vehicle can be tested by real world testing or simulation in an approved multi-body vehicle dynamics software package that has been validated with real world testing. This ensures that they are fit for safe operation on the road network [1].

Benefits of the PBS approach realised by Australia, New Zealand and Canada motivated South Africa to gain practical experience with the approach and evaluate the benefits within the South African context. The Australian PBS framework was identified as the most suitable for South Africa and after a successful trial of two demonstration vehicles, the Australian PBS framework was adopted [2].

As of June 2017, South Africa had 245 PBS vehicles in operation which had collectively travelled over 100 million km within 8 of the 9 provinces. All operators participating in the PBS pilot project are required to record monitoring data for both their legal and PBS fleets. This data has proven that safety and productivity improvements have been realised by enforcing PBS compliance in South Africa [3].

The process of assessing and optimising a heavy vehicle within the PBS framework is costly and time consuming. Initially, data for each vehicle in the combination being assessed needs to be sourced from all the relevant third-party OEMs. Should the required data be considered as proprietary by the Original Equipment Manufacturer (OEM), permission from overseas head offices needs to be obtained before the data may be released and a Non-disclosure Agreement (NDA) may need to be signed.

Once all of the data has been acquired, the combination is then modelled in a multi-body vehicle dynamics program to assess its performance within the PBS framework. Should a heavy vehicle not achieve the required PBS performance level iterative modifications are made to improve the design until the required performance is achieved.

Studies have been conducted in the past to evaluate how a selection of Vehicle Design Parameter (VDP) affect vehicle performance, however they omit many of the VDPs required to fully define a vehicle model. There is a need for a better understanding of how each VDP influences vehicle performance within the PBS framework. This will help assessors and designers focus on the design parameters that have a high influence on vehicle performance and spend less time tweaking parameters with a low influence.

In addition, understanding which VDPs have an insignificant effect on vehicle performance will allow for conservative estimates to be made for these parameters without significantly degrading the accuracy of the assessment. This will help speed up PBS assessments where OEM data is not readily supplied due to the red tape involved in distributing proprietary information which can drastically affect the time required to complete a PBS assessment.

2 Literature Review

2.1 Performance-based Standards (PBS)

The PBS approach to HCV design is an alternative to prescriptive legislation which regulates maximum mass and dimensions but does not directly regulate vehicle safety performance. PBS vehicles are allowed mass and overall length relaxations on condition that they comply to the required PBS performance level and are proven to be safe. Thus, the PBS approach results in safer and more productive HCVs.

The following section provides an overview of the PBS framework and highlights the positive impact it has had on the South African economy, society and infrastructure. The reader is referred to the Centre for Sustainable Road Freight in South Africa [4] for a complete set of PBS resources including the detailed PBS framework, PBS application process flowchart, detail of PBS manoeuvres with simulation videos as well as the documents required in the PBS application process.

2.1.1 PBS Framework

The South African PBS framework is based on the Australian PBS scheme [5]. It can be broken down into a set of 16 performance measures, 4 infrastructure standards (beyond the scope of this project) and a range of manoeuvres the vehicle is required to perform.

The manoeuvres and the performance measures recorded in each manoeuvre are summarised in Table 2.1.

The vehicle performance is categorised according to the performance level of the performance measure in which the combination achieved the worst performance. The performance requirements decreases in stringency from Level 1 to Level 4.

1. Level 1: General Access
2. Level 2: Significant Freight Routes
3. Level 3: Major Freight Routes
4. Level 4: Remote Areas

The performance measures relevant to this research can be grouped as Powertrain Standards (PS), Stability Standards (SS), Vehicle Manoeuvrability (VM), Ride Handling (RH) and Trailer

Table 2.1: PBS manoeuvres and related performance measures

PBS Performance Test	Performance Measures
Low speed 90° turn	LSSP, FS, MoD, DoM, TS, STFD
High speed travel along an unevenly surfaced straight road	TASP
Pulse steer test	YDC
Tilt-table test	SRT
Evasive lane-change procedure (ISO 14791)	RA, HSTO
Acceleration or starting from rest on an upgrade	STA
Maintaining speed on an upgrade	GRAa
Maintaining highest speed on a 1% upgrade	GRAb
Acceleration from rest to travel 100 m on a flat road	ACC

Dynamic Performance (TDP) [1]. The performance requirements for each of the measures as adopted by the SMART truck committee in South Africa (as of 1 Jan 2018) for each PBS performance level are summarised in Table 2.2.

Table 2.2: PBS performance measures and level requirements

				PBS Level			
Category	**Performance measure**	**Unit**	**Req.**	**1**	**2**	**3**	**4**
PS	Startability (STA)	%	$\geq$	15	12	10	5
	Gradeability A (GRAa)	%	$\geq$	20	15	12	8
	Gradeability B (GRAb)	km/h	$\geq$	80	70	70	60
	Acceleration Capability (ACC)	s	$\leq$	20	23	26	29
SS	Static Rollover Threshold (SRT)	g	$\geq$	0.4[1]; 0.35[3]			
	Yaw Damping Coefficient (YDC)	-	$\geq$	0.15			
VM	Frontal Swing (FS)	m	$\leq$	1.5[1]; 0.7[3]			
	Difference of Maximum (DoM)	m	$\leq$	0.2			
	Maximum of Difference (MoD)	m	$\leq$	0.4			
	Tail Swing (TS)	m	$\leq$	0	0.4	0.4	0.5
	Low-speed Swept Path (LSSP)	m	$\leq$	7	8.7	11	14
RH	Steer-tyre Friction Demand (STFD)	%	$\leq$	80			
TDP	Tracking Ability on a Straight Path (TASP)	m	$\leq$	3	3	3.1	3.3
	Rearward Amplification (RA)	-	$\leq$	5.7×SRT			
	High-speed Transient Offtracking (HSTO)	m	$\leq$	1	0.8	1	1.2

[1] Road tankers hauling dangerous goods in bulk, buses and coaches
[2] Buses
[3] Others

2.1.2 PBS Pilot Project in South Africa and Its Benefits

The PBS framework has been used in South Africa as part of a pilot project aiming to improve the safety and productivity of heavy vehicles in the country. Over the course of the project, PBS vehicles have been monitored and data from their operation has been recorded. The first PBS demonstration vehicles were commissioned successfully in 2007 and as of June 2017, over 100 million km were travelled by PBS vehicles within the South African road network. Details of the PBS vehicles in operation as part of the pilot project are summarised in Figure 2.1.

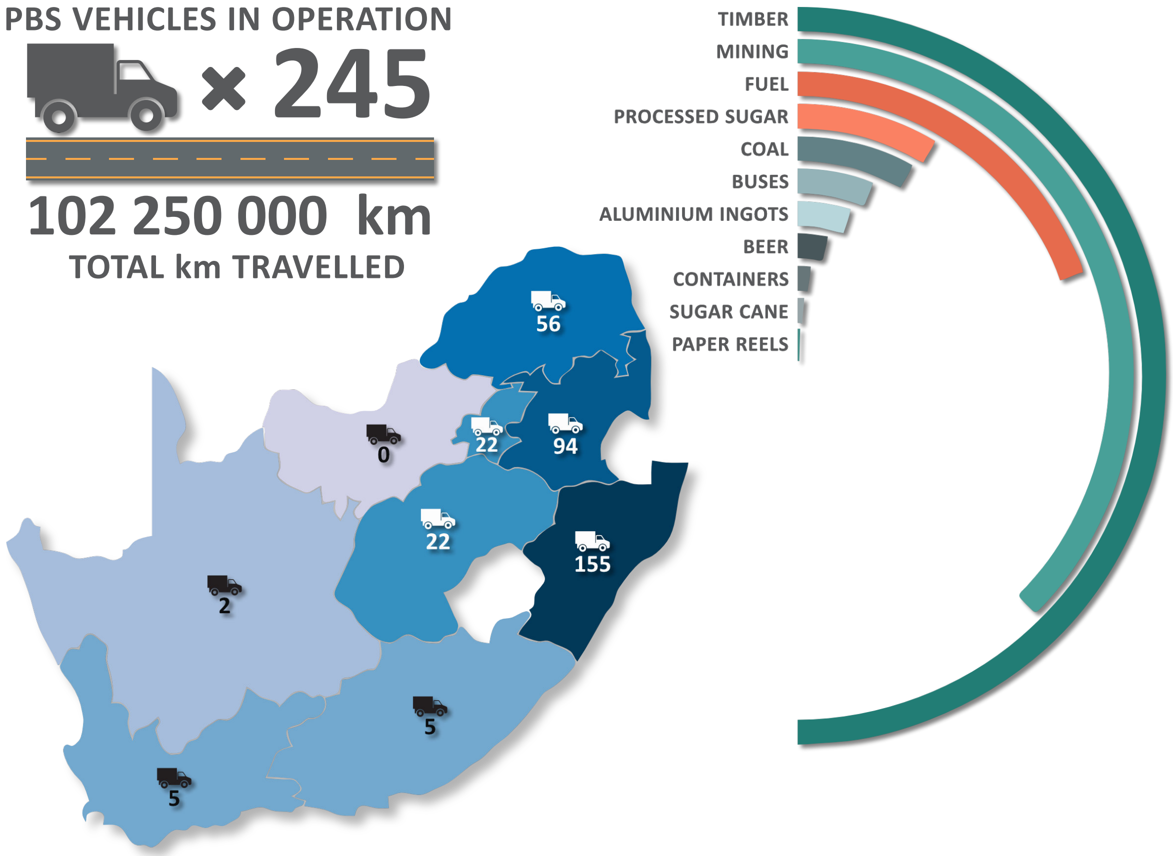


Figure 2.1: Summary of operating PBS vehicles and commodities in South Africa as of June 2017 [3]

The monitoring data that has been collected and analysed for the duration of the PBS pilot project shows PBS vehicles require fewer trips to transport the same amount of payload which leads to reductions in fuel usage and CO_2 emissions. PBS vehicles are recorded to have a 39% reduction in accidents relative to their baseline equivalents. This highlights the improved safety performance of the PBS vehicles. The monitoring data shows that the PBS vehicles operating as of June 2017 were saving 74067 trips per year which resulted in R 26.64 million of fuel saved and a reduction of 6246 tons of CO_2. Each PBS vehicle saves R 24448 in

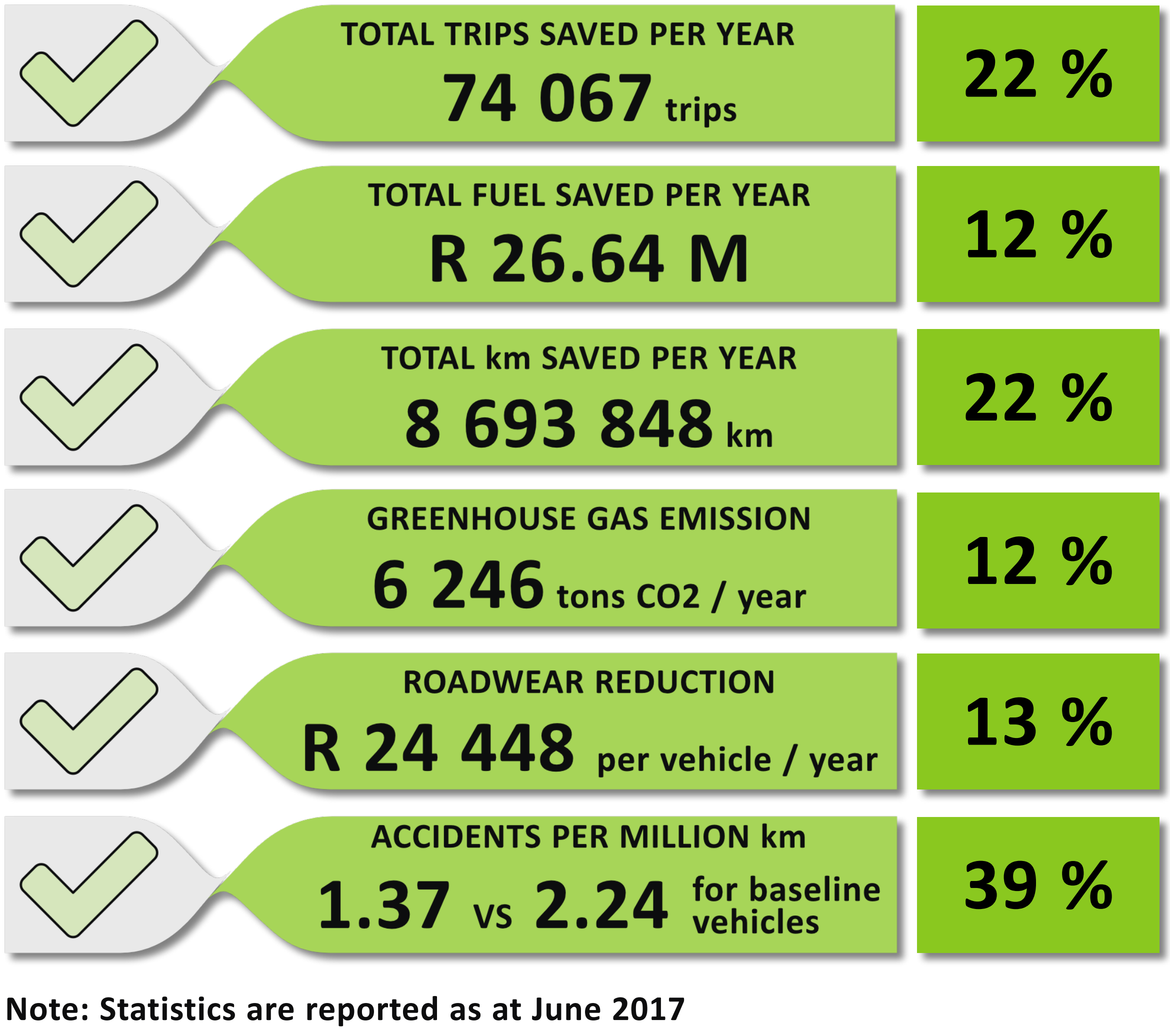


Figure 2.2: Summary of PBS monitoring data as of June 2017 [3]

road wear per vehicle per year and PBS vehicles have a 39% reduction in accidents relative to their baseline equivalents (see Figure 2.2).

The benefits realised by the small sample of PBS vehicles is clear. Increasing participation in the PBS project will improve the productivity of the South African logistics, decrease the environmental impact of transport operations and reduce damage to infrastructure. Thus, it is beneficial to make the PBS assessment process as attractive and efficient as possible to motivate more parties to participate.

2.2 Towards Quicker PBS Assessments

The process of performing a PBS assessment requires accurate vehicle details to be sourced from OEMs, the expertise to interpret the information and tools to perform the assessment.

The multi-body vehicle dynamics packages required to simulate vehicle performance are expensive, require know-how to correctly build a representative vehicle model and require a significant amount of computational power to operate.

This leads to a lengthy and computationally expensive process that requires input from multiple experts. Studies that have been done to simplify and speed up the assessment process are explored in this section.

2.2.1 Pro-forma Design

De Pont [6] initially introduced the concept of pro-forma designs to alleviate time and cost constraints of a PBS assessment. The pro-forma design methodology sets geometrical constraints for a vehicle combination that when used in the design of a vehicle ensures satisfactory low-speed directional PBS performance (FS, TS, LSSP) eliminating the need for futher low-speed performance testing.

De pont generated geometrical constraints for three typical heavy vehicle configurations in New Zealand (truck and full trailer, truck and simple trailer and B-double) by performing a parametric sensitivity analysis on the effect of key HCV geometrical parameters on their low-speed PBS performance using the yaw/roll multi-body vehicle dynamics package developed by The University of Michigan Transportation Research Institute (UMTRI) . This resulted in diagrams indicating the range within which key dimensional parameters could be varied while achieving the required PBS safety performance.

Benade extended the pro-forma design concept to car-carriers in South Africa by Benade et al. [7]. To enable rapid evaluation of low-speed vehicle performance, he made use of a Low-speed Mathematical Model (LSMM) developed by de Saxe [8] which was shown to correlate well with vehicle performance evaluated with TruckSim® while obtaining solution speed improvements of between 261% and 546%.

Benade et al. developed the pro-forma constraints by performing a sensitivity analysis of each of the critical parameters affecting low-speed vehicle performance. Each parameter was varied up and down in increments of 10% (or increments of 1 for certain parameters such as number of steer axles) to develop upper and lower constraints. MATLAB® code developed by Benade et al. was used to generate 10 000 vehicle configurations satisfying the generated constraints. The low-speed PBS performance of the generated combinations was then evaluated using the LSMM and it was found that all of them achieved Level 1 PBS performance requirements.

Benade et al. found that making effective use of the pro-forma design method could lead to reducing the cost of PBS assessments by an estimated 1.2 million rand [7] per year. However in its current form it is limited as it only ensures compliance with Level 1 low-speed PBS performance measures and further work would need to be performed to ensure compliance with the high-speed PBS performance measures.

A similar pro-forma approach has been developed by the National Heavy Vehicle Regulator (NHVR) who made blueprint designs for a variety of truck configurations publicly available on their website [9]. Blueprint HCV configurations have been pre-approved by the NHVR and designs based on these configurations will shorten the lead time in the PBS approval process.

2.2.2 Predicting PBS Performance

Dessein [10] explored consideration of the PBS framework prior to the detail design phase through optimisation of HCV design within the PBS framework. Simplified models for eight performance measures (SRT, RA, LSSP, FS, TS, STA, GRAa) were used to estimate the HCV performance. Limiting the number of performance measures evaluated allowed the calculations to be automated by using a sequential quadratic programming algorithm within MATLAB.

The routine varied the five vehicle parameters listed for four types of vehicle (A-Double, B-Double, truck and pig trailer, truck and dog trailer):

- Number of axles in each axle group
- Wheelbases of all vehicle units
- Hitch offset
- Payload (size/location/density)

The optimisation routine considered a Level 2 PBS requirement, and the vehicle configuration yielding the highest payload (and hence highest productivity) was chosen as optimal. The optimised vehicles were compared to those designed using prescriptive methods.

It was discovered that the vehicles designed using a prescriptive approach were in fact more productive than the PBS equivalent for payloads with a density lower than 400 kg/m^3. This suggests that an optimisation approach would be very useful in evaluating whether a vehicle can be designed to be more productive using the PBS approach; potentially preventing a costly, unsuccessful, iterative design process.

Dessein showed that the prescriptive vehicles failed to meet the PBS Level 2 SRT requirement of 0.35 g for most payload densities. Dessein highlighted one of the major disadvantages of the prescriptive approach in that it does not directly consider the vehicles safety performance but imposes only geometrical and mass constraints. Importantly, there is an opportunity using the PBS approach to increase safety and reduce road fatalities even if at the lower payload densities there is little scope to increase the vehicle productivity.

The results of the Automated Design Routine (ADR) developed by Dessein indicated that there is a potential for determining an estimated productivity gain of a PBS assessment before detailed design begins. It can also yield optimal HCV configurations that can be used as a starting point in the detailed design of the HCV, speeding the process up and increasing the probability of PBS approval.

2.2.3 Machine Learning Models

Berman et al. [11] developed a lightweight tool requiring only vehicle geometry to predict the low-speed PBS performance measures of a B-double combination. In total 22 input parameters were randomly selected to conduct 10 000 simulations on a B-double. Supervised machine learning techniques were used to develop a model to predict LSSP, FS, MoD, DoM and TS performance measures from the simulated data. The model provides an accessible way for OEMs to quickly and accurately evaluate the low-speed PBS performance of their vehicle before a formal PBS assessment without the need for extensive mechanical knowledge of multi-body vehicle dynamics systems using only geometric parameters of the vehicle combination.

Following his initial research, Berman et al. [12] developed a lightweight prediction tool using neural networks to predict the high-speed performance of a 9-axle B-double combination. Upper and lower bounds were selected for 30 unique input parameters defining the vehicle geometry, payload and suspension. 36 470 vehicle configurations were created using random sampling within the range of each input parameter assuming a uniform distribution. The model can rapidly predict the HSTO, SRT, TASP, RA and YDC PBS performance of a 9-axle B-double combination as well as overall PBS performance with a high level of accuracy. The model is intended for determining preliminary PBS performance of a vehicle combination as a guide for OEMs and transport regulators as a precursor to a formal PBS assessment.

2.3 Design Parameter Effect on Vehicle Performance

The following Section discusses previous studies that have focused on determining the influence of HCV design parameters on heavy vehicle safety.

2.3.1 Influence of Heavy Vehicle Design Parameters on Vehicle Performance

Prem et al. [13] conducted a study on the Australian heavy vehicle fleet to determine the influence of various design parameters on vehicle safety as assessed using the PBS framework. A baseline configuration was chosen for a variety of vehicle configurations. The design parameters were then varied by +/-20% and the effects on each performance measure were tabulated, indicating the influence of each performance measure using a scale with four discrete quantifiers (++, + for improved performance and - -, - for degraded performance). The results of this study are summarised in Table 2.3.

Table 2.3: Influence of design features and broad summary of parametric effects [13]

Performance measure	Increase Engine Power/Torque	Increase Driveline Gear Ratio	Increase CG Height	Increase Axle Loads	Longer Prime Mover Wheelbase	Longer Trailer Wheelbase	Longer Dolly Wheelbase	Increase Number of Articulation Points	Increase Axle Group Spread	Increase Coupling Rear Overhang	Increase Suspension Roll Stiffness	Increase Tyre Cornering Stiffness	Increase Front Overhang	Increase Rear Overhang	Decrease Speed
Startability		++		- -											
Gradeability A	++	++		- -											
Gradeability B	++	+/-		-											
Acceleration Capability	+	-		-											+
Tracking Ability on a Straight Path			- -	- -	-	-	-	-	+	-	+	++			++
Low-speed Offtracking					- -	- -	-	++		+			-		
Frontal Swing					- -								- -		
Tail Swing						+								- -	
Steer Tyre Friction Demand					++				- -						
Static Rollover Threshold			- -	-							+				
Rearward Amplification			-	-	+	++	+	- -	+	-	+	++			++
High-speed Transient Offtracking			- -	- -	+	++			+	-		++			++
Yaw Damping Coefficient			- -			++			+			++			++
GM per SAR				-											
Horizontal Tyre Forces	- -			- -					- -						
Max. Effect Relative to Ref. Vehicles				- -	++	++	+		+						

[1] ++ Significant positive effect on performance
[2] + Moderate positive effect
[3] *blank* Little or no influence
[4] - Moderate negative effect
[5] - - Significant negative effect

The results of the study conducted by Prem et al. provide useful insight into how the design parameters effect each performance measure within a range of 20% of the baseline design parameters. The design parameters of a heavy vehicle are often constrained due to manufacturing limitations and regulations that need to be adhered to. A design parameter could heavily influence the performance of a heavy vehicle; however, it may not be possible to alter that parameter due to design and legal constraints. On the other hand, a parameter may have little effect on the vehicle safety performance but be able to be varied within a large range. The study considered a wide range of vehicle configurations and lumped the results of each vehicle into one summarised result. This loses any insights into how the effect of changing certain design parameters may differ between the vehicle configurations.

2.3.2 The UMTRI Component Factbook

Fancher et al. at UMTRI compiled a comprehensive document in 1986 detailing the mechanical properties of components used in heavy vehicles, their influences on manoeuvring performance and a collection of parametric data from the United States heavy vehicle fleet [14]. The mechanical properties discussed were categorised as follows:

1. Geometric layout
2. Mass distribution
3. Tyres
4. Suspensions
5. Steering systems
6. Brakes
7. Frames
8. Hitches

In each category, the effect of the mechanical properties on vehicle performance was discussed. A summary of the effect of each mechanical property considered is included in Tables 2.4 to 2.10. Steering systems, frames and braking are beyond the scope of this dissertation, however their effects on vehicle dynamic performance are included for completeness and the interest of the reader.

Table 2.4: Effect of the mechanical properties of tyres on vehicle dynamic performance [14]

Pertinent Mechanical Property	**Low-speed tracking**	**Hi-speed tracking**	**Roll stability**	**Handling stability**	**Response time**	**Rearward amplification**	**Braking efficiency**	**Transient braking & turning**	**Downhill braking**	**Response to disturbances**
Cornering coefficient C_{alpha}/F_z	-	Hi	-	Hi	Hi	Hi	-	Hi	-	Hi
Curvature in C_{alpha} (C_{alpha} vs Vertical Load)	Low	-	-	Hi	Low	Low	-	-	-	-
Aligning stiffness (pneumatic trail)	-	-	-	Low	-	-	-	-	-	-
Vertical stiffness	-	-	Med	-	-	-	-	-	-	-
Peak friction, m_p	-	-	-	-	-	-	Hi	Hi	-	-
Sliding friction, m_s	-	-	-	-	-	-	-	Med	-	-
Long./Lat Interaction	-	-	-	-	-	-	-	Med	-	-

Table 2.5: Effect of the mechanical properties of suspension systems on vehicle dynamic performance [14]

Pertinent Mechanical Property	Low-speed tracking	Hi-speed tracking	Roll stability	Yaw stability	Response time	Rearward amplification	Braking efficiency	Transient braking	Downhill braking	Response to disturbances
Vertical stiffness	-	-	-	-	-	-	-	Med	-	-
Roll stiffness	-	Med	Hi	Hi	Hi	Hi	-	-	-	Med
Roll centre height	-	Med	Hi	Hi	Hi	Hi	-	-	-	Med
Damping	-	-	-	-	Med	Med	-	Low	-	Low
Roll steer	-	Low	-	Low	Low	Low	-	-	-	Low
Compliance steer	-	Low	-	Low	Low	Low	-	-	-	Low
Interaxle load transfer	-	-	-	-	-	-	Hi	-	-	-

Table 2.6: Effect of the mechanical properties of steering systems on vehicle dynamic performance [14]

Pertinent Mechanical Property	Low-speed tracking	Hi-speed tracking	Roll stability	Yaw stability	Response time	Rearward amplification	Braking efficiency	Transient braking	Downhill braking	Response to disturbances
Roll steer	-	-	-	Low	-	-	-	-	-	-
Lateral force compliance steer	-	-	-	Hi	-	-	-	-	-	-
Brake steer	-	-	-	-	-	-	-	Med	-	Hi
Gear Ratio	-	-	-	-	-	-	-	-	-	-

Table 2.7: Effect of the mechanical properties of brakes on vehicle dynamic performance [14]

Pertinent Mechanical Property	Constant deceleration braking	Braking while turning	Mountain descents
Effectiveness	Hi	Hi	Hi[1]
Torque rise and fall characteristics	-	Hi	-
Thermal capacity and cooling	-	-	Hi

[1] Effect could be high

Table 2.8: Effect of the mechanical properties of frames on vehicle dynamic performance [14]

Pertinent Mechanical Property	Low-speed tracking	Hi-speed tracking	Roll stability	Yaw stability	Response time	Rearward amplification	Braking efficiency	Transient braking	Downhill braking	Response to disturbances
Torsional stiffness	Low	Low	-	Low	-	-	-	Low	-	-

Table 2.9: Effect of the mechanical properties of the geometric layout on vehicle dynamic performance [14]

Pertinent Mechanical Property	Low-speed tracking	Hi-speed tracking	Roll stability	Yaw stability	Response time	Rearward amplification	Braking efficiency	Transient braking	Downhill braking
Wheelbase - truck/tractor	Med	Low	-	Med	Med	-	Low	Low	-
Wheelbase - trailer	Hi	Hi	-	-	Med	Hi	Low	-	-
Wheelbase - dolly	Med	Med	-	-	-	Med	Low	-	-
Track width	-	-	Hi	Med	-	-	-	Med	-
Fifth wheel offset - tractors	Low	-	Low	Low	-	-	Med	Med	-
Pintle overhang - trucks & trailers	Low	Low	-	-	-	Hi	-	-	-
Fifth wheel height - tractor	-	-	Low	-	-	-	Low	-	-

Table 2.10: Effect of the mechanical properties of the mass distribution on vehicle dynamic performance [14]

Pertinent Mass Distribution	Low-speed tracking	Hi-speed tracking	Roll stability	Yaw stability	Response time	Rearward amplification	Braking efficiency	Transient braking	Downhill braking	Response to disturbances
Weight	-	Hi	Hi	Hi	Hi	Hi	Hi	Hi	Hi	Hi
CG height	-	-	Hi	Hi	Low	Hi	Med	Med	-	Low
Fore-aft CG location	-	Hi	Med	Hi	Hi	Hi	Hi	Hi	-	Hi
Yaw moment of inertia	-	-	-	-	Hi	Med	-	Low	-	Low
Pitch moment of inertia	-	-	-	-	-	-	-	Med	-	-
Sprung roll moment of inertia	-	-	Med	-	Low	Low	-	Low	-	Low

2.4 Collections of Heavy Vehicle Design Parameters

Heavy vehicle design parameters are well documented for overseas vehicles (US and Canada), however there have been limited studies conducted in South Africa with the intention of cataloguing the mechanical properties of heavy vehicle components.

Fancher et al. [14] summarised heavy vehicle design parameters for the US heavy vehicle fleet in the component Factbook mentioned in Section 2.3.2. This data was collected in 1986 and is outdated, however is still a useful source to estimate approximate vehicle design parameters.

A more recent collection of heavy vehicle design parameters collected in 2003 is included in a review of truck characteristics performed by Harwood et al. [15] as part of the National Cooperative Highway Research Program (NCHRP) with the intention of using this information to better guide the design of roadways.

Additional resources for heavy vehicle design parameters and their influence on heavy vehicle performance include studies conducted by Ervin et al. [16] and Winkler et al. [17], [18].

2.5 Significance of This Research

The review of the literature presented in Sections 2.1 to 2.4 highlights the significance of this research:

1. Published studies have looked at VDP influence on vehicle performance by varying a limited number of parameters within set percentage range of values without considering allowable ranges within which each design parameter could be varied. This presents a gap in current research to evaluate the effect of a larger number of VDP on overall vehicle performance based on allowable ranges within which VDP could be varied based on physical, legal and OEM imposed constraints.
2. Research exists to show how VDPs affect vehicle performance. To some extent this can be used as a guide to determine if a design parameter should be included in a vehicle performance model. There is however a lack of research investigating the relative effect of each VDPs making up a multi-body vehicle dynamics model on vehicle performance within the PBS framework.
3. Performing PBS assessments is a costly and time consuming exercise. OEM data needs to be collected to define the mechanical properties of each vehicle unit within the combination being assessed to ensure that a model representative of the actual vehicle is built, resulting in accurate evaluation of vehicle performance within the PBS framework. Red-tape can often slow the process and should certain parameters not be available, conservative estimates need to be made to ensure on-road performance will at the very least be as good as that predicted by the PBS assessment. Evaluating the relative influence of each VDP required for a multi-body vehicle dynamics model will yield insight as to the VDPs that have little influence on vehicle performance and can be safely estimated while still simulating representative vehicle performance.

3 Objectives

The objectives of this MSc dissertation are as follows:

1. Determine reasonable ranges of variation for pertinent vehicle design parametersVDPs of a multi-body vehicle dynamics model.
2. Quantify the relative effect of pertinent VDPs on the vehicle safety as measured using the PBS framework currently being used in South Africa for three commonly used HCV designs.
3. Develop easy-to-use look-up tables displaying the relative effect of each of the evaluated VDPs on each of the PBS performance measures for vehicle designers and PBS assessors to use in vehicle design, optimisation and PBS vehicle data acquisition.
4. Highlight interesting observations from the results and discuss their implications for the PBS initiative in South Africa and globally.

Achieving these objectives is important as it will provide guidance as to which VDPs can be safely estimated in the absence of definitive data when evaluating the PBS performance of a HCV and provide guidance as to the critical VDPs which need to be accurately estimated to predict representative vehicle safety of a HCV. Furthermore, it will provide insight into which VDPs should be focused on when attempting to improve a vehicles performance for a performance measure within the PBS framework.

4 Methodology

A high-level overview of the study performed on the relative effect of the VDPs of HCVs is as follows:

1. Develop a set of baseline combinations to represent a range of highly productive HCVs.
2. Define reasonable ranges for each pertinent VDP to be varied within.
3. Evaluate the relative effect of altering each VDP within its selected range on overall vehicle performance within the PBS framework.

4.1 Baseline Combinations

Three baseline HCV configurations were developed based on South African workhorse vehicles and Australia's most common PBS vehicle. Previous PBS assessments conducted by The University of the Witwatersrand, Johannesburg (Wits) and the CSIR were used to develop the design of each of the baseline combinations.

The same high-level prime mover was used for each baseline, with adjustments to the wheelbase where necessary. A set of representative suspensions were developed and used for all combinations to avoid inserting any bias from discrepancies between the baseline suspension designs. Sections 5.1.1 to 5.1.3 detail the development of each baseline vehicle configuration.

4.2 VDP ranges

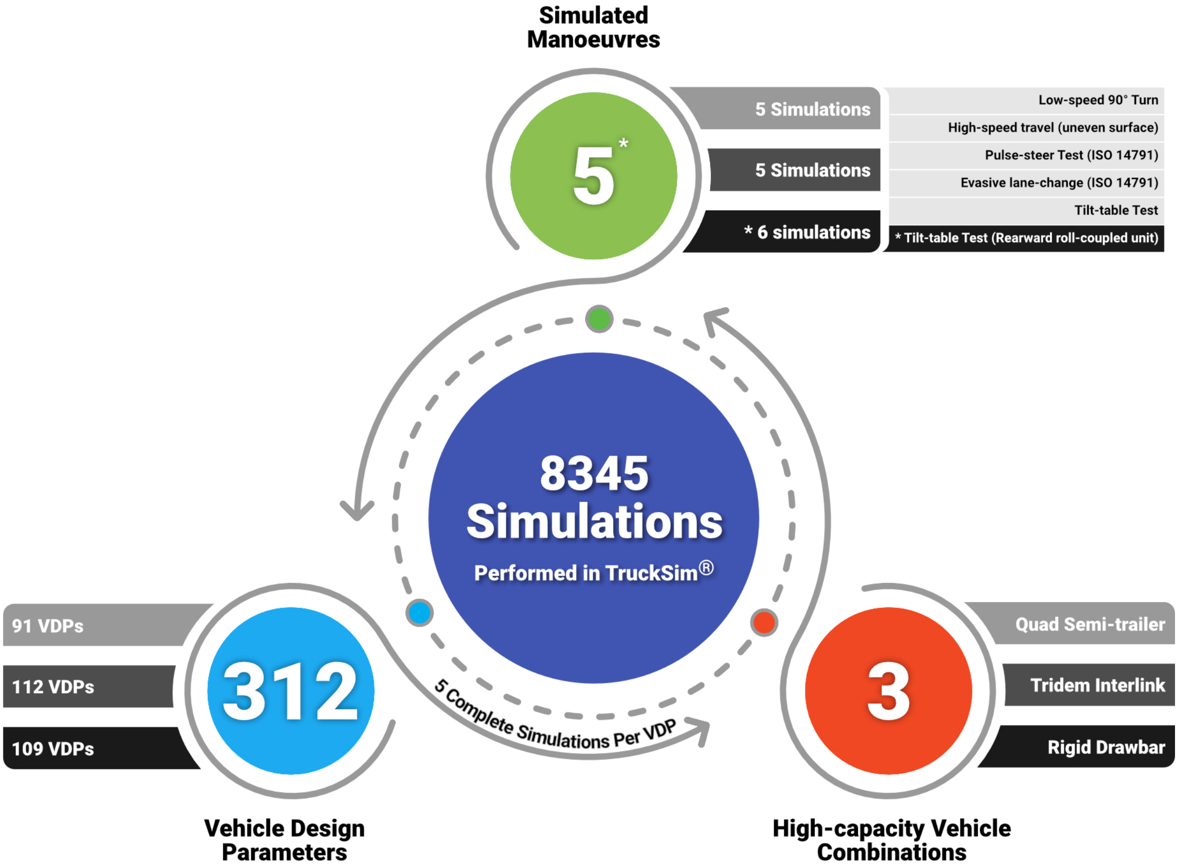
To define reasonable upper and lower limits for each pertinent VDP, OEM variations, legal restrictions, physical constraints, global studies, and data from PBS assessments previously conducted by Wits were consolidated and consulted. Details on how the range for each pertinent VDP was chosen are contained in Section 6.

The geometrical limits of a HCV are largely governed by the prescriptive legislation of the country in which the combination will be operating. The South African legislation was chosen for developing the geometrical limits to provide value to the PBS pilot project in South African. This would not limit the results to being applicable only in South Africa, but if used internationally, the local legislation should be consulted to determine where results may differ.

Inertial, suspension and tyre properties are not widely available which is one of the factors that drive the need for this research. OEM variations, data from PBS assessments conducted by Wits and Global studies were consulted and the information was consolidated to develop ranges for each of the pertinent VDPs that would represent the global HCV fleet as local legislation does not dictate any restrictions on the origins of HCV components.

4.3 Evaluating VDP Relative Influence

To evaluate the relative influence of each VDP on each of the baseline combinations, the VDPs were varied in isolation while keeping all other VDPs constant at their baseline value. To evaluate the influence of each VDP, the VDP was varied by 5 evenly distributed points from its maximum to minimum value within its range as determined in Section 6. This resulted in a total of 8345 simulations being run in TruckSim® as illustrated in Figure 4.1.



* The rigid combination required an extra tilt-table test to evaluate the static rollover threshold performance of the rearward roll-coupled unit resulting in 6 simulated manoeuvres

Figure 4.1: Overview of the number of HCV simulations performed

TruckSim® was used as the multi-body vehicle dynamics simulation package to simulate the HCV performing a set of PBS manoeuvres. The simulation results were used to determine the safety of each HCV within the PBS framework using a post processor developed in MATLAB® at Wits. A MATLAB® script automated the adjustment of each individual or combination of parameters within a TruckSim® model according to the work flow illustrated in Figure 4.2 allowing for the simulation of a large set of vehicle configurations. The versions of each software packaged used are included in Section 4.4.

The simulation software and models were calibrated using results published by the National Transport Commission (NTC) as detailed in Section 4.5.

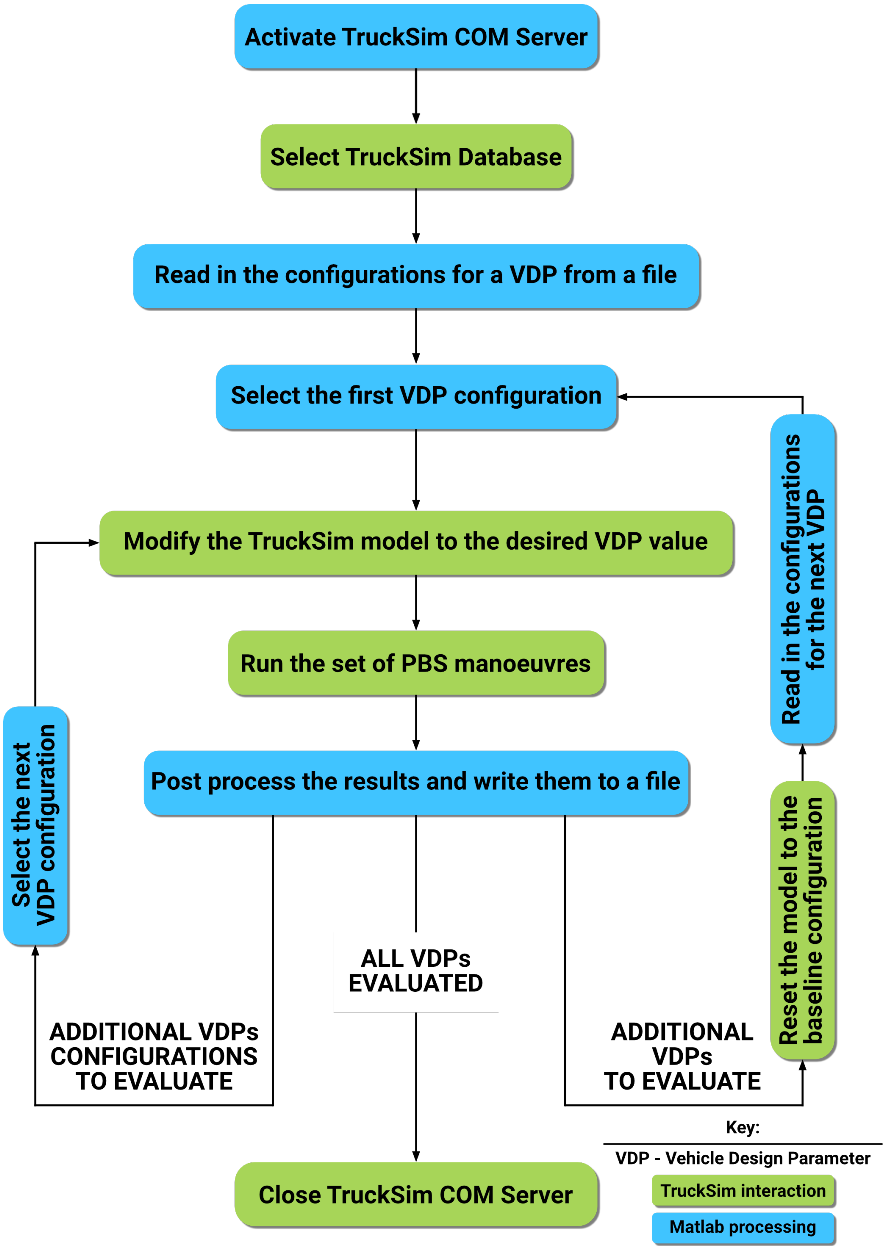


Figure 4.2: MATLAB® interaction with the TruckSim® 2018 API using a COM server

4.4 Software

The following software packages were used to perform the vehicle simulations:

1. **TruckSim® 2018 [19]:** a multi-body vehicle dynamics package used to simulate the various HCV vehicle configurations performing the PBS manoeuvres.
2. **MATLAB® 2018 [20]:** a high-level coding environment capable of performing numerical computation and visualisation. Matlab was used in two ways; to post process the simulation outputs of the TruckSim® simulations and determine vehicle performance within the PBS framework and to compare the relative effect of each VDP on vehicle performance.

TruckSim® is an industry leading multi-body vehicle dynamics simulation package and is utilised by well-established commercial vehicle OEMs, suppliers and top universities [21]. It has over twenty years of real-world validation and is the globally preferred software for evaluating a truck's performance characteristics.

4.5 Software Calibration

To perform real world testing to validate the software used to evaluate the PBS performance of HCVs, experts in the industry were consulted to determine the costs that would be involved.

In the cost analysis, KDG logistics was consulted to get a quotation of the cost to hire a 6 car car-carrier with a driver and Gerotek was contacted to get a quotation for the use of their test track and tilt-table facilities. An estimated minimum time required to perform the physical testing is included in Table 4.1 (taking into account safety precautions, fitting and testing of sensors that would be used to acquire the data required for validation) and the projected costs of physical testing of a single HCV is summarised in Table 4.2.

The author would like to thank KDG Logistics and Gerotek for their time and efforts involved in providing the quotations.

Table 4.1: Estimation of the minimum time required to perform physical PBS testing

Manoeuvre	Estimated Time Required to Test
Low-speed turn	4 hours
High-speed lane-change	4 hours
High-speed tracking on a straight path	4 hours
Pulse-steer test	4 hours
Tilt-table	8 hours

Additional funding of R 145 704.00 was not available for validating the software used with the physical testing of a HCV.

TruckSim® is an industry leading multi-body vehicle dynamics simulation package and is utilised by well-established commercial vehicle OEMs, suppliers and top universities [21]. It has over twenty years of real-world validation and is the globally preferred software for evaluating a truck's performance characteristics.

Thus, considering the objective of this study is to determine the relative influence of pertinent VDPs used as input parameters in multi-body vehicle dynamics simulation software, it was deemed suitable to omit real-world testing and validation as it has already been extensively validated by TruckSim®.

A calibration of the software as setup by the author was completed according to a framework developed for PBS assessors to test and ensure their simulation results and interpretation thereof are an accurate representation of an equivalent heavy vehicle in reality.

Table 4.2: Estimation of the minimum time required to perform physical PBS testing

Item	Cost	Duration	Total Cost
KDG Truck (incl. driver)	R 24 000 per day	3 days[1]	R72 000.00
Payload Cars	R 1 800 per day[1]	3 days	R5 400.00
Gerotek Straight track	R 3 019 per hour	16 hours	R48 304.00
Tilt-table test	R 20 000 per test	One test	R20 000.00
		Total	R145 704.00

[1] Assuming 8 hours per day
[2] Assuming 6 rental vehicles at R 300 each (excluding special insurances)
[3] Assuming the tilt-table test can be completed in a single day

The NTC framework was developed by requesting consultants to compare three computer-based modelling packages (ADAMS, AUTOSIM and UMTRIs Yaw/Roll) to evaluate (in isolation of each other) the PBS performance of a B-double and truck-trailer heavy vehicle combination [22] (known as an interlink and rigid drawbar combination in South Africa).

The NTC prescribed a set of inputs for a representative B-double and truck-trailer combination used by all consultants. The vehicles were simulated to perform identical pulse steer, step steer, standard SAE lane change and a low-speed 90° turn manoeuvres.

The B-double was found to have excellent agreement between all three of the modelling packages. The truck-trailer combination is an inherently less stable vehicle and produced larger but still acceptable amounts of variation in results between the modelling packages.

The Yaw/Roll simulation results were provided by the NTC for service providers to calibrate their computer-modelling software and techniques. This data was used to validate the models.

4.5.1 Software Calibration Results

The behaviour of the B-double and truck-trailer simulated in TruckSim® 2018 was found to have good correlation with the behaviour simulated in UMTRIs yaw/roll program. Similarly to the outcome of the NTC validation, the truck-trailer combination compared less favourably than the B-double combination due to it being a less stable configuration.

Differences in simulated behaviour are attributed to improvements to the prediction of heavy vehicle performance with the latest solvers, differences in the driver models and additional degrees of freedom in the TruckSim® modelling package.

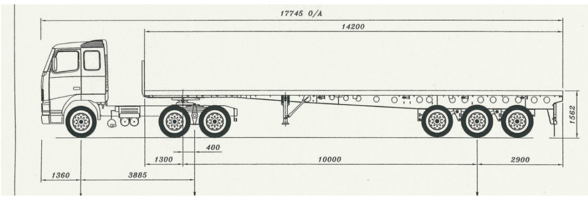
A set of graphs comparing the simulated vehicle behaviour in TruckSim® 2018 and UMTRIs yaw/roll program are included in Appendix C.

5 Development of the Baseline Vehicles

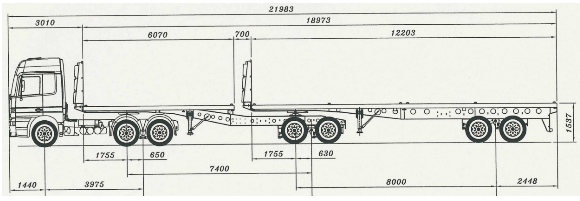
Three of the most productive HCV configurations were selected as baselines. A report from the compiled by Nordengen for the Organisation for Economic Co-operation and Development (OECD) highlighted that the following combinations were the four most common articulated truck configurations in South Africa [23]:

1. A 6x4 truck-tractor hauling a 3-axle semi-trailer
2. A 6x4 truck-tractor hauling two 2-axle semi-trailers connected with fifth-wheel couplings
3. A 6x4 truck-tractor hauling a 2-axle semi-trailer
4. A 6x4 truck-tractor hauling a tridem semi-trailer leader and tandem semi-trailer follower connected with fifth-wheel couplings

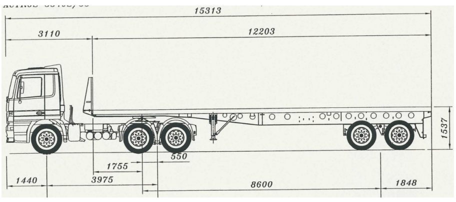
Illustrations of each of the workhorse combinations are included in Figure 5.1.



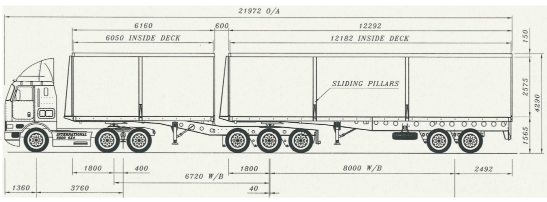
(a) Workhorse 1



(b) Workhorse 2



(c) Workhorse 3



(d) Workhorse 4

Figure 5.1: OECD workhorse combinations

These four workhorse vehicles have during the PBS pilot project in South Africa been replaced by two more productive PBS equivalents which were chosen as the first two baseline combinations:

1. A 6x4 truck-tractor hauling a quad-axle semi-trailer
2. A 6x4 truck-tractor hauling a set of tridem semi-trailers

As of 2016 a rigid drawbar combination (known as a truck and dog combination in Australia) was still the single biggest category of vehicles approved via PBS as can be seen in Figure 5.2 [24]. These combinations are not very prevalent in South Africa outside of the forestry industry, however it is envisioned that as the pilot project progresses in South Africa and PBS becomes more widely adopted, that this combination will become widely-used.

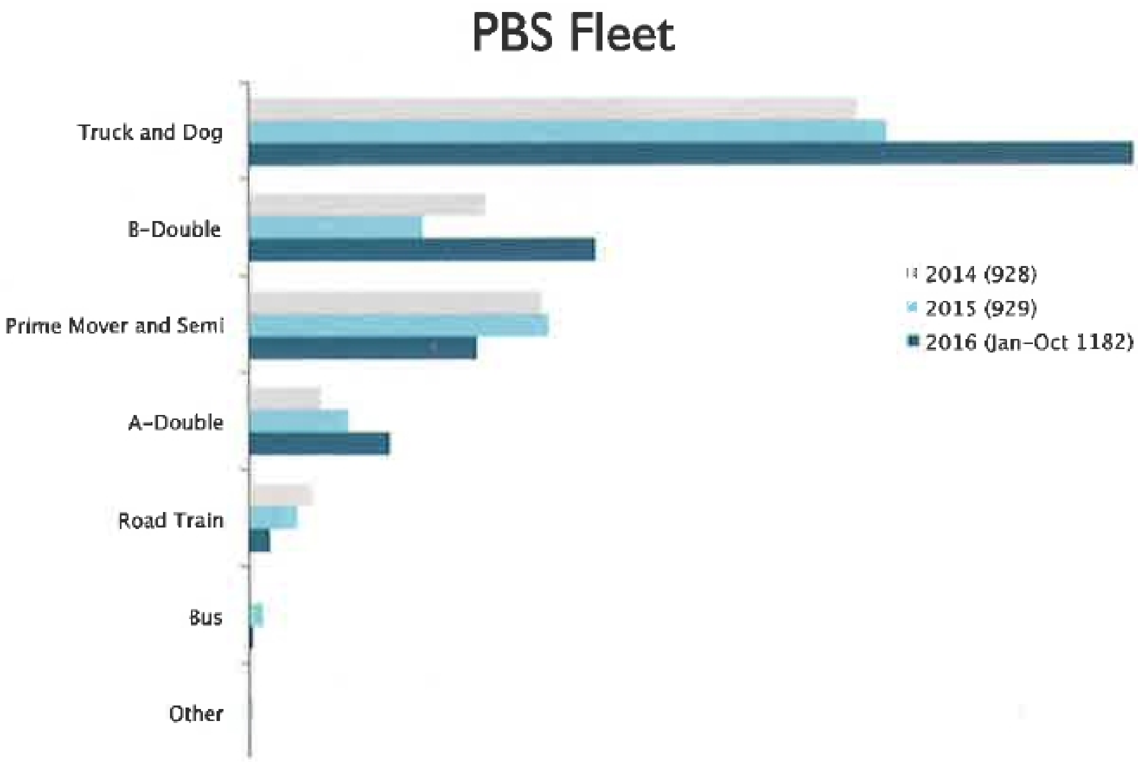


Figure 5.2: Distribution of the Australian PBS fleet as of Oct 2016 [24]

5.1 Design Parameters for the Baseline Vehicles

The design of the mechanical properties of the baseline vehicles is beyond the scope of this dissertation. Thus, combinations matching the designs chosen for baseline vehicles that were assessed within the PBS framework in South Africa were used as a guide to develop the baseline combinations.

The baseline combinations use the same baseline prime mover (for which data was provided by the OEM) with the geometrical properties of the prime mover (such as the wheelbase and hitch location) modified to suit the design of each baseline combination.

Representative axles were developed for the baseline combinations. The prime movers used the same set of steer and drive axles and the trailer axles differed in track width and tyre size for each trailer.

Sections 5.1.1 to 5.1.3 describe the configuration of each baseline combination according to the baseline prime mover units, trailer units and axles.

5.1.1 Baseline Quad Semi-trailer Combination

The quad semi-trailer fuel tanker is one of the most common quad-axle semi-trailer combinations operated in South Africa. A Liquefied Petroleum Gas (LPG) quad was selected as the baseline for this combination. The configuration of this baseline combination is as per Table 5.1 and a simplified General Arrangement (GA) drawing of the combination is included in Figure 5.3.

Table 5.1: Configuration of the baseline quad-semi combination

Vehicle unit, axle or tyre	Description	VDP Table (see Appendix A)
Prime mover unit	Truck tractor	Table A.1
Trailer unit	Quad semi-trailer	Table A.6
Steer axle	Steer axle with 315/80 R22.5 tyres	Table A.11
Drive axle	Drive axle with 315/80 R22.5 tyres	Table A.12
Trailer axle	Trailer axle with 445/65 R22.5 tyres	Table A.13
Steer tyre	315/80 R22.5 (singles)	Table A.17
Drive tyre	315/80 R22.5 (duals)	Table A.17
Trailer tyre	445/65 R22.5 (singles)	Table A.16

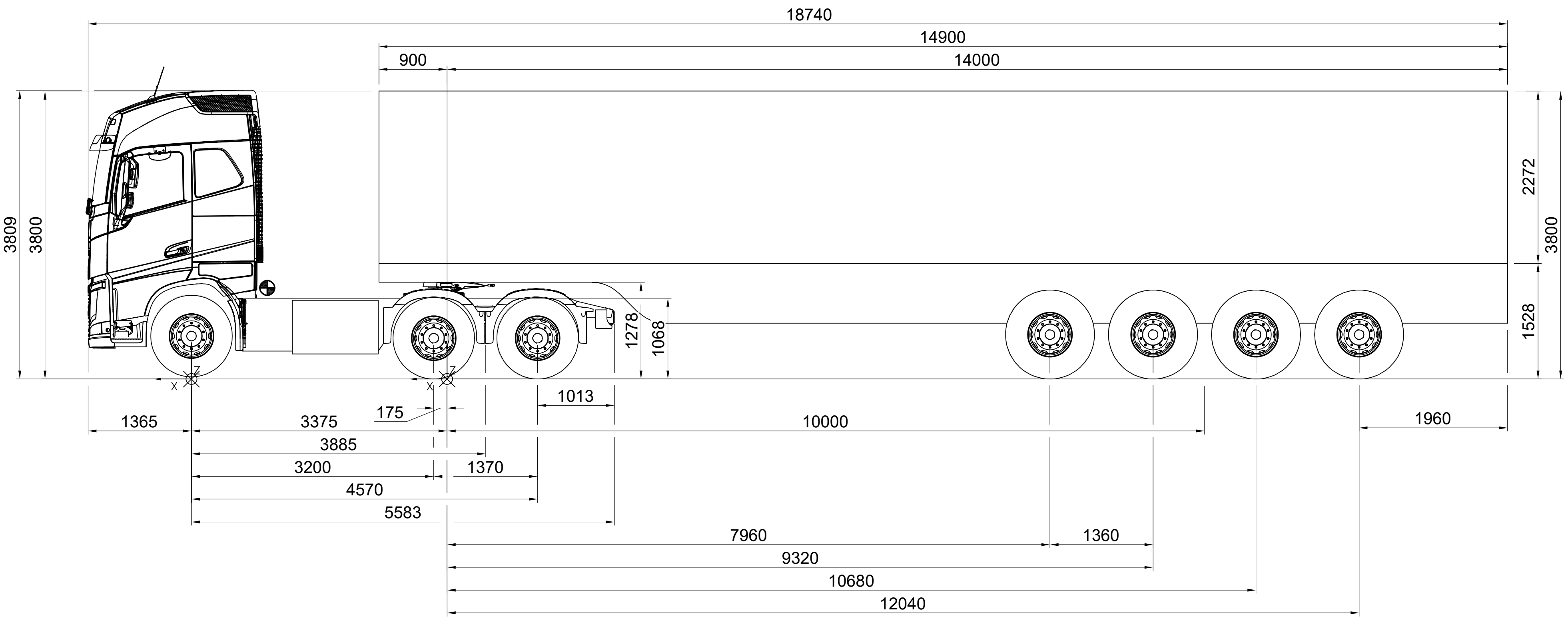


Figure 5.3: Baseline quad semi-trailer combination GA drawing

5.1.2 Baseline Tridem Interlink Combination

A tridem interlink side-tipper used for the transportation of coal ore was modelled as the baseline tridem interlink combination. The configuration of this baseline combination is as per Table 5.2 and a GA drawing of the combination is included in Figure 5.4.

Table 5.2: Configuration of the baseline tridem interlink combination

Vehicle unit, axle or tyre	Description	VDP Table (see Appendix A)
Prime mover unit	Truck tractor	Table A.1
Lead trailer unit	Tridem interlink leader	Table A.7
Follower trailer unit	Tridem interlink follower	Table A.8
Steer axle	Steer axle with 315/80 R22.5 tyres	Table A.11
Drive axle	Drive axle with 315/80 R22.5 tyres	Table A.12
Trailer axle	Trailer axle with 315/80 R22.5 tyres	Table A.14
Steer tyre	315/80 R22.5 (singles)	Table A.17
Drive tyre	315/80 R22.5 (duals)	Table A.17
Trailer tyre	315/80 R22.5 (duals)	Table A.17

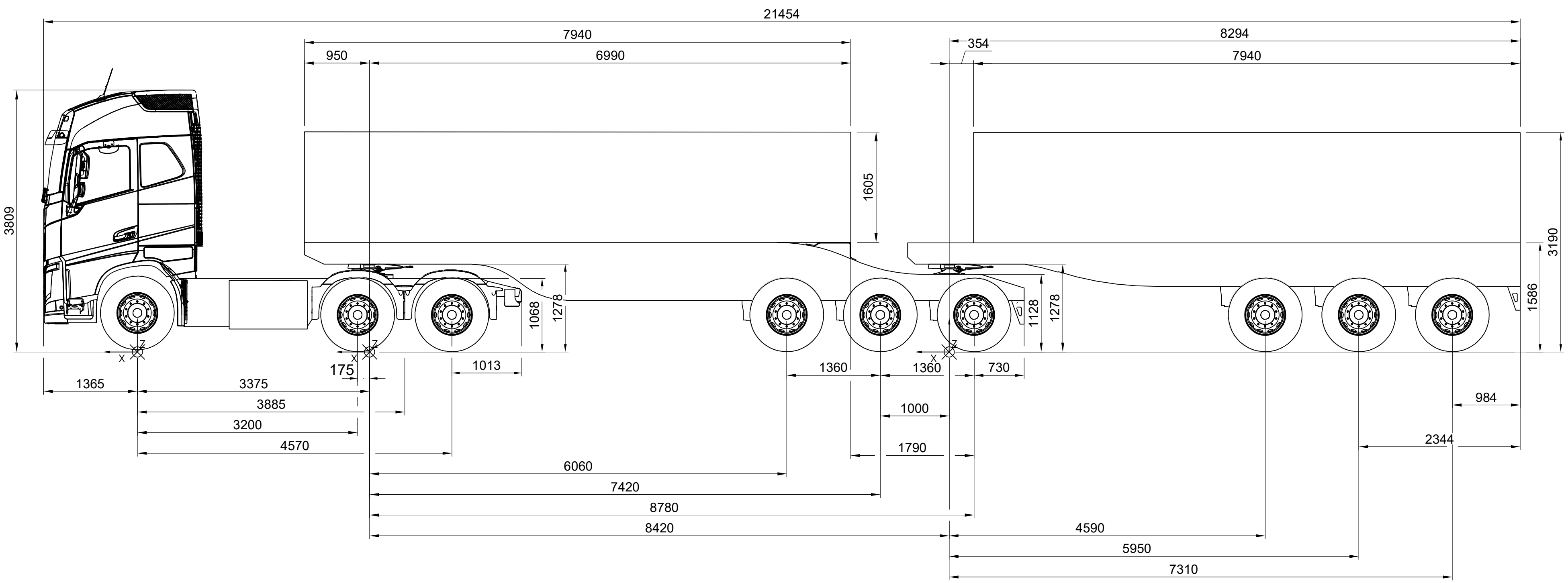


Figure 5.4: Baseline tridem interlink combination GA drawing

5.1.3 Baseline Rigid Drawbar Combination

The rigid drawbar combination is most prevalent in South Africa in the logging industry. The baseline rigid drawbar combination was modelled from a combination intended for the transport of timber. The configuration of this baseline combination is as per Table 5.3 and a simplified GA drawing of the combination is included in Figure 5.5.

Table 5.3: Configuration of the baseline rigid drawbar combination

Vehicle unit, axle or tyre	Description	VDP Table (see Appendix A)
Prime mover unit	Rigid truck	Table A.2
Lead trailer unit	Tridem semi-trailer	Table A.9
Dolly unit	Dolly	Table A.10
Steer axle	Steer axle with 315/80 R22.5 tyres	Table A.11
Drive axle	Drive axle with 315/80 R22.5 tyres	Table A.12
Trailer axle[1]	Trailer axle with 285/70 R19.5 tyres	Table A.15
Steer tyre	315/80 R22.5 (singles)	Table A.17
Drive tyre	315/80 R22.5 (duals)	Table A.17
Trailer tyre[1]	285/70 R19.5 (duals)	Table A.18

[1] The dolly axle is considered as a trailer axle

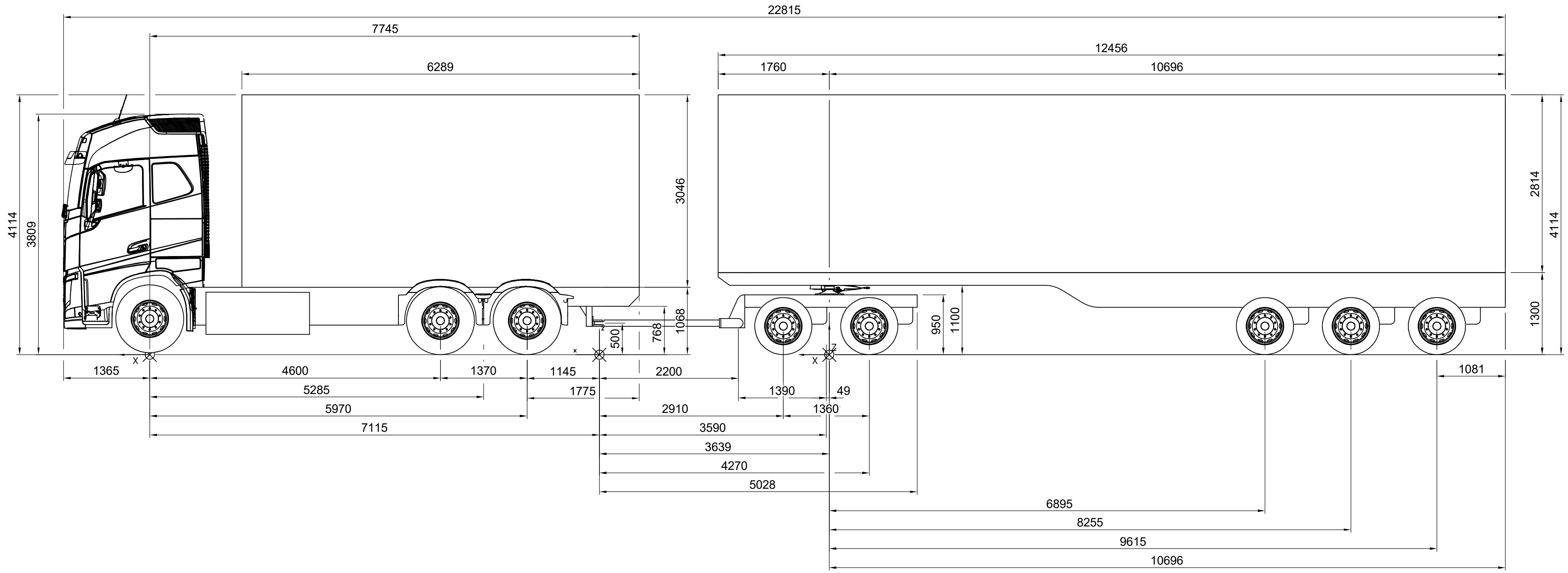


Figure 5.5: Baseline rigid drawbar combination GA drawing

6 VDP Range Selection

Ensuring that the ranges for each VDP are realistic and representative is critical in accurately quantifying the relative influence of each VDP. Overestimating a VDP range will overestimate its relative influence and vica versa underestimating a VDP range would underestimate its relative influence. The rationale for selecting the ranges for each VDP is presented in the sections that follow.

6.1 Geometric Parameter Limits

The PBS scheme is still in the pilot project stages in South Africa and as part of the pilot project the vehicles that form part of the PBS fleet still need to adhere to certain regulations as stipulated within the National Road Traffic Act (NRTA) unless special permission is given by the National Department of Transport (NDoT) in the form of a operational approval.

The PBS scheme is designed to develop safer, more productive HCVs without the requirement of being governed by a prescriptive framework. Kienhöfer et al. [25] evaluated the MoD and DoM performance and highlighted that the prescriptive framework allows for the most lenient geometrical constraints for frontal overhang when compared to Australia, the European Union, Canada, and the United States. Thus, the prescriptive framework was used as a guide to determine the maximum dimensional limits for each combination while simultaneously ensuring that the geometry would be structurally possible with the baseline design. The prescriptive legislation for maximum vehicle dimensions in South Africa is detailed in Part III of the NRTA (Act No. 93 of 1996) [26] and any regulation numbers included in the tables below refer to this document.

The vehicle geometry plays the largest role in the low-speed performance (LSSP, FS, TS, MoD, DoM). The geometrical reference points used to calculate these are described in the PBS scheme [5] as follows:

1. **Forward reference points:** “the vertical projection of the furthest forward or outside point, or points, on the vehicle”
2. **Rear reference points:** “the vertical projection of the furthest rearward or outside point, or points, on the vehicle”

Minimum dimensional limits are not explicitly defined in the NRTA and have been determined according to either physical constraints or other limitations which will be discussed in the sections that follow.

6.1.1 Front Overhang

A representative frontal overhang for the prime movers was determined from OEM catalogues, the data from which is included in Table 6.1.

Table 6.1: OEM prime mover front overhangs[1]

Prime mover model	Front overhang (mm)
Volvo FH42T3LA [27]	1365
Mercedes Benz Atego [28]	1380
Scania G440/480 8x4 [29]	1455
DAF FTT XF105.460 [30]	1370
Volvo FM64T3HBX [31]	1520

[1] SAE up co-ordinate system and origin taken from centre of steer axle or hitch point (for trailers) at ground level

Regulation 221 in the NRTA allows for a 300 mm projection forward of the front of cab for a bull-bar and therefore considering a worst case frontal cab overhang of 1520 mm, the maximum overhang with a bull-bar will be considered 300 mm ahead of this at the same width of the cab.

The front overhang in the case of the trailer units and rigid truck were limited according to regulation 226 (1)(a) which allows a frontal overhang of up to 1800 mm for a semi-trailer. The swing radius of all the models were checked to ensure that there would be no collision with the unit ahead of it. The limit was set such that there would be a 50 mm clearance between the leading unit and the swing radius of the following unit.

In the case of the tridem interlink follower, the baseline frontal overhang is negative (behind the hitch) which was used as the minimum. All other trailer frontal overhangs were evaluated as 0 mm from the hitch connection assuming a narrow chassis section extends further to structurally support the 5th wheel hitch connection.

The resulting parameter range for the front overhangs of each unit is provided in Table 6.2.

Table 6.2: Parameter range - front overhang[1]

Vehicle unit	Baseline (mm)	Min. (mm)	Max. (mm)	Rationale min.	Rationale max.
Truck tractor	1365	1300	1820	OEM variations	OEM variations
Rigid truck	1365	1300	1820	OEM variations	OEM variations
Quad semi-trailer	900	0	1800	Structural	Regulation 226 (a)
Tridem interlink leader	950	0	1800	Structural	Regulation 226 (a)
Tridem interlink follower	-354	-354	464	Structural	Structural
Tridem semi-trailer	1760	0	1800	Structural	Regulation 226 (a)

[1] SAE up co-ordinate system and origin taken from centre of steer axle or hitch point (for trailers) at ground level

6.1.2 Rear Overhang

All rear overhangs were considered at the point where the structure of the unit was at its widest. Narrow chassis extensions were ignored.

Regulation 226 (2)(c) states that the maximum rear overhang of any semi-trailer or other vehicle (other than refuse collectors, road making, road construction, farming vehicles and vehicles with a single axle or axle unit) may not exceed 60 % of the wheelbase measured from the centre of the rearmost axle on the unit. This was considered along with structural constraints to develop the maximum rear overhang reference points.

The reference point evaluated for the rear overhang of the 6x4 truck-tractor is at the furthest rear and widest point on the wheel arch. Further past this, the chassis extension is narrow and is not used as a reference point in the manoeuvres. As a result, the rear overhang was not evaluated for this vehicle unit.

In the case of the rigid truck, the superstructure could legally extend further back to the NRTA limit of 60% of the wheelbase. This would cause the rigid payload to extend into the rear semi-trailer. Considering the swing radius of the rear trailer of 2188 mm, the maximum rear overhang of the rigid payload with a 50 mm clearance to ensure no contact in dynamic manoeuvres would be 2546 mm from the rear axle as can be seen in Figure 6.1

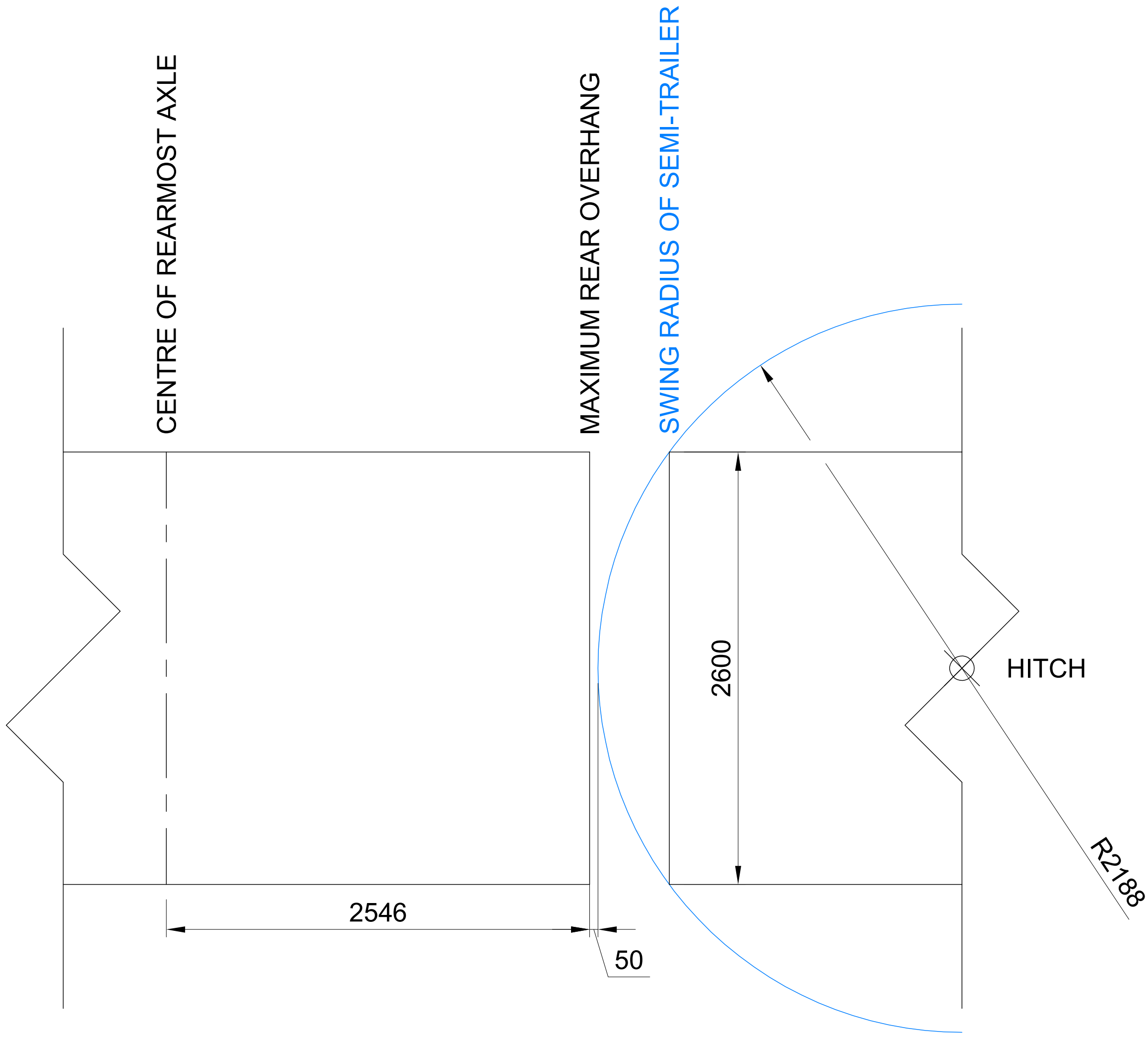


Figure 6.1: Rear overhang of the rigid truck

Similarly, the maximum rear overhang for the tridem interlink leader was determined geometrically from the swing radius of the narrow follower chassis as shown in Figure 6.2.

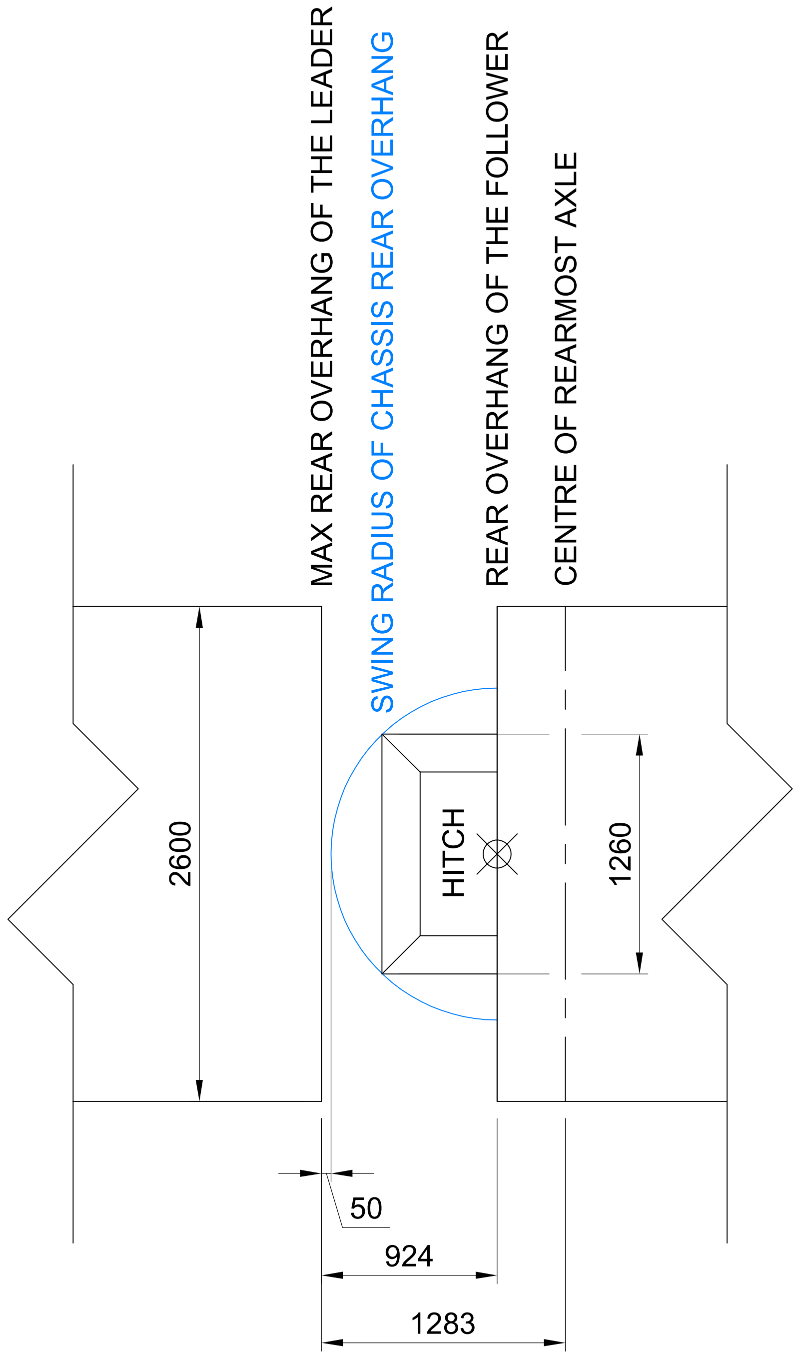


Figure 6.2: Rear overhang of the tridem interlink leader trailer

The resulting range of rear overhangs is summarised in Table 6.3.

Table 6.3: Parameter range - rear overhang [1]

Vehicle unit	Baseline (mm)	Min. (mm)	Max. (mm)	Rationale min.	Rationale max.
Truck tractor	1013	1013	1013	No impact	No impact
Rigid truck	1775	0	2546	Assumption	Structural
Quad semi-trailer	1960	0	6000	Assumption	Regulation 226 (2)(c)
Tridem interlink leader	-1790	-1790	-1283	Structural	Structural
Tridem interlink follower	984	0	3570	Assumption	Structural
Tridem semi-trailer	1081	0	4953	Assumption	Regulation 226 (2)(c)

[1] Measured from the centre of the rearmost axle in accordance with Regulation 226 (2)(c)

6.1.3 Vehicle Width

The maximum width for all vehicle units was assumed to be the legal maximum of 2600 mm.

The minimum vehicle width for the prime mover was determined from overall widths provided in OEM datasheets as summarised in Table 6.4.

Table 6.4: Selection of OEM prime mover widths

Prime Mover Model	Overall width (mm)
Volvo FM64T3HBX [31]	2490
Mercedes Benz Atego 1528 LS-36 [28]	2228
DAF FTT XF105.460 [30]	2540

The reference points used for the low-speed standards on the front of a cab are generally narrower than maximum vehicle width due to the curvature of the bumper. As a result, the width of the reference points (furthest forward or outside) used for the minimum and maximum vehicle width were determined as listed with an illustration following in Figure 6.3:

1. The maximum width at 2600 mm with a 100 mm radius corner, at a 30° angle anti-clockwise to the transverse axis [i]
2. The minimum width at 2200 mm with a 500 mm radius corner, at a 30° angle anti-clockwise to the transverse axis

[i] The low-speed performance of a combination is determined by the selected reference point on the vehicle. A reference point located further forward of the steer axle or outward of the vehicle centreline will result in greater road-width usage. When locating a reference point on a radius, using a more forward location will not necessarily indicate worse performance since the point will be located further inward towards the vehicle centreline. A 30° angle from the transverse axis has been found in practice to yield approximate worst-case evaluation of low-speed performance within a suitable accuracy and has become the standard method at Wits in evaluating the performance of a combination where reference points reside on a radius such as the payload of a car-carrier.

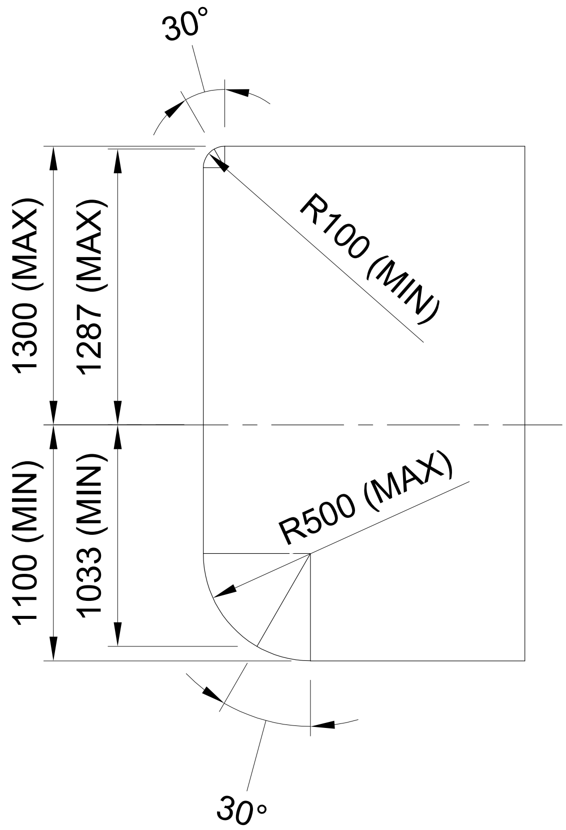


Figure 6.3: Parameter selection - prime mover frontal reference points

The trailer units were modelled as boxes without any curvature. The minimum width for a trailer was assumed to be 2400 mm, beyond which the deck width would become too small and unproductive.

A summary of the vehicle widths for all units is provided in Table 6.5.

Table 6.5: Parameter range - vehicle width

Vehicle unit	Baseline (mm)	Min. (mm)	Max. (mm)
Prime mover (all)	2495	2225	2600
Trailer (all)	2600	2400	2600

6.1.4 Reference Point Height

Geometrical reference points at the forward-most outer and rearward-most outer of a HCV are used to evaluating the amount of road space that a HCV requires when performing road manoeuvres. The NTC rules [5] state that if multiple points reside at the same reference point, the lowest of those points should be used.

The reference point height can range from ground height (for example a mud flap or sidewalls of a tyre) up to 4600 mm in the case of a car-carrier which is allowed an overall height of 4600 mm if approved as a PBS safe vehicle [32]. Thus, to encompass the worst case for all HCVs, the reference points on each vehicle unit were varied from 0 mm to 4600 mm.

6.1.5 Prime Mover and Trailer Wheelbase

The range of wheelbases selected for each vehicle unit was determined using structural limitations in conjunction with Regulation 225 (b) regulating the maximum wheelbase for a vehicle unit and the previously mentioned Regulation 226 (2)(c) regulating the maximum rear overhang from the centre of the rearmost axle (see Section 6.1.2).

Changing the wheelbase has a significant effect on the axle loadings and the baseline vehicles are based on PBS vehicles with axle loadings close to the legal limits. If the wheelbase were to be varied within a range where the axle loads remained legal, there would be minimal variation. This would remove insight into how the wheelbase impacts vehicle performance in the case of volume limited transport where the axle loadings have more scope to vary. Thus, for the selection of wheelbases, legal axle load requirements were ignored.

The minimum wheelbase was selected according to the following conditions:

1. The resulting rear overhang reached 60% of the wheelbase
2. The hitch location coincides with the centre of the rearmost axle
3. The vehicle configuration becomes unstable [ii]

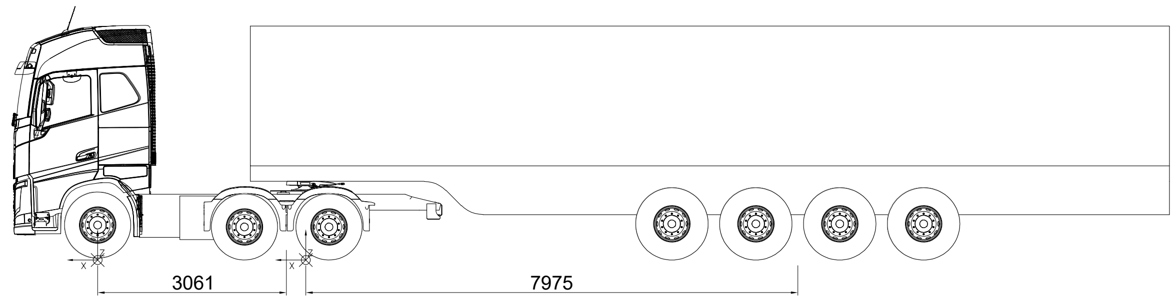
The maximum wheelbase was selected according to the following conditions:

1. The maximum wheelbase for a semi-trailer of 10 m according to Regulation 225 (b)
2. The edge of the tyre aligns with the edge of the chassis structure
3. The edge of the tyre aligns with the pintle hitch connection point

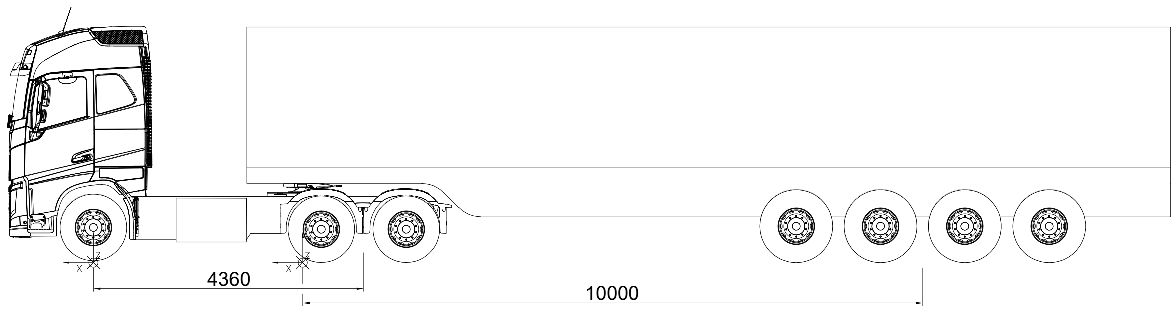
The maximum and minimum wheelbases are illustrated in Figures 6.4 to 6.6.

A summary of the range of wheelbases evaluated for each vehicle unit is included in Table 6.6.

[ii] Since the wheelbases are varied over a large range without altering the location of the payload, the vehicle model became unstable for short wheelbases. In these cases, the minimum wheelbase was increased in increments of 50 mm until the model became stable.

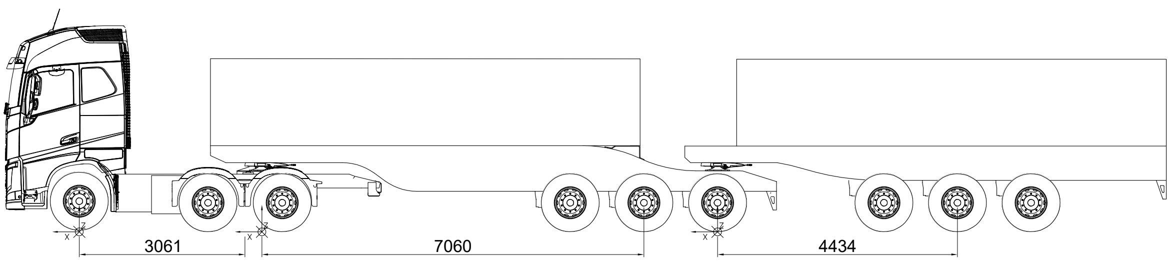


(a) Minimum wheelbase

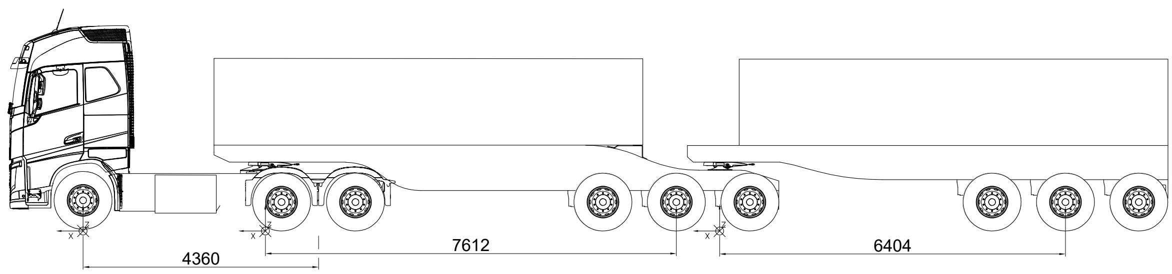


(b) Maximum wheelbase

Figure 6.4: Parameter selection - wheelbases for the quad semi-trailer combination

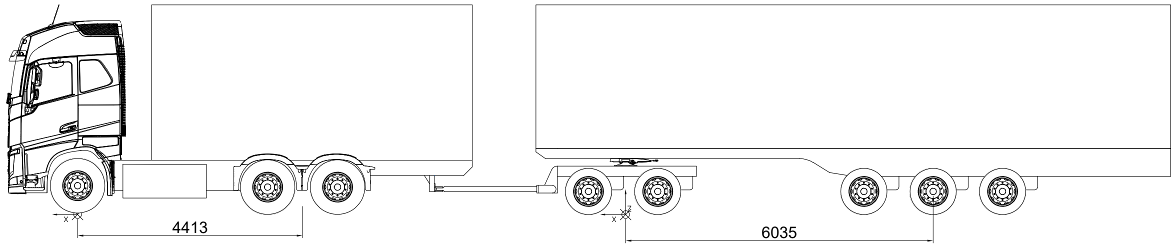


(a) Minimum wheelbase

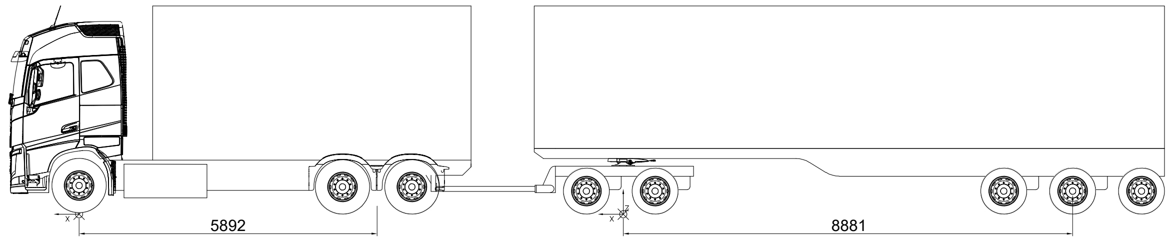


(b) Maximum wheelbase

Figure 6.5: Parameter selection - wheelbases for the tridem interlink combination



(a) Minimum wheelbase



(b) Maximum wheelbase

Figure 6.6: Parameter selection - wheelbases for the rigid drawbar combination

Table 6.6: Parameter range - wheelbase

Vehicle unit	Baseline (mm)	Min. (mm)	Max. (mm)	Rationale min.	Rationale max.
Truck tractor	3885	3061	4360	Regulation 226 (2)(c)	Structural
Rigid truck	5285	4413	5892	Regulation 226 (2)(c)	Structural
Quad semi-trailer	10000	7975	10000	Model stability	Regulation 225 (b)
Tridem interlink leader	7420	7060	7612	Hitch location	Structural
Tridem interlink follower	5950	4434	6404	Model stability	Structural
Tridem semi-trailer	8255	6035	8881	Model stability	Structural

6.1.6 Dolly Wheelbase (Drawbar Length)

The range for the dolly wheelbase was determined according to the range of allowed drawbar lengths. Regulation 222 (2b) states the length of an underslung drawbar may exceed 2 m in length if the distance between the two vehicles does not exceed 2.5 m. Using this regulation, the maximum allowed drawbar length is 3451 mm as shown in Figure 6.7.

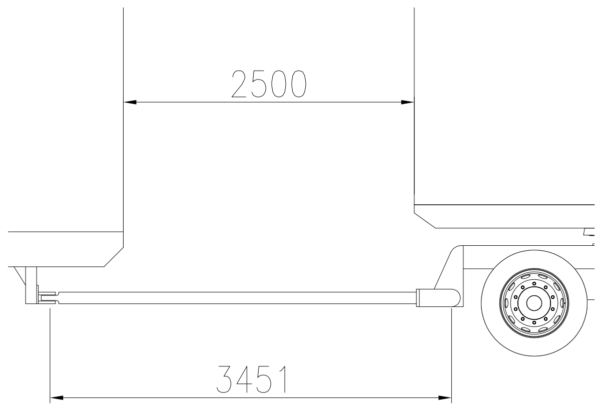


Figure 6.7: Maximum drawbar length according to regulation 222 (2b)

The minimum drawbar length was chosen such that there would be a 50 mm clearance between the trailer swing radius and the rigid truck chassis resulting in a minimum drawbar length of 1429 mm as shown in Figure 6.8.

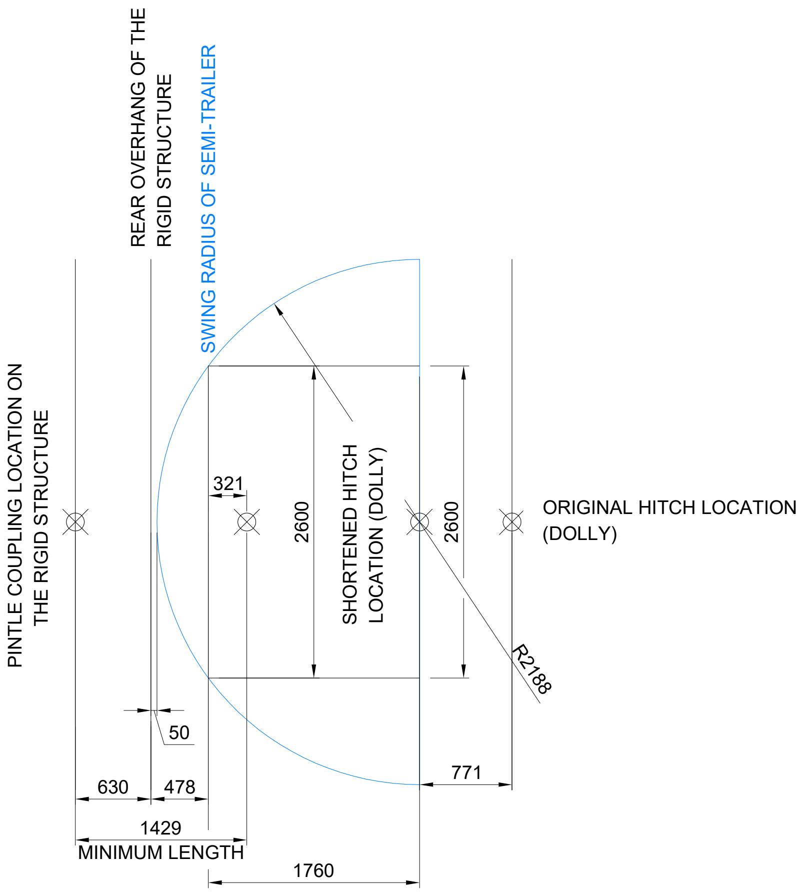


Figure 6.8: Minimum drawbar length

Table 6.7: Parameter range - dolly wheelbase and drawbar length

Details	Baseline (mm)	Min. (mm)	Max. (mm)	Rationale Min.	Rationale Max.
Drawbar length	2200	1429	3451	Structural	Regulation 222 (3)
Wheelbase	3590	2819	4841	Drawbar length	Drawbar length

6.1.7 Axle Spacing

The only publicly available legislation that could be found that explicitly governs axle spacing is the Canadian legislation (British Columbia) [33] which states that axle spacing should range between 1.2 m to 1.85 m and limits drive axles to a maximum spacing of 1.4 m. This legislation allowed a larger range of variation than typically observed in South Africa (trailer axle spacing of 1360 mm and drive axle spacing of 1400 mm are commonly observed in PBS assessments conducted in South Africa) and was thus deemed to represent a suitable and conservative range of variation for axle spacing.

The drive axle group spacing was varied from 1.2 m to 1.4 m. It was practical to vary all trailer axle group spacing from 1.2 m to 1.85 m as there were no interference's between adjacent axles. The dolly axle group was varied from 1.2 m to 1.8 m since the edge of the front tyre interferes with the pintle hitch position at larger spacing.

The resulting range of axle spacing evaluated for each vehicle unit is summarised in Table 6.8.

Table 6.8: Parameter range - axle spacing

Vehicle unit	Baseline (mm)	Min. (mm)	Max. (mm)	Rationale Min.	Rationale Max.
Truck tractor	1370	1200	1400	Legislation	Legislation
Rigid truck	1370	1200	1400	Legislation	Legislation
Quad Semi-trailer	1360	1200	1850	Legislation	Legislation
Tridem interlink leader	1360	1200	1850	Legislation	Legislation
Tridem interlink follower	1360	1200	1850	Legislation	Legislation
Tridem semi-trailer	1360	1200	1850	Legislation	Legislation
Dolly	1360	1200	1800	Legislation	Structural limitation

6.1.8 Hitch Longitudinal Location

Common longitudinal hitch positions on tractors were measured by Fancher et al. [14]. Hitch positions were measured relative to the centre of the rear axle or rear axle group of between 0" and 24" (610 mm) forward of the rear axle or centre of the tandem axle group.

Truck-tractor (5th wheel): Longitudinal positions for the tractor hitch position provided by the OEM[iii] correlated well with the data from Fancher et al. with hitch locations from 0 mm to 685 mm forward of the drive axle tandem group. The OEM range was evaluated for the largest range of possible locations.

Rigid truck (pintle hitch): It was assumed that the pintle hitch could be mounted on the rigid truck chassis from the edge of the chassis up until the hitch position reached 50 mm from the rearmost drive tyre.

Tridem interlink leader (5th wheel): The location of the hitch on the tridem interlink leader trailer is largely governed by the limited space on the chassis. It was graphically determined that limits of -380 and +620 from the baseline position would be possible with minimal modifications to the chassis design. The hitch centreline was not allowed further rear than the centreline of the last axle in the axle group. An illustration showing the graphically determined baseline, minimum and maximum position is shown in Figure 6.9.

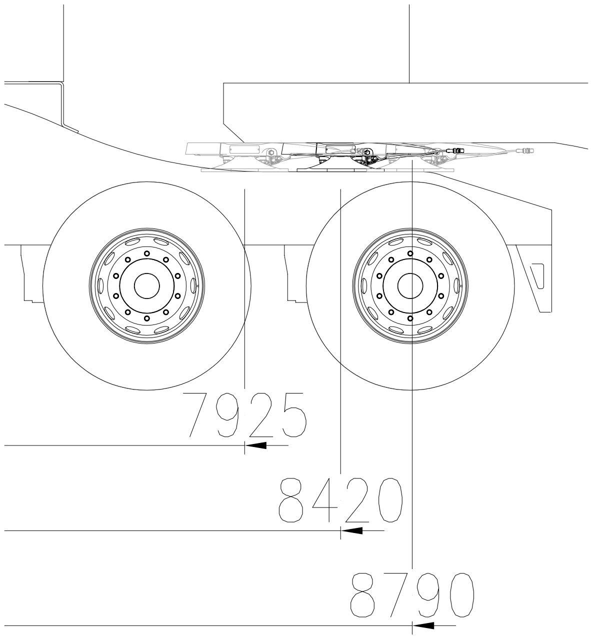


Figure 6.9: 5th wheel longitudinal locations for the tridem interlink leader trailer

Rigid drawbar combination dolly (5th wheel): The typical 5th wheel location should be located at or near the centre of the dolly to avoid instabilities, it was hence assumed that the dolly 5th wheel location could only be moved +/-200 mm from the centre of the dolly axle group.

A summary of the evaluated hitch locations as discussed above is included in Table 6.9.

[iii]Permission was not received to mention the name of the OEM

Table 6.9: Parameter range - longitudinal hitch locations

Vehicle unit	Baseline (mm)[1]	Min. (mm)	Max. (mm)
Truck tractor	-3375	-3200	-3885
Rigid truck	-7115	-6558	-7860
Tridem interlink leader	-8420	-7925	-8780
Dolly	-3639	-3385	-3785

[1] SAE up co-ordinate system and origin taken from centre of steer axle or hitch point at ground level

6.1.9 Hitch Height

5th wheel: The 5th wheel hitch heights (truck tractor, tridem interlink leader, and dolly) were assumed to vary from 20 mm above the deck of each vehicle unit (for low-profile 5th wheels), up until a maximum of 1350 mm which is a maximum that has been observed from PBS assessments in South Africa.

Pintle hitch: The minimum pintle hitch height for the rigid truck was assumed to be 300 mm above the ground to ensure that the cross chains do not hit the floor. The maximum pintle hitch height was assumed to be at the centre of the rigid truck chassis. While this may not be physically possible in the case of the underslung pintle arrangement, it is possible if the pintle hitch is connected to the rear of the rigid truck chassis. To be inclusive of other pintle hitch arrangements, the full range of possible heights were evaluated.

The resulting range of hitch heights evaluated is summarised in Table 6.10.

Table 6.10: Parameter range - hitch heights

Vehicle unit	Baseline (mm)[1]	Min. (mm)	Max. (mm)
Truck tractor	1278	1088	1350
Rigid truck	500	300	918
Tridem interlink leader	1278	1148	1350
Dolly	1100	970	1350

[1] Measured relative to the ground

6.2 Inertial Parameter Limits - Vehicle Units

The inertial parameters are mainly influenced by the type of commodity being transported. This governs the payload geometry, orientation and the structure of the trailer which is designed to accommodate the payload.

Limited data was available for trailers and prime movers of similar wheelbase and payloads with the same loading deck space. For most of these inertial limits, assumptions were made based on practical operation, experience from performing PBS assessments and data from South African PBS assessments. The inertial VDP ranges for each of the baseline combinations are detailed in the sections that follow.

6.2.1 Vehicle Unit Sprung Mass

The baseline vehicles operate at or near the legal axle load limits and as a result, the sprung mass of each vehicle unit was varied from a minimum to the baseline value.

The minimum sprung mass was determined by consolidating data from South African PBS assessments (see Appendix E). The ratio of the sprung mass to the wheelbase was found for each trailer and prime mover as per Equation 6.1. The minimum sprung mass to wheelbase ratio was then multiplied with the baseline wheelbase to determine the minimum sprung mass of each vehicle unit as per Equation 6.2.

$$R_{sw} = \frac{m_{sprung}}{d_{wb}} \tag{6.1}$$

$$m_{sprung,min} = R_{sw} \times d_{wb-baseline} \tag{6.2}$$

It was deemed more appropriate to use the sprung mass to axle spacing ratio (see Equations 6.3 to 6.4) to determine the minimum sprung mass for the dolly vehicle unit.

$$R_{sa} = \frac{m_{sprung}}{d_{axle}} \tag{6.3}$$

$$m_{sprung,min} = R_{sa} \times d_{axle-baseline} \tag{6.4}$$

Where:

R_{sw} = Ratio of vehicle unit sprung mass to wheelbase (kg/m)

R_{sa} = Ratio of vehicle unit sprung mass to axle spacing (kg/m)

d_{wb} = Wheelbase (m)

d_{axle} = Axle spacing (m)

m_{sprung} = Sprung mass (kg)

The minimum sprung masses were calculated according to Equations 6.2 to 6.4 for each vehicle unit and are included in Table 6.11.

Table 6.11: Minimum sprung mass for each vehicle unit

Vehicle unit	Wheelbase (mm)[1]	Baseline sprung mass (kg)	Min. R_{sw} or R_{sa} (kg/m)	Min. sprung mass (kg)
Truck tractor	3885	6598	1140	4428
Rigid truck	5285	6698	902	4767
Quad semi-trailer	10000	10410	250	2500
Tridem interlink leader	7420	4632	250	1855
Tridem interlink follower	5950	4167	250	1488
Tridem semi-trailer	8255	3150	250	2064
Dolly	1360	453	294	400

[1] Or axle spacing in the case of the dolly

6.2.2 Vehicle Unit Longitudinal Centre of Gravity

The CG_x for the prime mover is influenced mainly by the cab and chassis design as well as any optional extras. It was assumed that the CG_x could vary by +/-20% for both prime movers.

Trailers can differ significantly in design depending on the payload it is intended to haul. However for a specific wheelbase, the CG_x would not be able to vary by extreme amounts. The variation for the trailer CG_x was assumed to vary slightly more than for the prime mover at +/-30% from the baseline value.

The structure of a dolly is relatively compact and has little scope to vary between manufacturers. Thus, a smaller range of variation of +/-10% from the baseline CG_x value was assumed.

The resulting range of CG_x locations for the prime movers is included in Table 6.12 with the locations for the trailers and dolly following in Table 6.13.

Table 6.12: Parameter range - prime mover CG_x

Vehicle unit	Baseline (mm)[1]	Min. (mm)	Max. (mm)
Truck tractor	-1001	-801	-1201
Rigid truck	-1860	-1488	-2232

[1] SAE up co-ordinate system and origin taken from centre of steer axle or hitch point at ground level

Table 6.13: Parameter range - trailer CG_x

Vehicle unit	Baseline (mm)[1]	Min. (mm)	Max. (mm)
Quad semi-trailer	-6455	-4519	-8392
Tridem interlink leader	-3656	-2559	-4753
Tridem interlink follower	-4269	-2988	-5550
Tridem semi-trailer	-5575	-3903	-7248
Dolly	-3450	-3105	-3795

[1] SAE up co-ordinate system and origin taken from centre of steer axle or hitch point at ground level

6.2.3 Vehicle Unit Lateral Centre of Gravity

To account for eccentric loading about the longitudinal axis which could arise due to fuel tanks, spare tools, pneumatic equipment, storage compartments etc., a variation of 10% of the unit overall width was assumed for both the sprung mass and payload CG_y.

In the case of the dolly, there would be no reason for lateral eccentricity of the CG_y and therefore it was not varied.

The range of CG_y locations evaluated (measured according to the SAE up coordinate system with the origin at the centre of the combination) are:

- **Truck tractor:** +/- 250 mm
- **All other units (excluding the dolly unit):** +/- 260 mm

6.2.4 Vehicle Unit Vertical Centre of Gravity

The CG_z of a vehicle unit can vary due to various cab and trailer designs for the same wheelbase. A flatbed or stepdeck may have a low sprung mass centre of gravity, while a side tipper or tanker would have a higher sprung mass centre of gravity. To develop a representative range of possible vehicle configurations, the CG_z locations of various trailers were identified from South African PBS assessments and anonymised for presentation in Tables E.1 to E.3 in Appendix E. The resulting range of CG_z positions is summarised in Table 6.14.

Table 6.14: Parameter range - vehicle unit CG_z

Vehicle unit	Baseline (mm)[1]	Minimum (mm)	Maximum (mm)
Truck tractor	1204	1070	1426
Rigid truck	1017	1000	1315
Quad semi-trailer	2025	1280	2025
Tridem interlink leader	1777	1280	2025
Tridem interlink follower	1912	1280	2025
Tridem semi-trailer	1500	1280	2025
Dolly	868	868	1050

[1] SAE up co-ordinate system and origin taken from centre of steer axle or hitch point at ground level

6.2.5 Vehicle Unit Roll Moment of Inertia

The vehicle unit I_{xx} is rarely supplied for the purposes of a PBS assessment. Most of the engineering drawings provided are drawn in 2D Computer-aided Design (CAD) and 3D models which allow for accurate calculation of the inertial properties are often not available.

Winkler et al. [18] and Fancher et al. [14] provide simplified estimates for the moment of inertia for conventional trailers and prime movers. These simplified estimates are useful for when measured values are not provided, however they in no way encompass the full range of prime movers. It is presently unsure as to whether using these estimates predicts vehicle performance from simulations conservatively. Since the moment of inertia for a vehicle is not often supplied, to be inclusive of all vehicle designs, broad ranges are developed as discussed in Sections 6.2.5 to 6.2.6.

The radius of gyration (r) of an inertial object can be related to the I with its mass according to Equation 6.5. The radius of gyration is an easier metric to read and compare and will be used in place of the moment of inertia where possible.

$$r = \sqrt{\frac{I}{m}} \tag{6.5}$$

Where:

r = Radius of gyration (m)

I = Moment of inertia (kg.m^2)

m = Mass of the inertial object (kg)

6.2.5.1 Prime mover units

Fancher et al. [14] measured the r_x of the sprung mass for some prime movers. The roll radius of gyration for each of the measured vehicles was calculated using Equation 6.5 and the results are displayed in Table 6.15.

Comparing calculated r_x values to that of the baseline prime movers (see Table 6.16), a minimum variation of 75% and a maximum variation of 95% was observed. Due to the small sample of measured values and considering that the measured data encompasses only USA native cab styles, a conservative variation of +/-30% was chosen to encapsulate all varieties of prime movers and cab designs, therefore:

- **Prime mover r_x variation:** +/-30%

Table 6.15: Measured values for prime mover r_x estimated from Fancher et al. [14]

Vehicle description	Tare mass (kg)	Estimated sprung mass (kg)	I_{xx} (kg.m^2)	r_x (m)
Ford 9000 (WB = 185.75")	7772	5051	2869	0.608
GMC Astro 95 Tractor (WB = 150")	7888	5166	2582	0.572
GMC Tractor	4933	3300	2576	0.723
Ford 800 Conventional Tractor (WB = 150")	5163	2442	2576	0.706
International Harvester Tractor (WB = 143")	6695	3974	2518	0.613

Table 6.16: Variation of estimated prime mover r_x measurements from Fancher et al. [14]

Baseline description	Baseline r_x (m)	Min. variation (%)	Max. variation (%)
All prime movers	0.76	75%	95%

6.2.5.2 Trailer and dolly units

A similar exercise was performed with measured data for trailers from Fancher et al. [14]. The calculated r_x for the measured trailers is provided in Table 6.17.

Table 6.17: Measured values for trailer r_x calculated from Fancher et al. [14]

Typical tare masses	Tare mass (kg)	Estimated sprung mass (kg)	I_{xx} (kg.m^2)	r_x (m)
48" Semi-trailer, tandem axle (WB=40')	6260	4663	9039	1.202
45' Semi-trailer, tandem axle (WB=37')	5916	4320	8405	1.192
42' Semi-trailer, tandem axle (WB=36')	5573	3976	7769	1.181
28' Semi-trailer, single axle (WB=21')	2981	2183	5934	1.411
27' Semi-trailer, single axle, (WB=21')	2948	2150	5649	1.384

In comparison to the baseline trailer r_x (see Table 6.18), the measured values varied by from 43% higher to 36% lower. Using this as a guideline and acknowledging that the measured data represents only a small sample of trailer designs, a conservative range of +/-45% was evaluated. No data was available for dollies. Due to their design being inherently simpler, it was assumed to vary by +/-20% and therefore:

- **Trailer r_x variation:** +/-45%
- **Dolly r_x variation:** +/-20%

Table 6.18: Variation of estimated trailer r_x measurements from Fancher et al. [14]

Baseline description	Baseline r_x (m)	Min. variation (%)	Max. variation (%)
Quad semi-trailer	1.588	74%	89%
Tridem interlink leader	0.985	120%	143%
Tridem interlink follower	1.007	117%	140%
Tridem semi-trailer	1.277	92%	110%

6.2.6 Vehicle Unit Pitch and Yaw Moment of Inertia

The I_{yy} and I_{zz} are approximately equal for a vehicle unit and were treated as a single VDP.

The sprung mass can be distributed with more variability along the pitch and yaw axes, especially in the case of superstructures designed to accommodate specialised loads. Thus, the r_y and r_z were assumed to vary by +/-40% for the prime mover units and +/-50% for the trailer units with the intent to encompass the wide variety of trailer, prime mover and cab designs. No data was available for dollies and due to their inherently simpler design, it was assumed to vary by +/-30% and therefore:

- **Prime mover r_y / r_z variation:** +/- 40%

- **Trailer r_y / r_z variation:** +/-50%
- **Dolly r_y / r_z variation:** +/-30%

6.3 Inertial Parameter Limits - Payloads

The inertial properties of the payload are dependent on the type of commodity being transported as well as the available loading deck area. The sections that follow discuss the ranges determined for the inertial properties of the payloads.

6.3.1 Payload Mass

The baseline combinations operate at or near the legal axle load limits. As a result the payload masses were assumed to vary from 0 kg for operation in the unladen state up to the baseline payload mass. The payloads for each unit are included in Table 6.19.

Table 6.19: Parameter range - payload mass

Vehicle unit	Payload Mass (kg)
Rigid truck	15352
Quad Semi-trailer	32000
Tridem interlink leader	24615
Tridem interlink follower	24615
Tridem semi-trailer	34000

6.3.2 Payload Longitudinal Centre of Gravity

In most transport operations, payload is distributed evenly on the trailer in an effort to make full use of the load deck. In transport operations where payload density is uniform, the centre of gravity (CG) of the payload will be located near the longitudinal centre of the payload. There are however cases where payload density will not be uniform, or the loadable deck will be offset from the centre of the trailer chassis (such as in a stepdeck trailer). Thus, a variation of +/-5% of the outer profile of the loadable deck was considered to account for this. The variation of the payload CG_x location is summarised in Table 6.20.

Table 6.20: Parameter range - payload CG_x

Vehicle unit	Baseline (mm)[1]	Min. (mm)	Max. (mm)
Rigid truck	-4490	-4176	-4804
Quad semi-trailer	-6500	-5755	-7245
Tridem interlink leader	-3111	-2714	-3508
Tridem interlink follower	-4403	-4006	-4800
Tridem semi-trailer	-4702	-4079	-5325

[1] SAE up co-ordinate system and origin taken from centre of steer axle or hitch point at ground level

6.3.3 Payload Lateral Centre of Gravity

Payloads are generally arranged such that there is no lateral offset of their CG. However, eccentric loading could occur due to the payload shifting during transport if the payload has not been properly secured, or if poor practices have been followed when partially unloading the vehicle. Thus, similarly to the vehicle units, the range of CG_y for each payload was evaluated as follows:

- **Payload CG_y variation:** +/-260 mm

6.3.4 Payload Vertical Centre of Gravity

The range of payload CG_z heights was determined by considering the two loading scenarios illustrated in Figures 6.10 and 6.11.

To determine the minimum CG_z height, the payload was assumed to be a box with the same width and length as the load deck for each payload carrying vehicle unit (as shown in Figure 6.10).

Considering the baseline payload mass, the minimum height was determined with a payload density of 8050 kg/m^3 (standard structural steel has a density of 7850 kg/m^3 and depending on the composition can reach up to 8050 kg/m^3 [34]). The height of the CG_z relative to the loading deck was assumed to reside at the centre of the payload volume as per Equation 6.7.

$$\rho = \frac{m}{v} = \frac{m}{W \times L \times H} \tag{6.6}$$

$$\frac{H}{2} = \frac{m}{2 \times W \times L \times \rho} \tag{6.7}$$

Where:

m = Baseline payload mass (kg)

W = Width of the load deck (m)

L = Length of the load deck (m)

$H/2$ = Height of the payload CG_z from the top of the loading deck (m)

ρ = Maximum density of the payload (8050 kg/m^3)

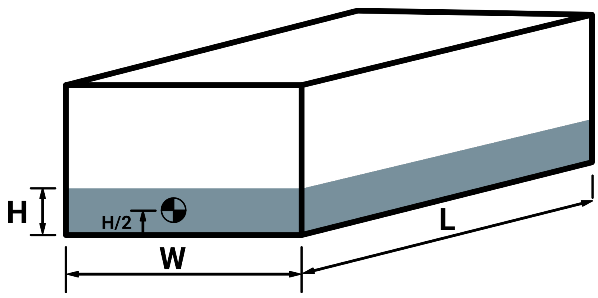


Figure 6.10: Minimum payload CG_z height

The calculations of the minimum CG_z for each vehicle unit are summarised in Table 6.21.

Table 6.21: Minimum CG_z for the payload

Combination	Width (m)	Length (m)	Payload density (kg/m^3)	Payload mass (kg)	H/2 (mm)	Deck height (mm)	Min. CG_z[1](mm)
Rigid truck	2.600	6.289	8050	14140	54	1068	1122
Quad semi-trailer	2.600	14.900	8050	32300	52	1528	1580
Tridem interlink leader	2.600	7.940	8050	24615	74	1593	1667
Tridem interlink follower	2.600	7.940	8050	24615	74	1593	1667
Tridem semi-trailer	2.600	12.456	8050	37000	71	1300	1371

[1] Measured from the ground

The maximum payload CG_z height was determined from the geometrical location of the centre of gravity for a trapezoid with sides sloped at 20° according to Equation 6.8. This represents the payload distribution of a side-tipper filled to the top with payload which is typical for the transport of payloads with low densities.

$$y = h\left(1 - \frac{1}{3} \times \frac{(b+2a)}{(b+a)}\right) \tag{6.8}$$

Where: y, h, b, and a are the dimensions of the trapezoid as illustrated in Figure 6.11.

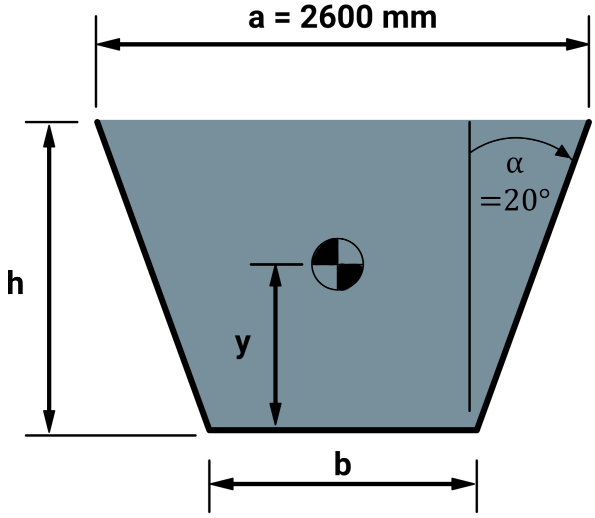


Figure 6.11: Maximum payload CG_z height

The calculations for the maximum CG_z above ground are summarised in Table 6.22.

Table 6.22: Calculation of the maximum CG_z above ground

Combination	h (mm)	b (mm)	y (mm)	Deck height (mm)[1]	Max. CG_z (mm)[1]
Rigid truck	3046	383	1900	1068	2968
Quad semi-trailer	2272	946	1313	1528	2841
Tridem interlink leader	1605	1432	880	1593	2473
Tridem interlink follower	1605	383	880	1593	2473
Tridem semi-trailer	2814	552	1712	1300	3012

[1] Measured from the ground

6.3.5 Payload Roll Moment of Inertia

The payload roll moment of inertia was assumed to vary according to the roll radius of gyration by an additional 5% variation in comparison to the trailer vehicle units (see Section 6.2.5.2) to account for the fact that payload geometry has additional scope to vary.

- **Payload r_x variation:** +/-50%.

6.3.6 Payload Pitch and Yaw Moment of Inertia

Similarly to the sprung mass of a HCV, payload geometry can have more variability along the pitch and yaw axes. This results in additional scope for the pitch and yaw moment of inertia to vary relative to the roll moment of inertia. Thus, the payload pitch and yaw moment of inertia was assumed to vary according to the pitch and yaw radius of gyration by an additional 10% in comparison to the trailer vehicle units unit (see Section 6.2.6) to account for the fact that payload has additional scope to vary.

- **Payload r_y and r_z variation:** +/-60%.

6.4 Suspension Parameter Limits

The suspension parameter limits are often difficult to acquire from OEMs. Local distributors require permission from overseas design offices to release the proprietary information. Additionally, non-disclosures need to be signed when receiving technical information which can delay the data acquisition process.

To develop the evaluated ranges of the suspension parameter limits, existing literature was consulted for methods of estimating parameters and publicly available OEM datasheets were used to determine representative design parameters.

For some suspension parameters, data collected from PBS assessments completed by Wits was used to investigate reasonable ranges. This data is protected by non-disclosure agreements and cannot be publicly disclosed in this dissertation. Thus only variations in parameter values relative to the baseline models are presented.

A collection of measured vehicle design parameters is contained in studies such as those conducted by Fancher et al. [14] , [35], Ervin et al. [16] and Harwood et al. [15]. These studies were conducted in the USA and Canada and may not be representative of the South African heavy vehicle fleet. These sources were used due to the lack of similar studies related to South African vehicles.

6.4.1 Unsprung Mass

Prime mover: The unsprung masses recorded by Fancher et al. [14] for steer and drive axles as shown in Table 6.23 are significantly lower than those generally observed in more modern prime movers. Therefore these were conservatively used as the minimum. The maximum steer and drive axle unsprung masses were determined from South African PBS assessments and are included in Table 6.27.

Table 6.23: Measured unsprung mass for steer, drive and trailer axles - Fancher et al. [14]

Axle type	Minimum (kg)	Maximum (kg)
Steer	544	
Drive	1043	1134
Trailer	798	

The range of unsprung masses for the trailer axles was determined from a collection of OEM data, weights of generic suspension components collected from previous on-site measurements and South African PBS assessments.

To determine the minimum unsprung mass, data from the BPW axle catalogue was consolidated (see Tables D.1 to D.5 included in Appendix D.1).

The minimum axle unpsrung mass was determined by combining the lightest BPW axle was with aluminium rims. The results of these calculations are summarised in Tables 6.24 to 6.26.

The maximum trailer unsprung mass for each axle was determined from South African PBS assessments since these were found to be heavier than the combination of the heaviest BPW axle with steel rims. The range of evaluated unsprung masses is summarised in Table 6.27.

Table 6.24: Minimum unsprung mass for a trailer axle with 445/65 R22.5 singles

Component	Description	Quantity	Unit mass (kg)	Total mass (kg)
Tyre	445/65 R22.5	2	103.0	206.0
Rim	Aluminium - 13"	2	26.5	53.0
Axle	SKHSF 9010 (singles)	1	265.0	265.0
Spring	Generic	2	5.6	11.2
Damper	Generic	2	5.0	10.0
			Total	545.2

Table 6.25: Minimum unsprung mass for a trailer axle with 315/80 R22.5 duals

Component	Description	Quantity	Unit mass (kg)	Total mass (kg)
Tyre	315/80 R22.5	4	68.7	274.8
Rim	Aluminium - 9"	4	22.6	90.6
Axle	SKHZF 9010 (duals)	1	280.0	280.0
Spring	Generic	2	5.6	11.2
Damper	Generic	2	5.0	10.0
			Total	666.5

Table 6.26: Minimum unsprung mass for a trailer axle with 285/70 R19.5 duals

Component	Description	Quantity	Unit mass (kg)	Total mass (kg)
Tyre	285/70 R19.5	4	41.0	164.0
Rim	Aluminium - 7.5"	4	18.7	74.7
Axle	SKHZF 9008 (duals)	1	270.0	270.0
Spring	Generic	2	5.6	11.2
Damper	Generic	2	5.0	10.0
			Total	529.8

Table 6.27: Parameter range - axle unsprung mass

Axle	Baseline (kg)	Min (kg)	Max (kg)
Steer	750	544	800
Drive	1300	1043	1350
Trailer (445/65 R22.5 - singles)	760	545	800
Trailer (315/80 R22.5 - duals)	900	667	1000
Trailer (285/70 R19.5 - duals)	757	530	850

6.4.2 Axle Roll and Yaw Moment of Inertia

According to Winkler et al. [18], the axle roll and yaw moment of inertia (I_{xx}/I_{zz}) for steer, drive and trailer axles can be estimated with the range of radii of gyration provided in Table 6.28. The axle r_x and r_z are approximately equal and are thus treated as a single VDP.

Table 6.28: Estimation range for axle r_x/r_z [18]

Axle type	Min. r_x/r_z (mm)	Max. r_x/r_z (mm)
Steer	840	910
Drive	690	740
Trailer	790	860

The minimum and maximum axle roll and yaw inertias were determined using the baseline axle unsprung mass with the minimum and maximum axle roll and yaw radii of gyrations from Winkler et al. (see Table 6.28).

The resulting range of axle roll and yaw inertia for each baseline axle is provided in Table 6.29.

Table 6.29: Parameter range - axle roll and yaw moment of inertia

Axle	Baseline ($kg.m^2$)	Min. ($kg.m^2$)	Max. ($kg.m^2$)
Steer	529	529	621
Drive	619	619	712
Trailer (445/65 R22.5 singles)	474	474	562
Trailer (315/80 R22.5 duals)	562	562	666
Trailer (285/70R22.5 duals)	472	472	560

6.4.3 Axle Spin Moment of Inertia

The spin inertia of the rotating components of the axle is generally quite small. A value of 2 $kg.m^2$ was derived by de Saxe [8] from measured data published by Winkler et al. [17] which was considered the minimum value. The TruckSim® 2018 database includes spin inertias of up to 20 $kg.m^2$ (*18t Trailer, Dual Wheels*) which was deemed reasonable as the maximum value for the spin inertia of the rotating axle components.

6.4.4 Damper Dynamic Response

Linear damping models in the TruckSim® 2018 database range from 2.5 kN-s/m to 50 kN-s/m. Due to the complex nature of comparing the damping characteristics of non-linear damping, the effectiveness of which is dependent on the range of operation, the baseline damping was linearised and the damping was varied from 2.5 to 50 kN-s/m.

6.4.5 Roll Steer Coefficient

Roll steer is the tendency for a non-steered rigid axle to exhibit some level of steering as an axle rolls relative to the vehicles sprung mass such as when travelling over a disturbance or when performing certain turning manoeuvres. An exaggerated illustration of this effect is shown in Figure 6.12.

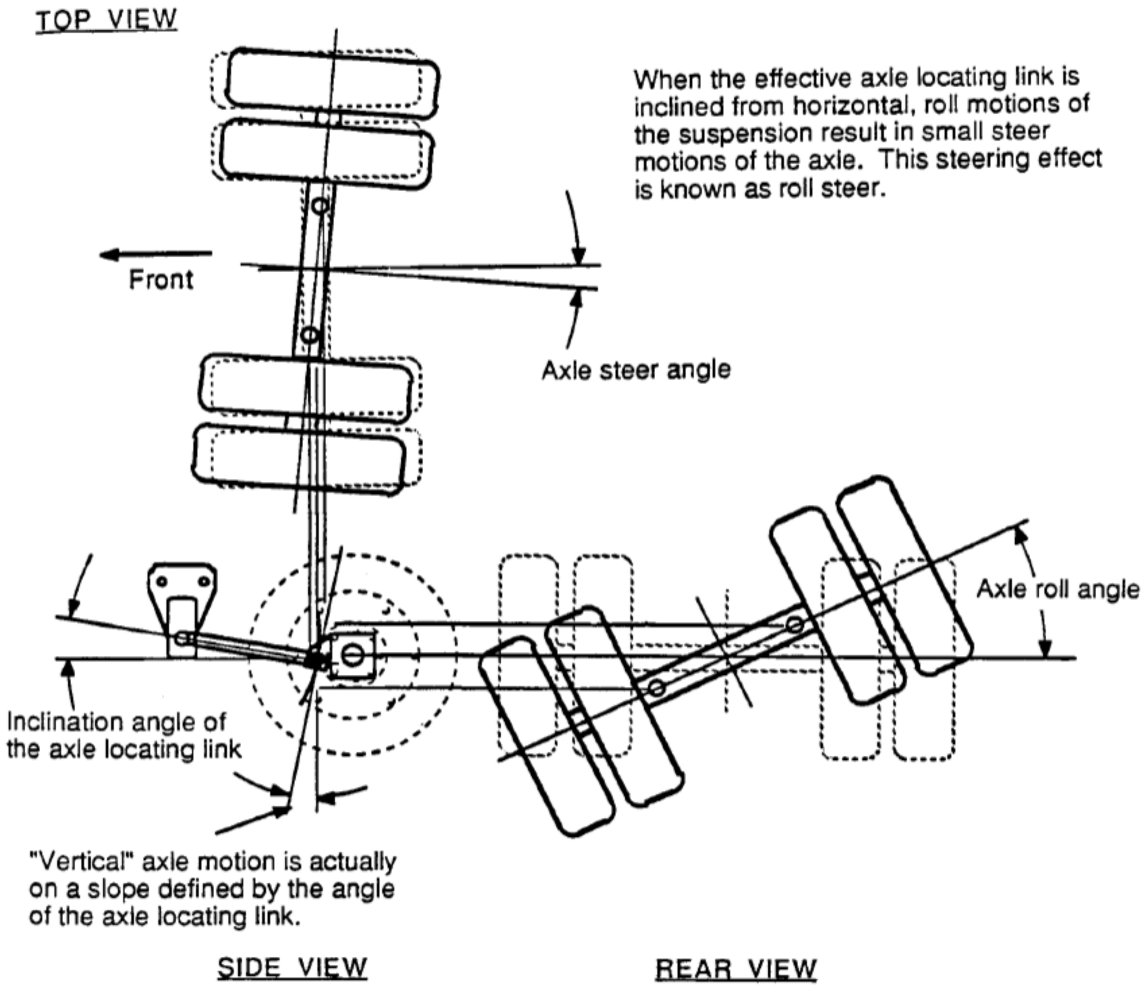


Figure 6.12: Illustration of the roll steer effect on a rigid axle [14]

Studies conducted by both Fancher et al. [14] and Harwood et al. [15] have resulted in a collection of measured roll steer coefficients. A comparison of the data from these sources is included in Table 6.30[iv].

Table 6.30: Measured roll steer coefficients from published data

	Fancher et al. [14]		Harwood et al. [15]	
Suspension type	**Min.**	**Max.**	**Min.**	**Max.**
Air suspension	-0.01	-0.225	-0.01	-0.23
Single-axle leaf spring	0	-0.08	0	-0.07
Steer axle	0	-0.2	-	-
Walking beam	-0.175	-0.21	-0.16	-0.21
4-spring suspensions	0.04	-0.22	-0.23	0.04

The minimum and maximum values for the roll steer coefficient from Table 6.30 were chosen to evaluate the broadest range of roll steer on each of the axles. The resulting range of values evaluated is summarised in Table 6.31.

Table 6.31: Parameter range - roll steer coefficients

Axle	Baseline (°/°)	Min. (°/°)	Max. (°/°)
Steer	-0.087	0	-0.2
Drive	0	0.04	-0.23
Trailer (singles)	-0.035	0.04	-0.23
Trailer (duals)	-0.156	0.04	-0.23

6.4.6 Axle Track

At a Smart Truck Review Panel meeting held in 2017, it was passed that the overall axle track width on a PBS vehicle may exceed the legal limit of 2600 mm up to 2650 mm (zero tolerance and including tyre bulge). This is to allow increased axle track and thus improved stability for PBS combinations.

It would not be practical for prime mover manufacturers to modify their designs to consider the new relaxations since they would not be able to be used in conjunction with a legal vehicle. Thus, a maximum overall width of 2600 mm was evaluated for the steer and drive axle. To account for new trailer designs that may take advantage of this new relaxation, the maximum

[iv] The data published is according to the ISO coordinate system with the Z-axis (vertical) positive down and steering to the right as positive. The TruckSim® coordinate system makes use of the SAE up coordinate system with the Z-axis positive up and steering to the left as positive. The data in this table has been converted from the published values to the SAE up coordinate system

axle track was found using a maximum overall axle width of 2650 mm with the minimum tyre spacing as specified by Michelin in their tyre data book [36].

Maximum axle track conditions:

1. Overall width of 2600 mm for steer and drive axle and 2650 mm for trailer axles.
2. The dual tyres were arranged to have the minimum spacing as recommended by Michelin [36].

Minimum axle track conditions:

No regulations were defined for minimum axle track width. A catalogue of rigid axles supplied by BPW (see Appendix D.1) [37] was consulted to determine the minimum axle tracks available to avoid evaluation of unrepresentative narrow axle tracks. Only axles in the 9000 kg + rated load category were considered.

A selection of the BPW axles illustrating the variability of their axle tracks is provided in Table 6.32.

Table 6.32: BPW axle tracks

Axle Model	Tyre arrangement	Rim	Rated load (kg)	Min. (mm)	Max. (mm)
NHZF	Duals	19.5"	9000	1830	1995
SHZF	Duals	22.5"	9000-12000	1820	1880
SKHSF	Singles	22.5"	9000	2000	2140

A limiting factor was the baseline spring and damper track, it was ensured that the edge of the tyres did not move past the spring or damper centre. In all cases, the minimum tracks from the BPW catalogue were suitable and did not cause interference with the spring or damper track.

In addition to the BPW axles, data collected from Fancher et al. [14] was used to consider alternative OEMs as well as ranges of steer axle track widths. A summary of the representative track widths is included in Table 6.33. The data from Fancher et al. is for American based vehicles with tractor widths of 96" (approx. 2439 mm) and trailer widths of 102" (approx. 2591 mm) which closely approximate the widths of local heavy vehicles. Thus, the axle track widths were deemed to be representative for vehicles operating within South Africa.

Table 6.33: Measured axle track widths from Fancher et al. [14]

Axle	Min. (mm)	Max. (mm)
Steer (96" cab width)	1956	2057
Drive (96" cab width)	1803	1829
Trailer (102" trailer width)	1956	1981

Considering the worst-case minimum from either the BPW data book or Fancher et al. [14], the range of axle tracks evaluated for each axle is included in Table 6.34.

Table 6.34: Parameter range - axle track width

Axle	Baseline (mm)	Min. (mm)	Max. (mm)
Steer	2109	1950	2282
Drive	1837	1800	1932
Trailer (445/65 R22.5 singles)	2140	2000	2178
Trailer (315/80 R22.5 duals)	1920	1820	1982
Trailer (285/70R22.5 duals)	2040	1830	2042

6.4.7 Spring and Damper Track

The BPW axle catalogues [37] (see Appendix D.1) were also used to develop the range of spring tracks.

The minimum spring track from the BPW catalogues was chosen as the minimum for the trailer, drive and steer axles. The maximum BPW spring track was used as the maximum for the trailer axles. The maximum steer and drive axle tracks was limited by the baseline suspension geometry.

For all axles, it was assumed that the damper track could vary within the same range as the spring track. The resulting range of evaluated spring and damper tracks is summarised in Table 6.35.

Table 6.35: Parameter range - spring and damper track width

Axle	Min. (mm)	Max. (mm)
Steer	780	1150
Drive	670	1100
Trailer (single tyre)	780	1500
Trailer (dual tyre)	670	1200

6.4.8 Spring Vertical Stiffness

The range of spring vertical stiffness values were determined from spring data collected from PBS assessments conducted by Wits University[v].

The dynamic spring response for airbags is dependent on the vertical load. To compare the dynamic spring response, the response was linearly interpolated to a vertical load of 25000 N.

The results contained in Table 6.36 indicate that there are significant variations (up to 186%) in the spring stiffness between the different airbags at the static vertical load of 25000 N. It was assumed that any of the springs could be fitted to any of the axles to evaluate the full range of possibilities.

Table 6.36: Comparison of the stiffness of airbag springs at 25000 N

Airbag type	Interpolated stiffness at 25000 N (N/mm)	Variation from drive axle baseline (%)	Variation from trailer axle baseline (%)
Trailer	104	47%	69%
Trailer	205	92%	137%
Drive	94	42%	62%
Steer	157	71%	105%
Drive	115	52%	77%
Drive	155	70%	103%
Drive	270	121%	180%
Drive	130	59%	87%
Drive	150	67%	100%
Drive	280	126%	186%
Drive	100	45%	67%
Drive	122	55%	82%
Drive	222	100%	148%
Drive	140	63%	93%
Drive	280	126%	186%
Trailer	150	67%	100%
Trailer	151	68%	100%

The baseline steer axles are fitted with a steel spring suspension. Sample steel spring stiffness values are provided in the TruckSim® 2018 database that range from 200 N/mm to 350 N/mm. 350 N/mm was used as the maximum steel suspension stiffness. The minimum stiffness was evaluated as 185 N/mm according to the conservative spring stiffness used in the TERNZ SRT calculator [38] when a generic steer axle suspension is selected.

[v] OEM data protected by non-disclosure agreements and hence anonymised in this dissertation

The resulting range of spring vertical stiffness values are provided in Table 6.37. In the case of air springs, the baseline value is reported as 100% of the baseline spring response, with the minimum and maximum variations scaled as a percentage of the baseline spring response.

Table 6.37: Parameter range - spring vertical stiffness

Axle	Baseline	Min.	Max.
Steer	273 N/mm	185 N/mm	350 N/mm
Drive	100%	42%	126%
Trailer	100%	62%	186%

6.4.9 Jounce and Rebound Stops

The jounce (upward movement) and rebound (downward movement) stops indicate the possible range of vertical movement for a suspension assembly as limited by mechanical constraints. Data collected from OEMs range from 45 mm to 110 mm up (jounce) and 50 mm to 120 mm down (rebound).

The TruckSim® 2018 database includes jounce rebound stops of up to +250 mm / -250 mm. This is generally used as a conservative estimate in the case that an OEM does not supply sufficient information to determine jounce/rebound stops for the suspension. This was hence used as the worst case.

The lower end of the range was conservatively chosen from the OEM data with the upper end chosen from the TruckSim® 2018 database due to the jounce and rebound stops rarely being supplied.

To simplify the modelling, it was assumed that the jounce and rebound stops would be equal, resulting in the limits summarised in Table 6.38 used for all baseline axles.

Table 6.38: Parameter range - jounce and rebound stops

Axle	Baseline	Min. (mm)	Max. (mm)
All	Varies	+45/-45	+250/-250

6.4.10 Auxiliary Roll Stiffness

To adhere to the PBS requirement of a minimum SRT of 0.35 g, PBS combinations are designed with higher auxiliary roll stiffness values to improve their rollover performance. Thus, the collected OEM data from South African PBS assessments is skewed towards the suspensions with higher auxiliary roll stiffness.

The OEM data is a good indicator of the upper end of auxiliary roll stiffness values while the data collected by Fu et al. [39] from an analysis of several contemporary suspension designs is assumed to be a good indicator of the lower end of auxiliary roll stiffness values.

A comparison of the ranges of auxiliary roll stiffness provided by OEMs is made with the data collected by Fu et al. in Table 6.39. The resulting limits for auxiliary roll stiffness of each of the baseline axles is provided in Table 6.40.

Table 6.39: Comparison of auxiliary roll stiffness ranges from OEMs and Fu et al. [39]

Axle	Min. (Nm/deg) (OEM)	Max. (Nm/deg) (OEM)	Min. (Nm/deg) (Fu et al.)	Max. (Nm/deg) (Fu et al.)
Steer	1850	5009	1070	1470
Drive	7226	12689	790	2030
Trailer	23736	35954	2260	13560

Table 6.40: Parameter range - auxiliary roll stiffness

Axle	Baseline	Min. (Nm/deg) (Fu et al.)	Max. (Nm/deg) (OEM)
Steer	2950	1070	5009
Drive	7487	790	12689
Trailer	24700	2260	35954

6.4.11 Wheel and Axle Centre Height

The wheel centre height was assumed to vary from the laden height up to an increased height by half of the deflection between laden and unladen conditions (using the Michelin data book [36] for the unladen heights). These wheel centre height maximums are presented in Table 6.41.

The height of the axle CG is generally assumed equal to the wheel centre height since it is not supplied by the OEMs and detailed drawings (which tend to be proprietary) would be needed to determine the offset of the axle centre height relative to the wheel centre height.

The TruckSim® 2018 database has a maximum axle centre offset relative to the wheel centre height of 60 mm (*3t Drive, single wheels*). This was assumed to be the maximum offset above or below the wheel centre height resulting in the range of axle centre heights being evaluated as per Table 6.42.

Table 6.41: Wheel centre height variation due to tyre deflection [36]

Tyre	Laden radius (mm)	Unladen radius (mm)	Deflection (mm)	Max. wheel centre height (mm)
285/70 R19.5	413	456	42.50	434.3
315/80 R22.5	507	548	41.00	527.5
445/65 R22.5	534	587	53.00	560.5

Table 6.42: Parameter range - wheel and axle centre height

Parameter	Baseline (mm)[1]	Min. (mm)	Max. (mm)
Wheel centre height (445/65 R22.5)	534.0	534.0	560.5
Wheel centre height (315/80 R22.5)	507.0	507.0	527.5
Wheel centre height (285/70 R19.5)	413.0	413.0	434.3
Axle centre height (445/65 R22.5)	534.0	474.0	594.0
Axle centre height (315/80 R22.5)	507.0	447.0	567.0
Axle centre height (285/70 R19.5)	413.0	353.0	473.0

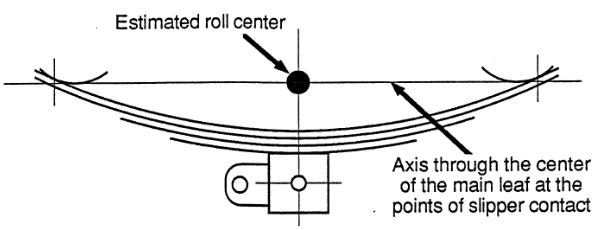
[1] Height relative to the ground

6.4.12 Roll Centre Height

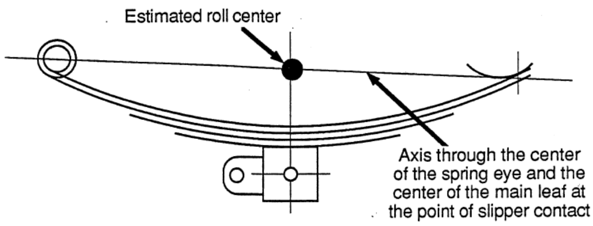
Winkler et al. [18] has documented a set of graphical methods for determining the roll centre based on the geometry of the suspension (see Figure 6.13). Using the graphical method for typical trailing arm suspensions, the maximum distance of the roll centre height from the centre of the axle is when the leaf spring makes an angle of 0° to the horizontal. Thus, the vertical distance from the centre of the lever arm to the centre of the axle will be a maximum when the thickness of the lever arm and cross-sectional height of the axle are at a maximum.

The maximum axle cross section in the BPW rigid axles catalogue [37] is 150 mm. Thus, assuming a maximum trailing arm thickness at the location of the axle of 100 mm to account for mounting plates, the maximum roll centre height from the centre of the axle is 125 mm below when the suspension is overslung and above when underslung as shown in Figure 6.14.

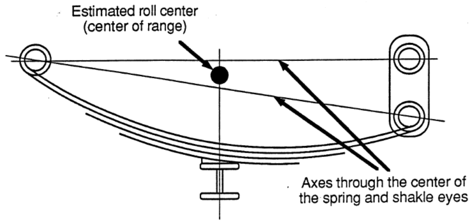
It is desirable from a stability perspective that the roll centre height be raised as high as possible. This is made possible with track bars as noted by Winkler et al. Thus, it was assumed with the use of additional lateral restraints such as a track bar that the maximum height of the roll centre above the trailing arm suspension could reach up to 200 mm.



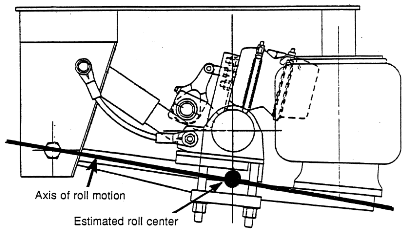
(a) Typical four spring suspensions



(b) Typical single axle rear suspensions

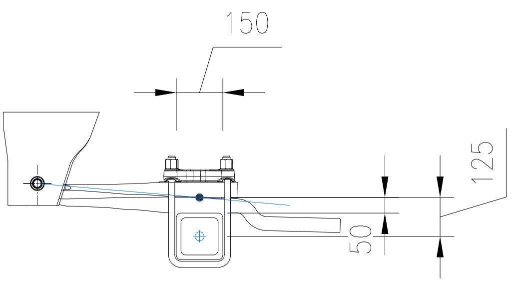


(c) Typical front axle suspensions

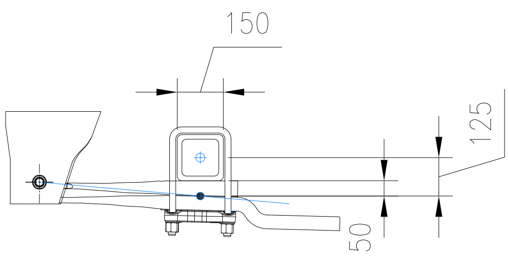


(d) Typical trailing arm suspensions

Figure 6.13: Estimate of roll centre heights for typical suspension configurations [18]



(a) Overslung (+125 mm)



(b) Underslung (-125 mm)

Figure 6.14: Roll centre height estimates for trailing arm suspension

The suspension used for baseline drive axle tandem bogie is of the A-frame type which is laterally constrained on the chassis, leading to a high roll centre height of 400 mm above the wheel centre height. An illustration of this type of suspension is included from a Volvo data sheet for the Volvo RADD-GR [40] suspension in Figure 6.15.

Figure 6.15: Volvo RADD-GR rear axle installation

The baseline value of 400 mm was assumed as the maximum height, while the minimum roll centre height was assumed to be the same as for the trailer axles to evaluate the performance with various drive axle suspension designs.

The roll centre height of the steel steer axle suspension is governed by the geometry of the leaf springs as shown by the graphical estimation in Figure 6.13. The TERNZ SRT calculator [38] uses a roll centre height of 20 mm below the wheel centre for generic suspensions which was assumed as the minimum. A reasonable maximum was assumed to be 100 mm above the axle centre. The roll centre heights for front air suspension are typically near the axle centre (evident from OEM data) which was deemed to be representative of both front air and steel suspension designs.

Table 6.43: Parameter range - roll centre height

Axle	Baseline (mm)[1]	Min. (mm)	Max. (mm)
Steer	+21	-20	+100
Drive	+400	-125	+400
Trailer	+114	-125	+200

[1] Roll centre height is reported relative to the wheel centre height

6.5 Tyre Parameter Limits

Tyre data is well protected by OEMs and they are often not willing to disclose measured tyre test data. PBS assessments are currently performed using conservative tyre data for lateral tyre force as extracted from [41]. This data is from 1981 and modern tyres are expected to have improved properties with advances in material and construction. The use of conservative data aligns with the NTC requirements that worst-case tyre data be used in the absence of measured data for the tyres in question [5].

Historically, both bias and radial ply tyres have been used on commercial heavy vehicles. However heavy trucks have been phasing out bias ply in favour of radial ply tyres since 1984 as mentioned by Ervin et al. [16]. All modern heavy commercial vehicles use radial ply tyres and hence the mechanical properties of bias ply tyres were not considered.

6.5.1 Effective Rolling Radius

The rolling radius is influenced by a multitude of operational factors such as the state of tyre wear, inflation pressure and speed. The effective rolling radius can be estimated from the unloaded tyre radius according to Genta [42] as 98% of the unladen tyre radius.

The effective rolling radius for the baseline tyre models was calculated from the Michelin data book [36] using the supplied rolling circumference for each tyre. The effective rolling radius as a percentage of the unladen radius was calculated and it is shown in Table 6.44 that it is approximately 95% of the unladen radius, with the 445/65 R22.5 tyre model having the lowest ratio of 94.5%.

Table 6.44: Effective rolling radius of baseline tyre models

Tyre	Unladen radius (mm)	Effective rolling radius (mm)	% of unladen radius
445/65 R22.5	587	555	94.5%
315/80 R22.5	548	522	95.3%
285/70 R19.5	456	434	95.2%

Accounting for various operating conditions and considering the effective rolling ratios of the baseline combinations, it was assumed that the effective rolling radius could vary from 94% to 98% of the baseline unladen radius. The resulting range of effective rolling radii for each tyre is summarised in Table 6.45.

Table 6.45: Parameter range - tyre effective rolling radius

Tyre	Baseline (mm)	Min. (mm)	Max. (mm)
445/65 R22.5	555	552	575
315/80 R22.5	522	515	537
285/70 R19.5	434	429	447

6.5.2 Unloaded Radius

Data collected from tyre manufacturer data books (Bridgestone [43], Goodyear [44] and Michelin [36]) and summarised in Tables D.6 to D.8 in Appendix D.2 were consulted to determine the variation in unloaded radii between manufacturers. The range of unloaded radii evaluated is summarised in Table 6.46.

Table 6.46: Parameter range - tyre unloaded radius

Tyre	Baseline (mm)	Min. (mm)	Max. (mm)
445/65 R22.5	587	575	589
315/80 R22.5	548	538	550
285/70 R19.5	456	448	456

6.5.3 Tyre Spring Rate

The vertical spring rate of each tyre model was calculated from the given axle load, considering the difference between the unladen and laden radius, the spring of the tyre was estimated assuming linear behaviour and using Equation 6.9 (Hooke's law).

$$k_{tyre} = \frac{F_z}{\Delta x} \tag{6.9}$$

Where:

k_{tyre} = Tyre spring rate (N/mm)

F_z = Vertical tyre load (N)

Δx = Tyre deflection (mm)

Tyre spring rates were calculated from the data from Bridgestone, Goodyear and Michelin [43, 44, 36] for dual and single tyre arrangements at various pressures and axle loads. Tables D.6 to D.8 in Appendix D.2 include the calculated tyre spring rates. The resulting range of tyre spring rates evaluated is summarised in Table 6.47.

Table 6.47: Parameter range - tyre spring rate

Tyre	Baseline (N/mm)	Min. (N/mm)	Max (N/mm)
445/65 R22.5	1193	773	1237
315/80 R22.5	987	565	1169
285/70 R19.5	801	473	901

6.5.4 Wheel and Tyre Assembly Spin Moment of Inertia

Spin inertias for wheel and tyre assemblies were derived as 10 kg.m^2 for 19.5" wheels and 12 kg.m^2 for 22.5" wheels by de Saxe [8] from UMTRI data [17], [45]. This correlates well with the TruckSim® database which has values of 13 kg.m^2 (*2000 kg rating, 425 mm Radius (Drive)*) to 28 kg.m^2 (*SAE Widebase, 4750 kg*) for truck tyres.

It was assumed that the above data are for steel rims. Thus, considering aluminium rims (approximately half the weight of a steel rim) and additional weight reductions in modern designs, the minimum spin moment of inertia was calculated with a reduction in wheel assembly mass of 50%. The evaluated range of wheel and tyre assembly spin moment of inertias is summarised in Table 6.48.

Table 6.48: Parameter range - wheel and tyre assembly spin moment of inertia

Tyre	Baseline (kg.m^2)	Min. (kg.m^2)	Max. (kg.m^2)
285/70 R19.5	10	6.5	13
315/80 R22.5	12	7	14
445/65 R22.5	28	14	28

6.5.5 Tyre Lag (relaxation length)

Literature defining truck tyre lag (also known as relaxation length) ranges could not be found, however TruckSim® indicates that reasonable estimates of tyre lag are as follows:

- L_x (longitudinal tyre lag): 1/10 of the tyre radius
- $L_{y,z}$ (lateral tyre lag): Twice the tyre radius

The NTC standards and vehicle assessment rules for the PBS framework [5] do not clearly state whether the simulated vehicle performance should include the effects of tyre lag. Thus tyre lag was varied from the recommended value down to values that would effectively simulate zero tyre lag to evaluate the impact of including the effects of tyre lag in the vehicle simulations.

When tyre lag is set to absolute zero, the driver model is unstable. To simulate zero tyre lag (on all but the steer tyres - see footnote [1] in Table 6.49) without causing instabilities in the driver model, resulting in erroneous vehicle performance, the following parameters were used.

- L_x: remains at approximately 1/10 of the tyre radius
- $L_{y,z}$: reduced to 100 mm

The resulting range of tyre lag values are presented in Table 6.49.

Table 6.49: Parameter range - tyre lag (L_x / $L_{y,z}$)

Tyre	Baseline (mm / mm)	Min. (mm / mm)	Max. (mm / mm)
445/65 R22.5	55 / 1100	55 / 100	55 / 1100
315/80 R22.5[1]	50 / 1000	50 / 100	50 / 1000
285/70 R19.5	45 / 900	45 / 100	45 / 900

[1] The steer tyre lag is set to 50/1 to prevent instabilities with the driver model. Lag response in the steer tyre causes the driver to overcompensate for the lagged response after a steering input, resulting in instability.

6.5.6 Tyre Cornering Stiffness

Cornering stiffness tyre data is not readily supplied by manufacturers and could not be used to determine the possible range of tyre data. Conservative tyre models sourced from measured tyre performance provided by UMTRI in studies performed by Fancher [41] and Bogard et al. [46] are generally used in PBS assessments in South Africa. These same tyre models were used for the baseline combinations.

Fancher et al. [14] measured cornering stiffness at rated load for a range of tyres and measured that tyre wear of 1/3 of the tread depth can yield an increase in cornering stiffness of approximately 0.04. This measured data was compared with the cornering stiffness of the baseline combinations to gauge a range of cornering stiffness that should be considered (including the effect of increased cornering stiffness with tyre wear).

The steer, drive and trailer tyres were evaluated separately to provide insight into how using tyres of varying cornering stiffness on the same combination could influence behaviour as well as yield insight into the sensitivity of vehicle performance to the cornering stiffness of the tyres. Situations like this can occur when worn tyres are rotated from the prime mover to the trailer or retreads of unknown cornering stiffness properties are used.

The cornering stiffness was calculated within the linear region of each tyre for the same vertical loading at which the tyres were tested by Fancher et al. of 26879 N (6040 Lbs). The cornering stiffness was then normalised with the vertical tyre load according to Equation 6.10 to determine the cornering coefficient which could then be compared to the data provided by Fancher et al.

$$C_c = \frac{C_\alpha}{F_z} \tag{6.10}$$

Where:

C_c = Cornering coefficient ($^{\circ -1}$)

C_α = Cornering stiffness (N/$^\circ$)

F_z = Vertical tyre load (N)

The variation for the cornering stiffness values are summarised in Table 6.50. The baseline cornering stiffness values are conservative in relation to the cornering stiffness values measured by Fancher et al. [14]. This is in-line with the requirements of the NTC for PBS assessments which state [5] that if no tyre data is available, conservative worst-case tyre data must be used.

Using the variations as a guideline, a conservative range of cornering stiffness values relative to the baseline models were evaluated as per Table 6.51.

Table 6.50: Cornering stiffness variation

Tyre	**Load**	C_α **(N/°)**	C_c **(/°)**	**Min.** C_c **(/°)**[1]	**Max.** C_c **(/°)**[1, 2]	**Min.**[3]	**Max.**[3]
445/65	26879	2886	0.1074	0.1121	0.1861	104%	173%
315/80	26879	2775	0.1033	0.1121	0.1861	109%	180%
285/70	26879	3115	0.1159	0.1121	0.1861	97%	161%

[1] Including the effects of tyre wear (additional 0.04 to the cornering coefficient)
[2] Fancher et al. [14]
[3] Variation relative to the baseline cornering coefficient

Table 6.51: Parameter range - tyre cornering stiffness

Tyre	Baseline[1]	Min.	Max.
445/65 R22.5	100%	100%	173%
315/80 R22.5	100%	100%	180%
285/70 R19.5	100%	97%	161%

[1] The cornering stiffness is reported as a percentage of the baseline value

Scaling the baseline tyre data causes the coefficient of friction for the data to be skewed to unrealistic values and this results in the tyre lateral force saturating at unrealistically low slip angles. To prevent this, the baseline tyre models were converted to equivalent Pacejka '89 models [47]. The Pacejka '89 models were then scaled by manipulating the maximum cornering stiffness shape factor ($a3$) within the tyre cornering stiffness range in Table 6.51 to generate more realistically scaled tyre curves.

6.5.7 Dual Tyre Spacing

Minimum dual tyre spacing is quoted by tyre OEMs to ensure that the tyres do not touch during operation which would severely reduce the tyre life as well as become a fire risk.

Minimum dual tyre spacing for the 315/80 R22.5 and 285/70 R19.5 dual tyre assemblies were found in the OEM data books from Michelin, Goodyear and Bridgestone [36, 44, 43] and are reported in Table 6.52. In general the minimum spacings are similar, with a maximum difference of 4 mm between OEMs.

The dual spacing of the baseline vehicles was modelled on the Michelin data, which is consistently the minimum between all manufactures. Thus, assuming that a standard 5 mm plate can be used as a spacer between rims to account for various tyre models, the baseline dual tyre spacing was varied from the baseline value to a maximum of 5 mm additional spacing as per Table 6.53.

Table 6.52: Minimum dual tyre spacings

Tyres	Michelin	Goodyear	Bridgestone
315/80 R22.5	350	351	350.5
285/70 R19.5	314	318	317.5

Table 6.53: Parameter range - dual tyre spacing

Tyres	Baseline (mm)	Minimum (mm)	Maximum (mm)
315/80 R22.5	350	350	355
285/70 R19.5	314	314	319

7 Results

To quantify the influence of each VDP on the performance of a baseline combination for a particular PBS performance measure, the coefficient of variation (CV) metric was used. The CV facilitates the comparison of datasets where the units of measurement may differ [48] and is a measure of the spread of data about its mean.

Each VDP was systematically varied in isolation with 5 equally distributed data points ranging from the minimum to the maximum value as per the ranges developed in Section 6. For each VDP, the CV of each PBS performance measure was calculated as per Equation 7.1.

$$CV = \frac{\sigma}{\mu} \times 100\% \tag{7.1}$$

To compare the relative influence of each VDP on each PBS performance measure, the CV for each PBS performance measure was normalised with respect to the parameter with the highest CV (CV_{max}). Thus the CV matrix columns are normalised according to CV_{max} for that column and the normalised values are denoted as CV_n as per Equation 7.2.

$$CV_n = \frac{CV}{CV_{max}} \times 100\% \tag{7.2}$$

Where:

σ = standard deviation for a single performance measure evaluated for a single VDP

μ = mean performance for a single performance measure evaluated for a single VDP

CV = coefficient of variation for a single performance measure evaluated for a single VDP

CV_n = normalised coefficient of variation for a single performance measure evaluated for a single VDP

CV_{max} = maximum coefficient of variation observed for a single performance measure (each column in the CV matrix represents a single performance measure)

Any parameter that produced a CV_n of less than 10% (i.e. a CV less than 10% of the maximum coefficient of variation for the same performance measure) for a performance measure was regarded as having a negligible relative influence and was omitted from the overall CV matrices in Section 7.2. A set of complete CV matrices containing all evaluated VDPs are included in Sections B.1 to B.3. Additional matrices comparing the relative influence of the inertial, geometrical, suspension and tyre VDPs in isolation can be found in Appendices B.4 to B.7.

7.1 Interpretation of the CV Matrix

The columns of the CV matrices represent PBS performance measures and the rows represent VDPs. The numerical value in a cell represents the CV_n for the VDP described in that row with respect to the PBS performance described in that column.

In a single column, the influence of each VDP on a PBS performance measure is recorded relative to the VDP that had the maximum influence on the PBS performance measure according to Table 7.2. Each row indicates the relative influence of the described VDP on each of the PBS performance measures. An example of interpreting the CV matrices is provided in Figure 7.1.

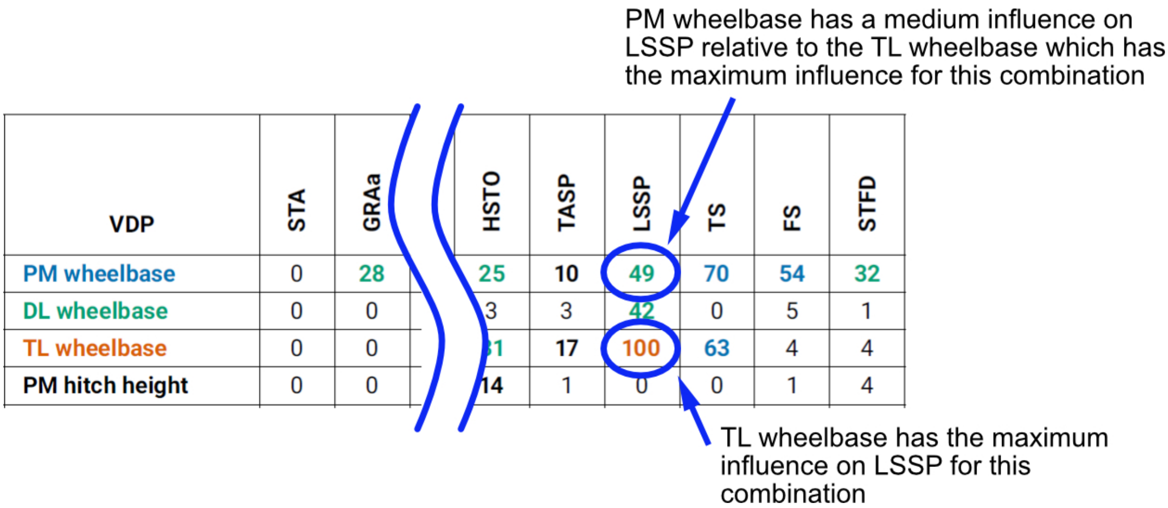


Figure 7.1: Interpretation of the CV matrix

To enhance the readability of the CV matrices, the conventions and abbreviations detailed in Tables 7.1 to 7.2 have been used throughout.

Table 7.1: CV matrix abbreviations

Abbreviation	Description
PM	Prime mover
TL	Trailer
St.	Steer axle
Dr.	Drive axle
Tl.	Trailer axle

Table 7.2: CV matrix conventions

Format	Description
VDP Parameter	VDP without a relative influence above 10% for any performance measure
VDP Parameter	**VDP with a relative influence $\geq$ 10% for at least 1 performance measure**
VDP Parameter	**VDP with a relative influence $\geq$ 25% for at least 1 performance measure**
VDP Parameter	**VDP with a relative influence $\geq$ 50% for at least 1 performance measure**
VDP Parameter	**VDP with a relative influence equal to 100% for at least 1 performance measure**
5	$0 \geq CV_n < 10$: VDP has a negligible relative influence on the performance measure
15	$10 \geq CV_n < 25$: **VDP has a low relative influence on the performance measure**
35	$25 \geq CV_n < 50$: **VDP has a medium relative influence on the performance measure**
65	$50 \geq CV_n < 100$: **VDP has a high relative influence on the performance measure**
100	$CV_n = 100(CV_{max})$: **VDP has the maximum relative influence on the performance measure**

7.2 Overall CV Matrices

The overall CV matrix for each of the baseline combinations is included in Tables 7.3 to 7.5. Only VDPs with a relative influence of at least 10% have been shown in these matrices to highlight the most influential parameters. A full CV matrix with all evaluated parameters is included for each of the combinations in Appendix B.

Table 7.3: Overall CV matrix - quad semi-trailer

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
PM wheelbase	0	63	0	0	3	40	14	62	4	31	4	63	16	19	100
TL wheelbase	100	100	0	0	18	70	100	80	8	100	44	9	5	1	2
PM axle spacing	0	0	0	0	1	0	2	0	0	1	0	2	0	0	14
TL axle spacing	0	0	0	0	1	1	0	12	0	9	3	5	4	2	8
PM hitch long. loc.	0	35	0	0	1	9	12	33	0	1	0	3	1	1	24
PM sprung mass	13	2	6	5	1	1	5	1	1	0	0	1	0	0	15
TL sprung mass	48	0	22	20	9	8	14	5	5	0	0	0	1	0	5
PM CG_x	0	10	0	0	0	0	5	3	0	0	0	0	0	0	7
TL CG_x	0	49	0	0	12	6	55	8	2	1	0	2	1	1	2
TL CG_y	0	0	0	0	14	1	0	0	11	0	3	0	4	2	0
TL CG_z	0	0	0	0	22	1	22	3	2	0	0	0	0	0	0
TL I_{yy}/I_{zz}	0	0	0	0	1	19	5	38	1	0	0	0	0	0	0
PM front overhang	0	0	0	0	0	0	0	0	3	17	0	88	3	11	0
TL front overhang	0	0	0	0	0	0	0	0	0	0	0	0	100	100	0
TL rear overhang	0	0	0	0	0	0	0	0	30	0	100	0	0	0	0
PM reference height	0	0	0	0	0	0	0	0	76	4	0	23	3	4	0
TL reference height	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
PM vehicle width	0	0	0	0	0	0	0	0	77	15	0	100	37	22	0
TL vehicle width	0	0	0	0	0	0	0	0	59	0	17	0	25	6	0
TL payload mass	56	7	100	100	48	100	82	20	21	2	2	3	4	3	22
TL payload CG_x	0	57	0	0	12	7	23	7	2	1	0	2	1	1	2
TL payload CG_y	0	0	0	0	44	4	26	0	33	0	8	1	11	6	0
TL payload CG_z	0	0	0	0	100	7	7	20	14	0	1	0	0	0	0
TL payload I_{yy}/I_{zz}	0	0	0	0	1	58	18	100	2	0	1	1	1	0	1
St. axle track	0	0	0	0	0	0	0	0	0	4	1	79	0	1	3
Tl. axle track	0	0	0	0	16	1	2	1	5	0	0	0	0	0	0
Dr. roll centre height	0	0	0	0	8	3	13	9	1	0	0	1	0	0	1
Dr. roll steer coef.	0	0	0	0	2	11	0	7	3	0	0	0	0	0	1
Tl. roll steer coef.	0	0	0	0	0	2	7	17	10	0	0	0	0	0	0
Dr. aux. roll stiffness	0	0	0	0	19	2	10	3	3	0	0	1	0	0	1
Tl. aux. roll stiffness	0	0	0	0	7	11	11	9	35	0	1	0	0	0	0
Dr. eff. rolling radius	15	0	1	3	0	0	0	0	0	0	0	0	0	0	0
Tl. tyre $L_{y,z}$	0	0	0	0	2	4	14	14	0	0	0	0	0	0	0
St. cornering stiffness	0	0	0	0	1	65	2	2	1	0	0	0	0	0	7
Dr. cornering stiffness	0	0	0	0	2	1	31	49	6	1	0	3	2	1	21
Tl. cornering stiffness	0	0	0	0	1	10	33	81	23	1	0	2	2	1	3

Table 7.4: Overall CV matrix - tridem interlink

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
PM wheelbase	0	43	0	0	3	16	20	62	5	43	21	62	24	4	100
TL 1 wheelbase	0	11	0	0	4	8	7	17	0	34	5	1	5	0	0
TL 2 wheelbase	0	8	0	0	11	100	19	100	40	100	42	4	8	0	4
PM axle spacing	0	0	0	0	0	1	0	0	0	1	0	2	1	0	13
TL 2 axle spacing	0	0	0	0	0	0	1	10	0	3	10	1	4	0	1
PM hitch long. loc.	0	21	0	0	1	12	6	25	1	1	1	3	0	0	25

Continued on next page

Table 7.4: Overall CV matrix - tridem interlink (cont.)

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
TL 1 hitch long. loc.	0	6	0	0	2	1	7	16	4	6	6	0	1	0	1
PM sprung mass	5	1	9	8	2	3	1	0	1	0	1	0	0	0	19
TL 1 sprung mass	6	5	12	10	2	1	0	4	2	0	0	0	0	0	1
TL 2 sprung mass	6	6	11	10	6	9	7	0	2	0	0	0	0	0	0
TL 1 CG_x	0	10	0	0	4	1	39	3	0	0	0	1	1	0	1
PM CG_y	0	0	0	0	7	3	6	2	4	1	10	1	2	0	1
TL 1 CG_y	0	0	0	0	11	1	7	1	3	1	6	0	2	0	0
TL 2 CG_y	0	0	0	0	17	0	8	2	5	0	9	0	0	0	0
TL 1 CG_z	0	0	0	0	11	0	3	2	0	0	0	0	0	0	0
TL 2 CG_z	0	0	0	0	19	1	10	2	1	0	0	0	0	0	0
PM I_{xx}	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0
TL 2 I_{yy}/I_{zz}	0	0	0	0	0	14	7	15	0	0	0	0	0	0	0
PM front overhang	0	0	0	0	0	0	0	0	2	25	0	89	6	1	0
TL 1 front overhang	0	0	0	0	0	0	0	0	0	0	0	0	100	100	0
TL 2 rear overhang	0	0	0	0	0	0	0	0	17	0	54	0	0	0	0
PM reference height	0	0	0	0	0	0	0	0	59	6	0	24	4	0	0
TL 1 reference height	0	0	0	0	0	0	0	0	95	0	0	0	3	0	0
TL 2 reference height	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
PM vehicle width	0	0	0	0	0	0	0	0	59	22	0	100	50	4	0
TL 1 vehicle width	0	0	0	0	0	0	0	0	0	0	0	0	38	3	0
TL 2 vehicle width	0	0	0	0	0	0	0	0	45	0	100	0	0	0	0
TL 1 payload mass	100	100	100	100	100	40	47	36	15	11	2	4	5	1	20
TL 2 payload mass	67	59	100	100	13	27	6	25	20	6	2	1	1	0	1
TL 1 payload CG_x	0	18	0	0	9	0	12	6	1	0	0	1	1	0	1
TL 2 payload CG_x	0	3	0	0	11	11	13	9	0	1	0	1	2	0	1
TL 1 payload CG_y	0	0	0	0	75	1	8	4	16	4	26	1	9	1	0
TL 2 payload CG_y	0	0	0	0	94	0	24	12	29	2	28	0	2	1	0
TL 1 payload CG_z	0	0	0	0	75	7	13	9	2	0	1	0	0	0	0
TL 2 payload CG_z	0	0	0	0	95	6	9	15	9	0	1	0	0	0	0
TL 1 payload I_{xx}	0	0	0	0	1	0	14	0	0	0	0	0	0	0	0
TL 2 payload I_{xx}	0	0	0	0	1	1	14	2	1	0	0	0	0	0	0
TL 1 payload I_{yy}/I_{zz}	0	0	0	0	0	8	8	22	1	0	1	0	0	0	0
TL 2 payload I_{yy}/I_{zz}	0	0	0	0	1	43	17	49	1	0	1	0	0	0	0
Tl. unsprung mass	5	4	8	7	16	1	1	2	1	0	0	0	0	0	0
St. axle track	0	0	0	0	0	0	0	0	0	5	17	79	0	0	3
Tl. axle track	0	0	0	0	44	1	4	4	4	0	0	0	0	0	0
Dr. roll centre height	0	0	0	0	12	0	2	6	1	1	0	1	1	0	36
Tl. roll steer coef.	0	0	0	0	0	4	1	21	18	0	0	0	0	0	0
Dr. spin inertia	0	0	0	0	0	0	0	0	0	1	0	1	1	0	22
Dr. aux. roll stiffness	0	0	0	0	25	2	8	1	2	0	1	1	0	0	1
Tl. aux. roll stiffness	0	0	0	0	47	17	100	14	99	0	9	0	1	0	0
Tl. tyre $L_{y,z}$	0	0	0	0	2	7	11	21	2	0	2	0	1	0	0
St. cornering stiffness	0	0	0	0	0	19	3	1	2	0	0	0	0	0	6
Dr. cornering stiffness	0	0	0	0	0	5	6	32	3	2	0	3	2	0	19
Tl. cornering stiffness	0	0	0	0	1	13	6	94	22	1	3	2	3	0	3
Tl. spring rate	0	0	0	0	13	6	22	2	3	0	0	0	0	0	0

Table 7.5: Overall CV matrix - rigid drawbar combination

VDP	STA	GRAa	GRAb	ACC	SRTt	SRTtrcu	YDC	RA	HSTO	TASP	LSSP	TS	FS	STFD
PM wheelbase	0	28	0	0	8	0	43	21	25	10	49	70	54	32
DL wheelbase	0	0	0	0	1	0	2	4	3	3	42	0	5	1
TL wheelbase	0	0	0	0	17	12	44	55	31	17	100	63	4	4
PM hitch height	0	0	0	0	1	0	2	14	14	1	0	0	1	4
PM hitch long. loc.	0	0	0	0	0	0	3	15	19	3	11	4	0	3
DL hitch long. loc.	0	0	0	0	3	2	18	6	4	2	3	1	1	4
PM sprung mass	3	1	6	4	0	0	3	1	1	0	1	1	1	18
PM CG_y	0	0	0	0	14	0	3	0	2	2	1	7	2	6
PM front overhang	0	0	0	0	0	0	0	0	0	1	18	0	100	0
PM rear overhang	0	0	0	0	0	0	0	0	0	0	0	91	0	0
TL rear overhang	0	0	0	0	0	0	0	0	0	11	0	100	0	0
PM reference height	0	0	0	0	0	0	0	0	0	63	4	9	23	0
TL reference height	0	0	0	0	0	0	0	0	0	66	0	0	0	0
PM vehicle width	0	0	0	0	0	0	0	0	0	50	13	49	85	0
TL vehicle width	0	0	0	0	0	0	0	0	0	28	0	0	0	0
PM payload mass	100	100	45	40	0	0	19	17	9	8	16	4	17	31
TL payload mass	67	36	100	100	18	79	100	100	65	14	7	0	5	5
PM payload CG_x	0	12	0	0	3	0	7	3	1	3	3	1	2	22
TL payload CG_x	0	0	0	0	18	9	4	2	4	1	1	0	2	2
PM payload CG_y	0	0	0	0	50	0	4	1	4	4	1	14	4	10
TL payload CG_y	0	0	0	0	85	40	2	5	9	30	2	39	0	0
PM payload CG_z	0	0	0	0	43	0	6	46	26	7	0	1	1	1
TL payload CG_z	0	0	0	0	82	100	32	23	30	16	0	0	0	0
PM payload I_{xx}	0	0	0	0	0	0	21	34	38	15	0	0	0	0
TL payload I_{yy}/I_{zz}	0	0	0	0	1	0	13	8	19	3	0	0	0	0
Tl. unsprung mass	3	3	5	4	10	5	0	1	1	0	0	0	0	1
St. axle track	0	0	0	0	0	0	0	0	0	0	4	0	70	35
Tl. axle track	0	0	0	0	36	17	2	2	3	5	0	0	0	0
Dr. roll centre height	0	0	0	0	4	0	5	11	7	0	1	1	1	1
St. roll steer coef.	0	0	0	0	0	0	10	0	0	0	0	0	0	2
Dr. roll steer coef.	0	0	0	0	0	0	25	8	21	12	0	2	1	1
Tl. roll steer coef.	0	0	0	0	0	1	3	0	15	6	0	0	0	0
Tl. spin inertia	0	0	0	0	5	13	0	0	0	0	0	0	0	0
St. aux. roll stiffness	0	0	0	0	8	0	1	11	11	3	0	0	0	1
Dr. aux. roll stiffness	0	0	0	0	77	0	46	68	100	8	0	1	2	4
Tl. aux. roll stiffness	0	0	0	0	100	46	28	70	22	100	1	0	0	0
Tl. damper	0	0	0	0	1	0	1	11	1	0	0	0	0	0
St. cornering stiffness	0	0	0	0	0	0	96	1	0	1	2	1	0	100
Dr. cornering stiffness	0	0	0	0	1	0	4	19	30	5	2	1	2	9
Tl. cornering stiffness	0	0	0	0	0	0	8	5	34	9	3	0	3	0
Tl. spring rate	0	0	0	0	13	6	4	1	5	4	0	0	0	0

8 Discussion

The overall CV matrices (see Tables 7.3 to 7.5) provide useful guidance and insight into which VDPs are the most influential in terms of each of the PBS performance measures. If a proposed design of a vehicle combination fails a PBS assessment, then the columns for the failed PBS measures in Tables 7.3 to 7.5 illustrate the VDPs which will have the most significant effect in correcting the vehicle performance. Furthermore, when sourcing input data for an assessment, the tables highlight the important VDPs which need to be accurately determined i.e. PBS assessments should ensure that VDPs which significantly affect the PBS assessment are accurate and those that don't affect the PBS assessment can justifiably use generic approximate data.

Experience has shown that once a vehicle design has been submitted for a PBS assessment, there is often little scope to redesign the entire combination since it is either already built or orders for some parts have already been placed. To aid in these situations, separate CV matrices were developed for the inertial, geometric, suspension and tyre parameters in isolation with the intention of providing insight into VDP influence within each of these categories independent of all other VDPs. These matrices can be found in Sections B.4 to B.7 in Appendix B. These additional matrices are useful in interpreting the overall CV matrix. Differences in the relative effect of certain VDPs between combinations may be due to other VDPs influencing the combination to a greater or lesser extent.

In the sections that follow, insights into the relative influence of heavy vehicle VDPs gained from the CV matrices are discussed for the most influential VDPs. The VDPs with a negligible relative influence for all combinations are then listed for quick reference of which VDPs could be safely estimated. Finally, limitations of the methodology used in this study are discussed.

8.1 Relative Influence of Heavy Vehicle Design Parameters

Considering the overall CV matrices (see Tables 7.3 to 7.5), the majority of the inertial and geometrical VDPs have a significant relative influence on each of the baseline vehicles. With the exception of the moment of inertia, these parameters can easily be determined from a detailed GA drawing of a vehicle combination.

A larger proportion of suspension and tyre VDPs have a negligible relative influence on vehicle performance relative to the inertial and geometrical VDPs. This is important since suspension and tyre details are often difficult to acquire from OEMs. VDPs with negligible relative influence can be conservatively estimated and represent vehicle performance as discussed further in Section 8.2.

8.1.1 Geometrical and Inertial VDPs

The **wheelbase** has a significant relative influence on high-speed and low-speed standards for all baseline combinations. It has a high to negligible relative influence on the longitudinal standards depending on the baseline vehicle.

The prime mover wheelbase has a medium to high relative influence on GRAa, HSTO, LSSP, FS and STFD for all baseline vehicles. It has a high influence on the TS for the rigid drawbar baseline since the critical reference point for TS in its baseline configuration is the rear of the rigid truck superstructure whereas for the other baselines the critical point is at the rear of the rearmost trailer.

The trailer wheelbase (predominantly the follower trailer for the tridem interlink) has the maximum influence on LSSP for all combinations and has a medium to high influence on TS. It has a medium to high influence on the high-speed standards YDC, RA and HSTO with the exception of it having a low influence on RA for the tridem interlink combination.

The rigid drawbar combination dolly wheelbase has a medium influence on the LSSP with negligible influence on all other performance measures.

The **moment of inertia** has a relatively low influence with the exception of the trailer payload pitch and yaw moment of inertia (I_{yy}/I_{zz}) which has a medium to high influence on the HSTO and YDC performance of the quad semi-trailer and tridem interlink (predominantly for the follower trailer) combinations.

The pitch and yaw moment of inertia (I_{yy}/I_{zz}) has a low influence on the rigid combination and instead the prime mover payload roll inertia (I_{xx}) has a medium influence on HSTO and RA. This highlights that the sensitivity of a combination to the inertial properties is dependent on the mechanics of the articulation points. The results suggest that a combination with roll-coupled articulation points will be affected to a higher degree by a change in pitch and yaw inertia compared to a unit with non roll-coupled articulation points.

The moment of inertia VDPs were varied within a large range since they are rarely supplied for PBS assessments, vary significantly for different payloads and vehicle configurations, and often need to be estimated using simplified geometries. For a specific commodity and vehicle configuration, these estimations of moments of inertia would differ from the actual inertias by far less than the variation considered in this study. The relatively low influence of the majority of the moments of inertia VDPs and the large ranges used for the moments of inertia in this study suggest that using simplified geometries to estimate the moments of inertia is an appropriate approach.

The **reference point height** has a high influence on the TASP of the baseline combinations. The TASP manoeuvre involves the combination travelling along a straight path along an uneven surface with an average cross fall of not less than 3% with the average crossfall standard deviation exceeding 1% [5]. The TASP performance is measured as the 99th percentile of the swept width between the path of the outer most left and outermost right reference points. The crossfall along with disturbances along the travelled path result in the vehicle rolling and offtracking in the direction of the crossfall during the manoeuvre. The roll motion of vehicle units causes the path scribed in the ground to be projected further in the direction of the roll motion.

A differential height between the outermost reference points either increases or decreases the measured TASP as shown in Figure 8.1. A worst case TASP is measured when the outermost left reference point (point 2 in Figure 8.1) is low to the ground with the outermost right reference point (point 3 in Figure 8.1) located at the top of the vehicle structure. The high relative influence of the reference point height on the measured TASP highlights a potential for discrepancies in measured TASP performance between various assessors depending on the height selected for each reference point. For example, one may ignore a buckle located at the top of a vehicle structure since it is ancillary equipment while another may consider it, resulting in a higher reference point height and higher measured TASP.

According to the NTC rules, if multiple points exist at the outermost points, the lowest of that should be chosen. With this definition, if the trailer structure of a combination such as a side tipper was uniform in width rather than having the widest point at the top of the bin, the measured TASP performance would be improved even though physically it takes up the same amount of road width. It is suggested that a standard height be determined for reference points to avoid discrepancies in the measurement of the TASP performance. In practice this may be difficult for real world tests since a mounting point may not be available, however it is trivial to set a reference point height in a simulation package.

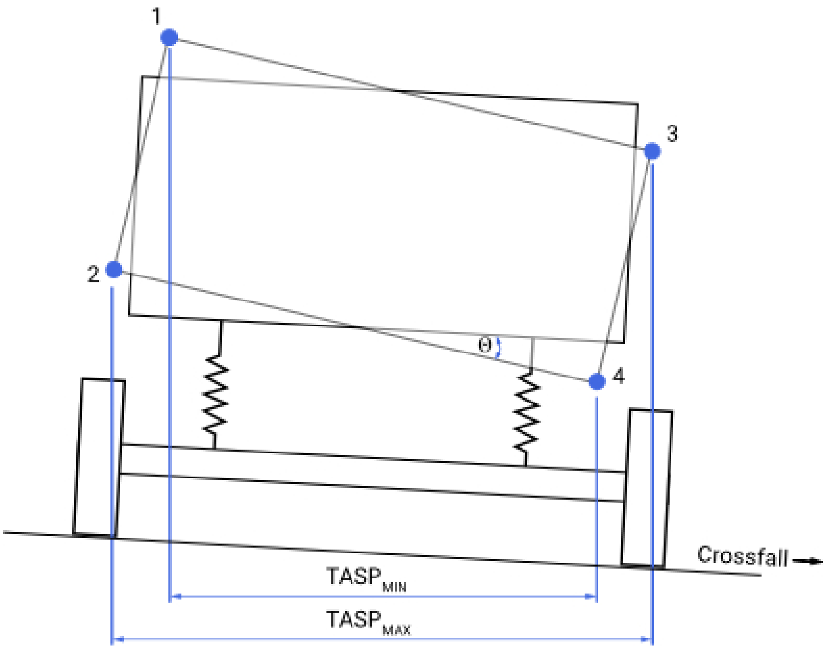


Figure 8.1: Influence of the reference point height on TASP performance

The **longitudinal standards** consisting of the STA, GRAa, GRAb and ACC performance measures are highly influenced by the payload mass for the tridem interlink and rigid drawbar combination. For the quad semi-trailer, the trailer wheelbase is the most important variable for STA and GRAa.

When a heavy vehicle has a sufficiently powered engine, such as in the case of the three baseline combinations, the STA and GRAa are dependent on the traction force available at the drive tyres which is a function of the drive axle load when the coefficient of friction is kept constant (the NTC rules state a coefficient of friction of 0.8 should be used for the test road surfaces [5]). Thus, the VDP that has the most relative influence on the vehicle performance would be the one that provides the largest variation on the drive axle load.

The range within which the quad semi-trailer wheelbase was varied led to the wheelbase approaching the combined trailer and payload sprung mass centre of gravity location. At this point, most of the combined sprung mass was supported by the trailer axle group with little load transfer to the prime mover through the 5th wheel hitch. As discussed in Section 6.1.5 the legal axle load limits were not considered in determining the range of viable wheelbases as this would limit the allowable wheelbase range for the baseline vehicles and insight would be lost into the effect of changing the wheelbase for combinations that are volume rather than payload limited. For vehicle combinations that are payload limited, the wheelbase will have a smaller range of variation when considering legal axle load limits resulting in a reduced influence.

The ACC and GRAa tests are performed on a road with a 0° to 1° grade respectively and as a result there is always sufficient traction at the drive axle tyres. The ACC and GRAa performance is therefore limited by the engine power and gross combination mass. The VDP providing the most variation in Gross Combination Mass (GCM) becomes the most influential and for all combinations this is the trailer payload. The tridem interlink is equally affected by both trailer payloads since they are identical in mass and were varied within the same range.

The study considered the payload to go from the unladen condition to the maximum laden condition since it is realistic for a combination to operate within that range. In practice, a combination would be optimised for a maximum payload and the payload would have a small envelope of variation. In this case, adjustments to the prime mover engine (which was beyond the scope of this study) and/or geometrical properties which result in a change in drive axle load would provide a larger relative influence.

The **longitudinal CG location (**CG_x**)** of the payload has a larger relative influence than those of the prime mover and trailer chassis. The prime mover and trailer chassis CG_x locations were varied within a larger range (20% and 30% respectively) relative to the payload (between 9% and 13% depending on baseline combination). However, since the mass of the payload is significantly higher than the chassis in all cases, a change in the payload CG_x has a higher influence.

The **lateral CG location (**CG_y**)** of the payloads (the prime mover and trailer chassis to a much lesser extent) have a medium to high relative influence on the high-speed performance of the combinations, in particular the SRT and the Static Rollover Threshold Rearward Roll-coupled Unit (SRT_{rrcu}). Therefore it is important to ensure that the CG_y location is accurately modelled (for payloads in particular) and emphasises that a shift in payload due to poor strapping will have a significant effect on the rollover stability of a vehicle combination. A shift in the CG_y location in the same direction as the roll motion of the sprung mass will amplify the roll. The additional roll motion will cause the rear reference points to be projected further outward affecting the TASP (as discussed above) as well as the TS performance of the vehicle.

The **vertical CG location (**CG_z**)** of the payload has a high influence on the SRT and the SRT_{rrcu} performance for all combinations. This is explained by the simple first-order estimate of SRT from Gillespie [49] shown in Equation 8.1 which ignores the effects of deflection in the suspension. The CG_z has a direct and higher impact on the first-order estimate of SRT than axle track which is confirmed in the CV matrices as the axle track (discussed below) has only a medium influence on SRT performance.

$$SRT = \frac{t}{2h} \tag{8.1}$$

Where

t = Vehicle track width (mm)

h = Vertical centre of gravity of the total vehicle mass (mm)

8.1.2 Suspension and Tyre VDPs

The **suspension and tyre VDPs** have a low to negligible influence on the low-speed standards except for the steer axle track which has a relatively high impact on the FS performance. The FS performance of a combination is measured as the swing out of the front of the cab relative to the steer axle path inscribed on the ground at the outer edge of the steer tyre around a 90° turn [5]. Considering that the cab dimensions remain constant, a wider steer axle track reduces the FS and a narrower track width increases the FS of the combination. Within the range of evaluated steer axle track widths, the axle track has a high influence on the FS performance for all combinations.

The **trailer axle track** for the tridem interlink and rigid combination have a medium influence on the SRT performance while it has a low influence on the SRT performance of the quad semi-trailer. The minimum axle track for the trailer axle with 445/65 R22.5 single tyres is close to the maximum for the other baseline combinations. The roll stiffness of the quad semi-trailer is therefore still high even at the minimum axle track and therefore other parameters have a larger effect on the SRT performance of the vehicle, diminishing the relative effect of the trailer axle track for this combination.

The **drive axle auxiliary roll stiffness** has a larger relative influence on the performance of the rigid drawbar combination. The rigid drawbar combination has a pintle hitch which is a non roll-coupled hitch. Thus, roll effects are not transferred between the trailer and rigid unit. The rigid prime mover acts as a single unit and the dolly along with the trailer act as the rearward roll coupled unit which are connected with a roll-coupled hitch (5th wheel) allowing transfer of roll moments between the dolly and trailer. Decreasing the auxiliary roll stiffness on the rigid prime mover degrades the overall roll stiffness of the prime mover to a larger degree than the other combinations since it is not assisted by the roll stiffness of the trailers. The amplified roll experienced by the rigid prime mover results in degraded high-speed performance. This suggests that compared to a combination with roll-coupled hitch points, a combination with non roll-coupled hitch points will be affected by a greater degree when the auxiliary roll stiffness is adjusted on a single vehicle unit.

The **trailer axle auxiliary roll stiffness** has a medium relative influence on TASP and low to negligible influence on all other performance measures for the quad semi-trailer. In the case of the tridem interlink and rigid combination, trailer axle auxiliary roll stiffness has a medium to high influence on SRT, YDC, RA and HSTO and the maximum effect on TASP.

The greater influence of trailer axle auxiliary roll stiffness on the RA of the tridem interlink (maximum influence) and rigid drawbar combination (high influence) relative to the quad semi-trailer (negligible influence) can be explained when considering the overall roll stiffness. The wider axle track and increased number of axles on the trailer unit of the quad semi-trailer results in the combination having a high overall roll stiffness even with a low auxiliary roll stiffness. The tridem interlink has the narrowest axle track which exacerbates the effect of decreasing the trailer auxiliary roll stiffness and results in the trailer axle auxiliary roll stiffness having the maximum influence on RA for this combination.

The baseline vehicles have reference points at the top of the trailer structure which assumes that the outermost point on the right of the vehicle is at the top of the trailer structure. This is typical of tautliners with buckles and side-tippers with the widest point at the top of the bin. The outermost left reference point is located near to the ground on the bumper of the prime mover. If the rear reference points were lower to the ground (at the base of the trailer deck for example), the height differential between the left and right outer reference points would be decreased. This would decrease how far outwards the reference points are extended from each other for a given amount of roll (see Figure 8.1) and the influence of auxiliary roll stiffness (affecting the amount of roll the vehicle experiences) on the TASP performance would hence be reduced.

The only **tyre VDP** that has a significant effect on overall vehicle performance is the cornering stiffness which has a medium to high influence on the HSTO performance for all the baseline combinations. The cornering stiffness has higher relative effect on the quad semi-trailer and tridem interlink.

The range by which the **trailer tyre cornering stiffness** was varied matches the relative influence for each tyre with the 315/80 R22.5 tyres (tridem interlink) having an 80% variation, the 445/65 R22.5 tyres (quad semi-trailer) having a 73% variation and the 285/70 R19.5 tyres (rigid drawbar combination) having a 64% variation. Taking this into consideration, the trailer lateral tyre force still has a relatively lower influence on HSTO for the rigid combination. Considering the isolated tyre CV matrices in Section B.7 in Appendix B, the trailer lateral tyre force has the maximum influence on HSTO for all combinations. This highlights that the lower influence is due to the HSTO being affected by the drive auxiliary roll stiffness to a much higher degree, diminishing the relative influence of the trailer lateral tyre force in relation to the complete set of vehicle VDPs.

The **steer tyre cornering stiffness** has a high relative influence on the YDC performance of the tridem interlink and quad semi-trailer combinations. A change in tyre cornering stiffness directly affects the magnitude of the input disturbance for a given pulse steer input.

The steer tyre cornering stiffness has the maximum relative influence on the STFD performance of the rigid combination while it has a negligible effect on the other baseline combinations where the prime mover wheelbase has the maximum influence. The wheelbase for the rigid prime mover were significantly longer than that of the tractor prime mover, resulting in less of an influence on the steer axle load. The NTC rules document [5] does indicate that STFD is typically only an issue for road trains with a tri-axle drive arrangement with a wide axle spread and is therefore not of concern for the baseline combinations considered in this study.

Tyre manufacturers do not make the lateral tyre force curves (from which tyre cornering stiffness is measured) for their tyres readily available and as a result, conservative lateral tyre curves are used for PBS assessments in South Africa. This is in alignment with the NTC rules requirement that if generic tyres are used in the analysis, the cornering characteristics must be consistent with worst-case performing tyres of the same size to ensure that any tyre of the same size can be used [5]. The tyre data used is from UMTRI [41, 46] measurements in the early 1980s and 1990s. Using these conservative tyre curves negates any performance benefits that modern HCVs tyres have due to advances made in their material and construction. Testing of newer tyre models to produce accurate lateral tyre curves would be of benefit to the transport industry as more productive combinations could achieve the required performance within the PBS framework when tested with actual tyre curves.

The **trailer tyre lag** had a negligible influence on the rigid drawbar combination and low influence on RA and HSTO for the quad semi-trailer. It has a higher but still low influence on the HSTO performance of the tridem interlink combination. Previous PBS assessments conducted by Wits have shown that longer HCVs achieve poor HSTO performance. This suggests that while the influence of tyre lag is relatively lower than tyre cornering stiffness, it is still important to include the effects of tyre lag (especially in the case of trailer axles) when evaluating the performance of longer HCVs or those which achieve PBS performance close to the limit of a PBS performance level.

8.2 VDPs with Negligible Influence on Overall Vehicle Performance

The complete CV matrices (see Tables B.1 to B.3 in Appendix B) contain all evaluated VDPs and provide insight into which VDPs have negligible influence on vehicle performance within the PBS framework. A VDP with a negligible relative influence on all of the baseline combinations analysed in this study would likely have negligible relative influence on all HCVs.

Inspecting the complete CV matrices in Appendix B, the VDPs listed below are seen to have a negligible effect on overall vehicle performance for all baseline combinations. With discretion, these VDPs could be conservatively estimated without significantly influencing the vehicle performance, providing a realistic prediction of vehicle performance without the need to acquire exact data from OEMs.

Inertial VDPs:

1. Prime mover and dolly sprung mass CG_z
2. Prime mover, trailer and dolly I_{xx}

Geometrical VDPs:

The geometrical reference points directly affect the low-speed and TASP performance measures. In some vehicle configurations, the reference points of certain vehicle units have no influence on the low-speed performance measures. These cases are listed below in the context of the baseline configurations.

1. Tridem interlink follower trailer front overhang
2. Tridem interlink leader trailer rear overhang
3. Rigid combination trailer front overhang

Suspension VDPs:

1. Steer and drive axle unsprung mass
2. Drive axle track width
3. Axle centre height
4. Steer and trailer roll centre height
5. Axle roll and yaw inertia
6. Axle wheel centre height
7. Axle damper response
8. Axle damper track width
9. Axle jounce and rebound stops

10. Axle spring response [i]
11. Axle spring track width

Tyre VDPs:

1. Dual tyre spacing
2. Steer and trailer effective rolling radius
3. Drive tyre lag
4. Steer and drive tyre vertical spring rate
5. Unloaded radius
6. Wheel spin inertia

8.3 Comparison with Similar Research

The parametric study completed by Fancher et al. [14] detailed in Section 2.3.2 was most similar in granularity with regards to the selection of the mechanical properties and the evaluation of the effect of these properties on vehicle performance.

The study was focused on braking and steering of the heavy trucks. Since braking is not currently a part of the PBS framework in South Africa as it is addressed by legislative requirements, these results could not be compared. The results for Low-speed tracking are compared to LSSP, Hi-speed tracking to HSTO, roll stability to SRT and rearward amplification to RA in tables 8.1 to 8.4.

The comparison tables include the pertinent mechanical property, and then for each performance measure the results are compared in the following format:

Fancher et al. Result (Quad Semi-trailer, Tridem Interlink, Rigid Drawbar Combination). A neglible result is denoted with "-".

The definition of Low, Medium, High is not explicit in Fancher et al.'s study, however for purposes of comparison they are assumed to have a similar definition to that which is defined in Table 7.2.

This dissertation looked at suspension and mass properties at a more granular level than Fancher et al.'s study (such as each axle type rather than all axles, and sprung mass at a

[i] The drive and trailer suspensions are all fitted with airbag springs. The auxiliary roll stiffness of air suspensions is a result of the rigid axle and trailing arm assemblies which work as a stabiliser bar. Steel suspension has auxiliary roll stiffness because of the twisting of the spring leaves as well as a stabiliser bar if present [39]. The spring response would have a larger effect on vehicle performance if a steel suspension is used as it would influence the overall roll stiffness to a greater degree.

chassis and payload level separately). In these cases, the VDP that had the highest influence is documented in the comparison.

The results of this study compare well with Fancher et al.'s results with a few exceptions in geometric layout and mass distribution.

These differences could be due to differences in HCV configuration with Fancher et al.'s study focusing on American HCV's in 1986 while this dissertation evaluated modern HVC's based on existing designs in South Africa. Fancher's paper focuses on a mathematical evaluation of the properties influence on heavy vehicle performance and and does not provide insight into how the parameter's influence changes in different vehicle configurations. This dissertation considers the ranges as developed in Section 4.2 on 3 different vehicle configurations and the results show that the vehicle configuration has a significant effect on the relative influence of the VDPs.

Table 8.1: Comparison of the effect of tyre properties on vehicle dynamic performance [14]

Pertinent Mechanical Property	Low-speed tracking	Hi-speed tracking	Roll stability	Rearward amplification
Cornering coefficient C_{alpha}/F_z	- (-, -, -)	Hi (Hi, Hi, Med)	- (-, -, -)	Hi (Med, -, Low)
Vertical stiffness	- (-, -, -)	- (-, -, -)	Med (-, Low, Low)	- (-, Low, -)

Table 8.2: Comparison of the effect of suspension properties on vehicle dynamic performance [14]

Pertinent Mechanical Property	Low-speed tracking	Hi-speed tracking	Roll stability	Rearward amplification
Vertical stiffness	- (-, -, -)	- (-, -, -)	- (-, -, -)	- (-, -, -)
Roll stiffness	- (-, -, -)	Med (-, Low, Hi)	Hi (Low, Med, Hi)	Hi (Low, Hi, Hi)
Roll centre height	- (-, -, -)	Med (-, -, -)	Hi (-, Low, -)	Hi (Low, -, Low)
Damping	- (-, -, -)	- (-, -, -)	- (-, -, -)	Med (-, -, Low)
Roll steer	- (-, -, -)	Low (Low, Low, Low)	- (-, -, -)	Low (-, -, -)

Table 8.3: Comparison of the effect of geometric layout properties on vehicle dynamic performance [14]

Pertinent Mechanical Property	Low-speed tracking	Hi-speed tracking	Roll stability	Rearward amplification
Wheelbase - truck/tractor	Med (Med, Med, Med)	Low (Hi, Hi, Med)	- (-, -, -)	- (Low, Low, Low)
Wheelbase - trailer	Hi (Hi, Hi, Hi)	Hi (Hi, Hi, Med)	- (Low, Low, Low)	Hi (Hi, Low, Hi)
Wheelbase - dolly	Med (-, Med, -)	Med (-, -, -)	- (-, -, -)	Med (-, -, -)
Track width	- (-, -, -)	- (-, -, -)	Hi (Low, Med, Med)	- (-, -, -)
Fifth wheel offset - tractors	Low (-, -, Low)	- (Med, Med, Low)	Low (-, -, -)	- (Low, -, Low)
Pintle overhang - trucks & trailers	Low	Low	-	Hi
Fifth wheel height - tractor	- (-, -, -)	- (-, -, Low)	Low (-, -, -)	- (-, -, Low)

Table 8.4: Comparison of the effect of mass distribution properties on vehicle dynamic performance [14]

Pertinent Mechanical Property	Low-speed tracking	Hi-speed tracking	Roll stability	Rearward amplification
Weight	- (-, Low, Low)	Hi (Low, Med, Hi)	Hi (Med, Hi, Hi)	Hi (Hi, Med, Hi)
CG height	- (-, -, -)	- (Low, Low, Med)	Hi (Hi, Hi, Hi)	Hi (Low, Low, Med)
Fore-aft CG location	- (-, -, -)	Hi (-, -, -)	Med (Low, Low, Low)	Hi (Hi, Med, -)
Yaw moment of inertia	- (-, -, -)	- (Hi, Hi, Low)	- (-, -, -)	Med (Low, Low, -)
Pitch moment of inertia	- (-, -, -)	- (Hi, Hi, Low)	- (-, -, -)	- (Low, Low, -)
Sprung roll moment of inertia	- (-, -, -)	- (-, -, Med)	Med (-, -, -)	Low (-, Low, Med)
Fifth wheel height - tractor	- (-, -, -)	- (-, -, Low)	Low (-, -, -)	- (-, -, Low)

8.4 Limitations of the Methodology

8.4.1 Simulated Manoeuvre Control Parameters

The control parameters for all of the manoeuvres were kept constant in this study. The lane change manoeuvre (evaluating RA and HSTO) and pulse steer test (evaluating YDC) both have control parameters that need to be adjusted to ensure that the vehicle is performing the PBS manoeuvre within the required limits.

The lane change manoeuvre control parameter is the driver preview time. The driver model looks ahead at the target path by a distance determined by the current speed of the vehicle and the driver preview time, and adjusts the angle of the steering wheel to minimise the tracking error between the actual and target path over the preview time [50]. A shorter preview time improves the vehicle tracking, but could lead to the vehicle becoming unstable while a longer preview time improves vehicle stability but results in a higher tracking error. For the ISO lane change manoeuvre, the vehicle is required to have a tracking error of no greater than 30 mm according to the NTC rules [5].

The control parameter for the pulse steer manoeuvre is the steering input gain. The steering input for the TruckSim manoeuvre is normalised to unity, the steering input gain then needs to be set such that the lateral acceleration of the lead unit reaches approximately 0.2 g (a value of between 0.19 g and 0.21 g is deemed reasonable to ensure fair assessment of vehicle performance) [51]. If the gain is set too high, the manoeuvre performed will be too harsh and result in poor YDC performance which could lead to failing a safe combination. Conversely if it is set too low, the YDC performance will be unfairly improved and could result in the passing of an unsafe combination.

In this study the RA and the HSTO are influenced by the lack of controls to ensure the lateral tracking error is below 30 mm and the YDC is influenced by not keeping the lateral acceleration of the steer axle and lead vehicle unit at 0.2 g.

8.4.2 Selection of VDP Ranges

The coefficient of variation is sensitive to the range of values evaluated (see Section 6) for each VDP as well as the design of the baseline vehicle which limits the results from being universally true. A range within which each VDP could be varied was determined in Section 6. These ranges are sensitive to the baseline designs and need to be considered when interpreting the CV matrix.

Some of the VDP ranges were developed by considering studies conducted in the USA, Canada, and Australia. The relative influence of the VDPs is influenced by these ranges, and as a result determining the actual variation in these parameters for the South African fleet would improve the applicability of the study to South Africa as well as eliminate any bias due to conservative ranges where a lack of data was available.

The baseline vehicles were designed to be at or near the legal axle load limits. This left little scope for adjusting the wheelbase, mass of any vehicle units or payloads and CG location of any of the mass VDPs without causing an axle group to exceed the legal limit. If the legal axle load limits were considered, then valuable insight would have been lost into the effect of changing these parameters in volume limited payloads. Thus, some of the vehicle configurations with altered wheelbase, mass, or CG locations of any of the masses are not legal vehicles.

Every effort has been made to consider a reasonable range for each vehicle design parameter to avoid biasing the influence of the VDPs. Percentage differences from the baseline have been provided should the reader wish to evaluate the affect of changing a VDP by a larger or lesser degree.

9 Conclusions

1. This study evaluated the relative effect of Vehicle Design Parameters (VDPs) on three of the most common High-capacity Vehicles (HCVs), a quad semi-trailer, tridem interlink and rigid drawbar combination. To prevent the relative influence of any VDP being over or underestimated, a range within which each VDP could be varied was determined by considering Original Equipment Manufacturer (OEM) data, legal restrictions, physical constraints and South African Performance-based Standards (PBS) assessment data. Evaluating the influence of each VDP within these ranges adds insight into the limitations imposed by restrictions on the variation of a VDP. This work expands on previous research conducted by Prem et al. [13] where the influence of a significantly smaller sample space of VDPs on HCV performance was evaluated by varying each VDP by a consistent +/- 20%.

2. The influence of a VDP on vehicle performance for each PBS performance measure was quantified with the Coefficient of Variation (CV) metric. A comparative matrix (denoted as the CV matrix) was developed for each baseline vehicle which compares the relative influence of each VDP in terms of each of the PBS performance measures.

3. The overall CV matrices (see Tables 7.3 to 7.5) provide insight into which VDPs are the most influential in terms of each of the PBS performance measures. If a proposed vehicle design fails a PBS assessment, the columns for each of the failed PBS performance measures can be consulted to determine which VDPs will yield the most improved performance for that PBS performance measure.
    (a) The complete CV matrices (see Tables B.1 to B.3) highlight the VDPs that have a negligible relative influence for all PBS performance measures for all baseline combinations. A much larger proportion of suspension and tyre VDPs were found to have a negligible relative influence compared to the inertial and geometric VDP. These VDPs (listed in Section 8.2) would likely have a negligible relative influence on all HCVs. Using discretion, these VDPs could be conservatively estimated and still provide realistic prediction of vehicle performance.
    (b) Additional CV matrices were developed comparing the inertial, geometrical, suspension and tyre VDPs in isolation (see Appendices B.4 to B.7). These CV matrices highlight the VDPs with the most influence within each category independent of all other VDPs and will guide efforts focused on a specific area of vehicle design.

4. A detailed discussion of the results and their implication is included in Section 8. The discussion recommends improvements to the PBS assessment methodology to avoid

bias in the evaluation of tracking ability on a straight path, summarises the parameters that had negligible influence and cautions on the applicability of the results for vehicle combinations not included in the range of baseline HCVs. The results contained in this study will help speed up the PBS assessment process and guide vehicle design efforts towards high-impact VDPs when optimising vehicle design leading to safer, more productive HCVs.

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A Baseline Vehicle Model Data

A.1 Summary of Baseline Vehicle Design Parameters

The sections that follow summarise the configuration of each baseline combination and include the range of values evaluated for each VDP. The ranges have been separated into the following categories; vehicle units (prime movers and trailers), axles and tyres.

A.1.1 Vehicle Design Parameters for Vehicle Units

A.1.1.1 Prime Movers

The axle configuration on the truck tractor and rigid truck is as follows:

1. **Steer:** Steer axle with 315/80 R22.5 tyres (see Table A.11)
2. **Drive:** Drive axle with 315/80 R22.5 tyres (see Table A.12)

A detailed summary of the VDPs and their evaluated range for the truck tractor and rigid truck is presented in Tables A.1 and A.2 respectively.

Both baseline prime movers are fitted with the same engine, gearbox and powertrain as per Tables A.3 to A.5 which remain unchanged for all simulations.

Table A.1: Vehicle design parameters - truck tractor

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Wheelbase	mm	3885	3061	4360	79%	112%
Axle spacing	mm	1370	1200	1400	88%	102%
Hitch height	mm	1278	1088	1350	85%	106%
Hitch longitudinal location	mm	-3375	-3200	-3885	95%	115%
Prime mover sprung mass	kg	6598	4428	6598	67%	100%
Prime mover CG_x	mm	-1001	-801	-1201	80%	120%
Prime mover CG_y	mm	0	-250	250	10% of width	10% of width
Prime mover CG_z	mm	1204	1070	1426	89%	118%
Prime mover r_x	m	0.760	0.532	0.988	70%	130%
Prime mover r_y	m	1.943	1.166	2.720	60%	140%
Prime mover r_z	m	1.943	1.166	2.720	60%	140%
Front overhang	mm	1365	1300	1820	95%	133%
Rear overhang	mm	1013	1013	1013	Not varied	Not varied
Vehicle width cab	mm	2495	2225	2600	89%	104%
Reference point height	mm	752	0	4600	0%	612%

Table A.2: Vehicle design parameters - rigid truck

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Wheelbase	mm	5285	4413	5892	84%	111%
Axle spacing	mm	1370	1200	1400	88%	102%
Hitch height	mm	500	300	918	60%	184%
Hitch longitudinal location	mm	-7115	-6558	-7860	92%	110%
Prime mover sprung mass	kg	6698	4767	6698	71%	100%
Prime mover CG_x	mm	-1860	-1488	-2232	80%	120%
Prime mover CG_y	mm	0	-260	260	10% of width	10% of width
Prime mover CG_z	mm	1017	1000	1315	98%	129%
Prime mover r_x	m	0.76	0.532	0.988	70%	130%
Prime mover r_y	m	2.643	1.586	3.700	60%	140%
Prime mover r_z	m	2.643	1.586	3.700	60%	140%
Front overhang	mm	1365	1300	1820	95%	133%
Rear overhang	mm	1775	0	2546	0%	143%
Vehicle width (superstructure)	mm	2600	2400	2600	92%	100%
Vehicle width (cab)	mm	2495	2225	2600	89%	104%
Reference point height	mm	752	0	4600	0%	612%
Payload sprung mass	kg	15352	0	15352	0%	100%
Payload CG_x	mm	-4490	-4176	-4804	93%	107%
Payload CG_y	mm	0	-260	260	10% of width	10% of width
Payload CG_z	mm	2504	1122	2968	45%	119%
Payload r_x	m	1.488	0.744	2.232	50%	150%
Payload r_y	m	1.839	0.736	2.942	40%	160%
Payload r_z	m	1.860	0.744	2.976	40%	160%

Table A.3: Baseline engine torque curve

Engine speed (rpm)	Torque (Nm)
600	1273
621	1305
688	1404
749	1499
810	1601
856	1704
901	1803
929	1893
965	1996
996	2099
1053	2201
1394	2205
1461	2095
1540	1996
1631	1897
1714	1803
1811	1700
1860	1601
1911	1499
1951	1404
1997	1301
2033	1203
2085	1100

Table A.4: Baseline gearbox transmission data

Gear	Ratio	Efficiencies
C	19.38	0.96
1	14.94	0.96
2	11.28	0.96
3	9.04	0.96
4	7.09	0.96
5	5.54	0.96
6	4.35	0.96
7	3.44	0.96
8	2.7	0.96
9	2.08	0.96
10	1.63	0.96
11	1.27	0.96
12	1	0.96

Table A.5: Baseline differential, clutch engagement and gear change speed

Differential ratio	Differential efficiency	Clutch engagement speed (rpm)	Clutch engagement torque (Nm)	Gear change speed (rpm)
3.09	0.98	600	1103	1631

A.1.1.2 Trailer and Dolly Units

The axle configuration on the **quad semi-trailer** is as follows:

1. **Trailer:** Trailer axle with 445/65 R22.5 tyres (see Table A.13).

A detailed summary of the VDPs and their evaluated range for the quad semi-trailer is presented in Table A.6.

Table A.6: Vehicle design parameters - quad semi-trailer

Parameter	**Unit**	**Baseline**	**Min.**	**Max.**	**Min. (%)**	**Max. (%)**
Wheelbase	mm	10000	7975	10000	80%	100%
Axle spacing	mm	1360	1200	1850	88%	136%
Trailer sprung mass	kg	10410	2500	10410	24%	100%
Trailer CG_x	mm	-6455	-4519	-8392	70%	130%
Trailer CG_y	mm	0	-260	260	10% of width	10% of width
Trailer CG_z	mm	2025	1280	2025	63%	100%
Trailer r_x	m	1.588	0.873	2.303	55%	145%
Trailer r_y	m	4.641	2.321	6.962	50%	150%
Trailer r_z	m	4.685	2.343	7.028	50%	150%
Front overhang	mm	900	0	1800	0%	200%
Rear overhang	mm	1960	0	6000	0%	306%
Vehicle width	mm	2600	2400	2600	92%	100%
Reference point height	mm	3800	0	4600	0%	121%
Payload sprung mass	kg	32000	0	32000	0%	100%
Payload CG_x	mm	-6500	-5755	-7245	89%	111%
Payload CG_y	mm	0	-260	260	10% of width	10% of width
Payload CG_z	mm	2025	1580	2841	78%	140%
Payload r_x	m	0.812	0.406	1.218	50%	150%
Payload r_y	m	4.368	1.747	6.989	40%	160%
Payload r_z	m	4.353	1.741	6.965	40%	160%

The axle configuration on the **tridem interlink leader and follower trailers** is as follows:

1. **Trailer:** Trailer axle with 315/80 R22.5 tyres (see Table A.14)

A detailed summary of the VDPs and their evaluated range for the tridem interlink leader and follower trailer is presented in Tables A.7 and A.8 respectively.

Table A.7: Vehicle design parameters - tridem interlink leader

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Wheelbase	mm	7420	7060	7612	95%	103%
Axle spacing	mm	1360	1200	1850	88%	136%
Hitch height	mm	1278	1148	1350	90%	106%
Hitch longitudinal location	mm	-8420	-7925	-8780	94%	104%
Trailer sprung mass	kg	4632	1855	4632	40%	100%
Trailer CG_x	mm	-3656	-2559	-4753	70%	130%
Trailer CG_y	mm	0	-260	260	10% of width	10% of width
Trailer CG_z	mm	1777	1280	2025	72%	114%
Trailer r_x	m	0.985	0.542	1.428	55%	145%
Trailer r_y	m	3.169	1.585	4.754	50%	150%
Trailer r_z	m	3.167	1.584	4.751	50%	150%
Front overhang	mm	950	0	1800	0%	189%
Rear overhang	mm	-1790	-1790	-1283	100%	72%
Vehicle width	mm	2600	2400	2600	92%	100%
Reference point height	mm	3198	0	4600	0%	144%
Payload sprung mass	kg	24615	0	24615	0%	100%
Payload CG_x	mm	-3111	-2714	-3508	87%	113%
Payload CG_y	mm	0	-260	260	10% of width	10% of width
Payload CG_z	mm	2375	1667	2473	70%	104%
Payload r_x	m	0.762	0.381	1.143	50%	150%
Payload r_y	m	2.211	0.884	3.538	40%	160%
Payload r_z	m	2.251	0.900	3.602	40%	160%

Table A.8: Vehicle design parameters - tridem interlink follower

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Wheelbase	mm	5950	4434	6404	75%	108%
Axle spacing	mm	1360	1200	1850	88%	136%
Trailer sprung mass	kg	4167	1488	4167	36%	100%
Trailer CG_x	mm	-4269	-2988	-5550	70%	130%
Trailer CG_y	mm	0	-260	260	10% of width	10% of width
Trailer CG_z	mm	1912	1280	2025	67%	106%
Trailer r_x	m	1.007	0.554	1.460	55%	145%
Trailer r_y	m	3.037	1.519	4.556	50%	150%
Trailer r_z	m	3.052	1.526	4.578	50%	150%
Front overhang	mm	-354	-354	464	100%	-131%
Rear overhang	mm	984	0	3570	0%	363%
Vehicle width	mm	2600	2400	2600	92%	100%
Reference point height	mm	4114	0	4600	0%	112%
Payload sprung mass	kg	24615	0	24615	0%	100%
Payload CG_x	mm	-4403	-4006	-4800	91%	109%
Payload CG_y	mm	0	-260	260	10% of width	10% of width
Payload CG_z	mm	2375	1667	2473	70%	104%
Payload r_x	m	0.762	0.381	1.143	50%	150%
Payload r_y	m	2.211	0.884	3.538	40%	160%
Payload r_z	m	2.251	0.900	3.602	40%	160%

The axle configuration on the **rigid drawbar combination** is as follows:

1. **Dolly:** Trailer axle with 285/70 R19.5 tyres (see Table A.15)
2. **Trailer:** Trailer axle with 285/70 R19.5 tyres (see Table A.15)

A detailed summary of the VDPs and their evaluated range for the rigid drawbar combination tridem semi-trailer and dolly is presented in Tables A.9 and A.10 respectively.

Table A.9: Vehicle design parameters - tridem semi-trailer

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Wheelbase	mm	8255	6035	8881	73%	108%
Axle spacing	mm	1360	1200	1850	88%	136%
Trailer sprung mass	kg	3150	2064	3150	66%	100%
Trailer CG_x	mm	-5575	-3903	-7248	70%	130%
Trailer CG_y	mm	0	-260	260	10% of width	10% of width
Trailer CG_z	mm	1500	1280	2025	85%	135%
Trailer r_x	m	1.227	0.675	1.779	55%	145%
Trailer r_y	m	5.434	2.717	8.151	50%	150%
Trailer r_z	m	5.501	2.751	8.252	50%	150%
Front overhang	mm	1760	0	1800	0%	102%
Rear overhang	mm	1081	0	4953	0%	458%
Vehicle width	mm	2600	2400	2600	92%	100%
Reference point height	mm	3198	0	4600	0%	144%
Payload sprung mass	kg	34000	0	34000	0%	100%
Payload CG_x	mm	-4702	-4079	-5325	87%	113%
Payload CG_y	mm	0	-260	260	10% of width	10% of width
Payload CG_z	mm	2575	1371	3012	53%	117%
Payload r_x	m	1.506	0.753	2.259	50%	150%
Payload r_y	m	3.656	1.462	5.850	40%	160%
Payload r_z	m	3.656	1.462	5.850	40%	160%

Table A.10: Vehicle design parameters - rigid combination dolly

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Wheelbase	mm	3590	2819	4841	79%	135%
Axle spacing	mm	1360	1200	1800	88%	132%
Hitch height	mm	1100	970	1350	88%	123%
Hitch longitudinal location	mm	-3639	-3385	-3785	93%	104%
Dolly sprung mass	kg	453	400	453	88%	100%
Dolly CG_x	mm	-3450	-3105	-3795	90%	110%
Dolly CG_y	mm	0	0	0	Not varied	Not varied
Dolly CG_z	mm	868	868	1050	100%	121%
Dolly r_x	m	0.515	0.412	0.618	80%	120%
Dolly r_y	m	0.818	0.573	1.063	70%	130%
Dolly r_z	m	0.959	0.671	1.247	70%	130%

A.1.2 Vehicle Design Parameters for Axles

Tables A.11 to A.15 summarise the VDPs for the baseline axles.

Table A.11: Vehicle design parameters - steer axle with 315/80 R22.5 tyres (singles)

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Axle track	mm	2109	1950	2282	92%	108%
Axle centre height	mm	507	447	567	88%	112%
Roll centre height	mm	21	-20	100	-95%	476%
Roll steer coefficient	°/°	-0.087	0	-0.2	0%	230%
Axle I_{xx}/I_{zz}	kg.m^2	529	529	621	100%	117%
Spin inertia for each side	kg.m^2	2	2	20	100%	1000%
Unsprung mass	kg	750	544	800	67%	107%
Wheel centre height	mm	507	507	528	100%	104%
Auxiliary roll stiffness	Nm/°	2950	1070	5009	36%	170%
Damper model	N-s/mm	20	2.5	50	13%	250%
Damper track	mm	1150	780	1150	68%	100%
Jounce stop	mm	204	45	250	22%	123%
Rebound stop	mm	-195	-45	-250	23%	128%
Spring vertical stiffness	N/mm	273	185	350	68%	128%
Spring track	mm	815	780	1150	96%	141%

Table A.12: Vehicle design parameters - drive axle with 315/80 R22.5 tyres (duals)

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Axle track	mm	1837	1800	1932	98%	105%
Axle centre height	mm	507	447	567	88%	112%
Roll centre height	mm	400	-125	400	-31%	100%
Roll steer coefficient	°/°	0	0.04	-0.23	-	-
Axle I_{xx}/I_{zz}	kg.m^2	619	619	712	100%	115%
Spin inertia for each side	kg.m^2	2	2	20	100%	1000%
Unsprung mass	kg	1300	1043	1350	69%	104%
Wheel centre height	mm	507	507	528	100%	104%
Auxiliary roll stiffness	Nm/°	7487	790	12689	11%	169%
Damper model	N-s/mm	20	2.5	50	13%	250%
Damper track	mm	1000	670	1100	67%	110%
Jounce stop	mm	250	45	250	18%	100%
Rebound stop	mm	-250	-45	-250	18%	100%
Spring vertical stiffness	%[1]	100%	42%	126%	42%	126%
Spring track	mm	755	670	1100	89%	146%

[1] Spring vertical stiffness response scaled as a percentage of the baseline spring response

Table A.13: Vehicle design parameters - trailer axle with 445/65 R22.5 tyres (singles)

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Axle track	mm	2140	2000	2178	93%	102%
Axle centre height	mm	534	474	594	89%	111%
Roll centre height	mm	114	-125	200	-110%	175%
Roll steer coefficient	°/°	-0.035	0.04	-0.23	-114%	657%
Axle I_{xx}/I_{zz}	kg.m^2	474	474	562	100%	119%
Spin inertia for each side	kg.m^2	2	2	20	100%	1000%
Unsprung mass	kg	760	545	800	71%	125%
Wheel centre height	mm	534	534	561	100%	105%
Auxiliary roll stiffness	Nm/°	24700	2260	35954	9%	146%
Damper model	N-s/mm	20	2.5	50	13%	250%
Damper track	mm	1080	780	1500	72%	139%
Jounce stop	mm	250	45	250	18%	100%
Rebound stop	mm	-250	-45	-250	18%	100%
Spring vertical stiffness	%[1]	100%	62%	186%	62%	186%
Spring track	mm	1300	780	1500	60%	115%

[1] Spring vertical stiffness response scaled as a percentage of the baseline spring response

Table A.14: Vehicle design parameters - trailer axle with 315/80 R22.5 tyres (duals)

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Axle track	mm	1920	1820	1982	95%	103%
Axle centre height	mm	507	447	567	88%	112%
Roll centre height	mm	114	-125	200	-110%	175%
Roll steer coefficient	$^\circ/^\circ$	-0.156	0.04	-0.23	-26%	147%
Axle I_{xx}/I_{zz}	kg.m^2	562	562	666	100%	118%
Spin inertia for each side	kg.m^2	2	2	20	100%	1000%
Unsprung mass	kg	900	667	1000	89%	111%
Wheel centre height	mm	507	507	528	100%	104%
Auxiliary roll stiffness	Nm/$^\circ$	24700	2260	35954	9%	146%
Damper model	N-s/mm	20	2.5	50	13%	250%
Damper track	mm	760	670	1200	88%	158%
Jounce stop	mm	250	45	250	18%	100%
Rebound stop	mm	-250	-45	-250	18%	100%
Spring vertical stiffness	%[1]	100%	62%	186%	62%	186%
Spring track	mm	1000	670	1200	67%	120%

[1] Spring vertical stiffness response scaled as a percentage of the baseline spring response

Table A.15: Vehicle design parameters - trailer axle with 285/70 R19.5 tyres (duals)

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Axle track	mm	2040	1830	2042	90%	100%
Axle centre height	mm	413	353	473	85%	115%
Roll centre height	mm	114	-125	200	-110%	175%
Roll steer coefficient	$^\circ/^\circ$	-0.156	0.04	-0.23	-26%	147%
Axle I_{xx}/I_{zz}	kg.m^2	472	472	560	100%	119%
Spin inertia for each side	kg.m^2	2	2	20	100%	1000%
Unsprung mass	kg	757	530	850	70%	112%
Wheel centre height	mm	413	413	434	100%	105%
Auxiliary roll stiffness	Nm/$^\circ$	24700	2260	35954	9%	146%
Damper model	N-s/mm	20	2.5	50	13%	250%
Damper track	mm	760	670	1200	88%	158%
Jounce stop	mm	250	45	250	18%	100%
Rebound stop	mm	-250	-45	-250	18%	100%
Spring vertical stiffness	%[1]	100%	62%	186%	62%	186%
Spring track	mm	1000	670	1200	67%	120%

[1] Spring vertical stiffness response scaled as a percentage of the baseline spring response

A.1.3 Vehicle Design Parameters for Tyres

Tables A.16 to A.18 summarise the VDPs for each of the baseline tyre models.

Table A.16: Vehicle design parameters - 445/65 R22.5 tyres

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Effective rolling radius	mm	555	552	575	99%	104%
L for F_x	mm	55	55	55	100%	100%
L for F_y & M_z	mm	1100	100	1100	0%	100%
Tyre cornering stiffness	%	100	100	173	100%	173%
Tyre spring rate	N/mm	1193	773	1237	65%	104%
Unloaded radius	mm	587	575	589	98%	100%
Wheel assembly spin moment of inertia	kg.m^2	28	14	28	50%	100%
Dual tyre spacing	-	-	-	-	-	-

Table A.17: Vehicle design parameters - 315/80 R22.5 tyres

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Effective rolling radius	mm	522	515	537	99%	103%
L for F_x	mm	50	50	50	100%	100%
L for F_y & M_z	mm	1000	100	1000	0%	100%
Cornering stiffness	%	100	100	180	100%	180%
Tyre spring rate	N/mm	987	565	1169	57%	118%
Unloaded radius	mm	548	538	550	98%	100%
Wheel assembly spin moment of inertia	kg.m^2	12	7	14	58%	117%
Dual tyre spacing	mm	350	350	355	100%	101%

Table A.18: Vehicle design parameters - 285/70 R19.5 tyres

Parameter	Unit	Baseline	Min.	Max.	Min. (%)	Max. (%)
Effective rolling radius	mm	434	429	447	99%	103%
L for F_x	mm	45	45	45	100%	100%
L for F_y & M_z	mm	900	1	900	0%	100%
Cornering stiffness	%	100	100	135	100%	135%
Tyre spring rate	N/mm	801	473	901	59%	113%
Unloaded radius	mm	456	448	456	98%	100%
Wheel assembly spin moment of inertia	kg.m^2	10	6.5	13	65%	130%
Dual tyre spacing	mm	314	314	319	100%	102%

A.2 Baseline Vehicle TruckSim® Datasets

The Sections that follow include the TruckSim® datasets used for the baseline vehicle models.

A.2.1 Control Parameters

The control parameters used for the lane change and pulse steer manoeuvre discussed in Section 8.4.1 are summarised in Table A.19.

Table A.19: TruckSim® control parameters for PBS manoeuvres

Baseline combination	Driver Preview Time	Steering Input Gain
Quad semi-trailer	0.3	105
Tridem interlink	0.3	105
Rigid drawbar combination	0.125	180

A.2.2 Spring Datasets

The air spring behaviour was linearised from measured performance as supplied by OEMs and simplified to have the same stiffness in loading and unloading.

TruckSim® assumes the spring is mounted vertically above the axle, all spring datasets included in this Section have transformed the measured spring response as if it were mounted vertically above the axle.

The spring response per baseline drive axle transformed as if mounted vertically above the axle is included in Table A.20.

The trailer axle spring dataset transformed as if mounted vertically above the axle is included in Table A.21.

Table A.20: Baseline spring dataset for drive axles

Vertical load (N) ->	2935	8856	14906	21033	27160
Compression (mm)	**Force during loading & unloading (N)**				
-40	784	4753	8944	13299	17640
40	5085	12959	20868	28767	36679

Table A.21: Baseline spring dataset for trailer axles

Vertical load (N) ->	3195	6636	20462	34535	47932
Compression (mm)	**Force during loading & unloading (N)**				
-45	345	2557	12145	22406	32239
45	9980	15388	36405	57729	77332

A.2.3 Tyre Datasets

The datasets used to define the properties of the baseline tyres are included in the sections that follow.

A.2.3.1 Lateral Tyre Force

Table A.22: Lateral tyre force dataset for the baseline 285/70 R19.5 tyre

Vertical load (N) ->	8896	17793	26689	35586
Slip angle (°)	**Lateral tyre force (N)**			
1	1432	2588	3306	3664
2	2532	4821	6475	7513
4	4397	8511	11699	13851
8	6851	12813	17575	20871
12	7868	14763	19906	24016

Table A.23: Lateral tyre force dataset for the baseline 315/80 R22.5 tyre

Vertical load (N) ->	8896	17793	26689	35586
Slip angle (°)	**Lateral tyre force (N)**			
1	1353	2266	2924	3307
2	2227	3947	5158	5919
4	3761	6888	9135	10591
8	5865	10754	14487	17117
12	6594	12522	17192	20916

Table A.24: Lateral tyre force dataset for the baseline 445/65 R22.5 tyre

Vertical load (N) ->	17828	35519	53210	66483
Slip angle (°)	**Lateral tyre force (N)**			
1	1976	3840	5678	6753
2	3712	7551	11227	13573
4	6662	13602	20287	24946
8	11477	22473	32627	39425
12	14641	27744	39038	46745

A.2.3.2 Longitudinal Tyre Force

The longitudinal properties of the baseline tyres were defined with Standard TruckSim® datasets as per Tables A.25 to A.26.

Table A.25: Longitudinal tyre force dataset for baseline 445/65 R22.5 & 315/80 R22.5 tyres [1]

Vertical load (N) ->	8584	17168	34335	51503	68670
Absolute slip ratio (kappa) (-)	**Longitudinal tyre force (N)**				
0.025	2656.1	5122.4	9485.9	13090.6	16126.1
0.050	4756	9172.4	16985.9	23440.5	28876
0.075	6140.8	11843	21931.5	30265.4	37283.5
0.100	6952.5	13408.4	24830.3	34265.8	42211.6
0.125	7389.9	14252	26392.6	36421.8	44867.4
0.150	7602.3	14661.7	27151.2	37468.7	46157.1
0.175	7682.5	14816.3	27437.5	37863.8	46643.8
0.200	7684.8	14820.7	27445.8	37875.2	46657.8
0.225	7640.9	14736	27288.9	37658.6	46391.1
0.250	7569.4	14598	27033.4	37306.1	45956.8
0.300	7384.3	14241.2	26372.5	36394.1	44833.3
0.350	7177.9	13843.1	25635.4	35376.9	43580.2
0.400	6969.9	13441.9	24892.5	34351.6	42317.2
0.450	6768.6	13053.7	24173.6	33359.6	41095.1
0.500	6577.6	12685.3	23491.3	32418	39935.3
0.550	6398	12339	22850	31533	38845
0.600	6230	12015.1	22250.1	30705.2	37825.2
0.650	6073.3	11712.7	21690.3	29932.6	36873.4
0.700	5927.1	11430.8	21168.2	29212.1	35985.9
0.750	5790.7	11167.9	20681.2	28540.1	35158.1
0.800	5663.5	10922.4	20226.7	27912.9	34385.5
0.850	5544.6	10693.2	19802.2	27327	33663.7
0.900	5433.4	10478.7	19405	26778.9	32988.5
0.950	5329.2	10277.8	19033	26265.5	32356
1.000	5329.2	10277.8	19033	26265.5	32356

[1] Standard TruckSim® Model *Fx: 3500 kg Load Rating*

Table A.26: Longitudinal tyre force dataset for baseline 285/70 R19.5 tyres[1]

Vertical load (N) ->	7358	14715	29430	44145	58860
Absolute slip ratio (kappa) (-)	**Longitudinal tyre force (N)**				
0.025	2276.6	4390.6	8130.8	11220.5	13822.4
0.050	4076.6	7862	14559.3	20091.9	24750.8
0.075	5263.6	10151.1	18798.4	25941.8	31957.3
0.100	5959.3	11492.9	21283.1	29370.7	36181.3
0.125	6334.2	12216	22622.2	31218.7	38457.8
0.150	6516.3	12567.1	23272.5	32116	39563.2
0.175	6585	12699.7	23517.9	32454.7	39980.4
0.200	6587	12703.5	23525	32464.4	39992.4
0.225	6549.3	12630.8	23390.5	32278.8	39763.8
0.250	6488	12512.6	23171.5	31976.6	39391.5
0.300	6329.4	12206.7	22605	31194.9	38428.5
0.350	6152.5	11865.5	21973.2	30323	37354.5
0.400	5974.2	11521.7	21336.4	29444.2	36271.9
0.450	5801.7	11188.9	20720.2	28593.9	35224.4
0.500	5637.9	10873.1	20135.4	27786.9	34230.2
0.550	5484	10576.3	19585.7	27028.3	33295.7
0.600	5340	10298.6	19071.5	26318.7	32421.6
0.650	5205.7	10039.5	18591.7	25656.5	31605.8
0.700	5080.4	9797.8	18144.1	25038.9	30845
0.750	4963.5	9572.4	17726.8	24462.9	30135.5
0.800	4854.4	9362.1	17337.2	23925.4	29473.3
0.850	4752.5	9165.6	16973.3	23423.1	28854.6
0.900	4657.2	8981.7	16632.8	22953.3	28275.8
0.950	4567.9	8809.5	16314	22513.3	27733.7
1.000	4567.9	8809.5	16314	22513.3	27733.7

[1] Standard TruckSim® Model *Fx: 3000 kg Load Rating*

A.2.3.3 Aligning Moment

The aligning moment properties of the baseline tyres were defined with Standard TruckSim® datasets as per Tables A.27 to A.28.

Table A.27: Aligning moment dataset for baseline 445/65 R22.5 & 315/80 R22.5 tyres [1]

Vertical load (N) ->	8584	17168	34335	51503	68670
Absolute slip angle (°)	**Aligning moment (N-m)**				
1	41.5	101.7	274.8	511.1	814.9
2	75.6	185.4	499.5	929.6	1484.2
4	117.8	288.9	773.5	1441.7	2309.8
6	128.2	313.9	833.3	1556.2	2505.3
8	116.9	285.7	749.4	1403.6	2275.4
10	94.5	230.3	592.2	1114.3	1827.0
12	67.7	164.1	406.7	772.1	1292.9
15	26.2	61.8	121.3	245.3	468.2
20	0	0	0	0	0
90	0	0	0	0	0

[1] Standard TruckSim® Model *Mz: 3500 kg Load Rated Tire*

Table A.28: Aligning moment dataset for baseline 285/70 R19.5 tyres[1]

Vertical load (N) ->	4905	9810	19620	29430	39240
Absolute slip angle (°)	**Aligning moment (N-m)**				
1	35.0	85.9	231.9	431.5	687.9
2	63.8	156.5	421.6	784.8	1252.9
4	99.5	243.9	653.0	1217.0	1949.8
6	108.2	265.0	703.5	1313.7	2114.8
8	98.7	241.2	632.6	1184.8	1920.8
10	79.8	194.4	499.9	940.6	1542.3
12	57.1	138.5	343.3	651.8	1091.5
15	22.1	52.1	102.4	207.0	395.3
20	0	0	0	0	0
90	0	0	0	0	0

[1] Standard TruckSim® Model *Mz: 3000 kg Load Rated Tire*

B Additional CV Matrices

Additional variations of the CV matrices for each of the baseline vehicles are included in this Appendix for the interest of the reader. The complete CV matrices in Sections B.1 to B.3 include all evaluated VDP including those that had a negligible relative influence. Following these in Sections B.4 to B.7 are CV matrices including the inertial, geometric, suspension and tyre parameters in isolation.

B.1 Complete CV Matrix - Quad Semi-trailer

Table B.1: Complete CV matrix - quad semi-trailer

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
PM wheelbase	0	63	0	0	3	40	14	62	4	31	4	63	16	19	100
TL wheelbase	100	100	0	0	18	70	100	80	8	100	44	9	5	1	2
PM axle spacing	0	0	0	0	1	0	2	0	0	1	0	2	0	0	14
TL axle spacing	0	0	0	0	1	1	0	12	0	9	3	5	4	2	8
PM hitch height	0	0	0	0	4	0	2	3	0	0	0	0	0	0	1
PM hitch long. loc.	0	35	0	0	1	9	12	33	0	1	0	3	1	1	24
PM sprung mass	13	2	6	5	1	1	5	1	1	0	0	1	0	0	15
TL sprung mass	48	0	22	20	9	8	14	5	5	0	0	0	1	0	5
PM CG_x	0	10	0	0	0	0	5	3	0	0	0	0	0	0	7
TL CG_x	0	49	0	0	12	6	55	8	2	1	0	2	1	1	2
PM CG_y	0	0	0	0	5	5	4	3	5	1	2	1	2	1	1
TL CG_y	0	0	0	0	14	1	0	0	11	0	3	0	4	2	0
PM CG_z	0	0	0	0	4	1	5	1	1	0	0	0	0	0	0
TL CG_z	0	0	0	0	22	1	22	3	2	0	0	0	0	0	0
PM I_{xx}	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1
TL I_{xx}	0	0	0	0	1	1	2	1	2	0	0	0	0	0	0
PM I_{yy}/I_{zz}	0	0	0	0	1	1	4	8	0	0	0	0	0	0	0
TL I_{yy}/I_{zz}	0	0	0	0	1	19	5	38	1	0	0	0	0	0	0
PM front overhang	0	0	0	0	0	0	0	0	3	17	0	88	3	11	0
TL front overhang	0	0	0	0	0	0	0	0	0	0	0	0	100	100	0
TL rear overhang	0	0	0	0	0	0	0	0	30	0	100	0	0	0	0
PM reference height	0	0	0	0	0	0	0	0	76	4	0	23	3	4	0
TL reference height	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
PM vehicle width	0	0	0	0	0	0	0	0	77	15	0	100	37	22	0
TL vehicle width	0	0	0	0	0	0	0	0	59	0	17	0	25	6	0
TL payload mass	56	7	100	100	48	100	82	20	21	2	2	3	4	3	22
TL payload CG_x	0	57	0	0	12	7	23	7	2	1	0	2	1	1	2
TL payload CG_y	0	0	0	0	44	4	26	0	33	0	8	1	11	6	0
TL payload CG_z	0	0	0	0	100	7	7	20	14	0	1	0	0	0	0
TL payload I_{xx}	0	0	0	0	2	1	2	1	2	0	0	0	0	0	0

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Table B.1: Complete CV matrix - quad semi-trailer (cont.)

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
TL payload I_{yy}/I_{zz}	0	0	0	0	1	**58**	**18**	**100**	2	0	1	1	1	0	1
St. unsprung mass	2	1	1	1	0	0	0	1	0	0	0	0	0	0	2
Dr. unsprung mass	4	6	2	2	0	0	2	3	0	0	0	0	0	0	1
Tl. unsprung mass	6	5	3	2	4	0	0	0	0	0	0	0	0	0	0
St. axle track	0	0	0	0	0	0	0	0	0	4	1	**79**	0	1	3
Dr. axle track	0	0	0	0	2	0	1	1	1	0	0	0	0	0	0
Tl. axle track	0	0	0	0	**16**	1	2	1	5	0	0	0	0	0	0
St. axle centre height	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Dr. axle centre height	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Tl. axle centre height	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
St. roll centre height	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0
Dr. roll centre height	0	0	0	0	8	3	**13**	9	1	0	0	1	0	0	1
Tl. roll centre height	0	0	0	0	2	1	3	0	2	0	0	0	0	0	0
St. roll steer coef.	0	0	0	0	1	7	0	0	0	0	0	0	0	0	0
Dr. roll steer coef.	0	0	0	0	2	**11**	0	7	3	0	0	0	0	0	1
Tl. roll steer coef.	0	0	0	0	0	2	7	**17**	**10**	0	0	0	0	0	0
St. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. wheel centre height	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
Dr. wheel centre height	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Tl. wheel centre height	0	0	0	0	2	1	1	1	2	0	0	0	0	0	0
St. aux. roll stiffness	0	0	0	0	4	1	2	1	0	0	0	0	0	0	0
Dr. aux. roll stiffness	0	0	0	0	**19**	2	**10**	3	3	0	0	1	0	0	1
Tl. aux. roll stiffness	0	0	0	0	7	**11**	**11**	9	**35**	0	1	0	0	0	0
St. damper	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1
Dr. damper	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
Tl. damper	0	0	0	0	1	0	2	1	1	0	0	0	0	0	0
St. damper track	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. damper track	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. damper track	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
St. jounce / rebound	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Dr. jounce / rebound	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Tl. jounce / rebound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. spring	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0
Dr. spring	0	0	0	0	2	1	3	3	0	1	0	3	1	1	5
Tl. spring	0	0	0	0	2	0	1	1	1	0	0	0	1	0	0
St. spring track	0	0	0	0	2	1	1	1	0	0	0	0	0	0	0
Dr. spring track	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0
Tl. spring track	0	0	0	0	1	1	2	1	2	0	0	0	0	0	0
Dr. dual spacing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. eff. rolling radius	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. eff. rolling radius	**15**	0	1	3	0	0	0	0	0	0	0	0	0	0	0
Tl. eff. rolling radius	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. L for F_y & M_z	0	0	0	0	4	2	9	6	0	0	0	0	0	0	0

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Table B.1: Complete CV matrix - quad semi-trailer (cont.)

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
Tl. L for F_y & M_z	0	0	0	0	2	4	**14**	**14**	0	0	0	0	0	0	0
St. cornering stiffness	0	0	0	0	1	**65**	2	2	1	0	0	0	0	0	7
Dr. cornering stiffness	0	0	0	0	2	1	**31**	**49**	6	1	0	3	2	1	**21**
Tl. cornering stiffness	0	0	0	0	1	**10**	**33**	**81**	**23**	1	0	2	2	1	3
St. spring rate	0	0	0	0	1	1	0	2	2	0	0	2	0	0	1
Dr. spring rate	0	0	0	0	4	1	4	4	1	0	0	1	0	0	1
Tl. spring rate	0	0	0	0	2	2	7	2	4	0	0	0	0	0	0
St. unloaded radius	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Dr. unloaded radius	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. unloaded radius	0	0	0	0	2	0	0	1	1	1	0	0	0	0	0
St. wheel spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. wheel spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. wheel spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

B.2 Complete CV Matrix - Tridem Interlink

Table B.2: Complete CV matrix - tridem interlink

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
PM wheelbase	0	43	0	0	3	16	20	62	5	43	21	62	24	4	100
TL 1 wheelbase	0	11	0	0	4	8	7	17	0	34	5	1	5	0	0
TL 2 wheelbase	0	8	0	0	11	100	19	100	40	100	42	4	8	0	4
PM axle spacing	0	0	0	0	0	1	0	0	0	1	0	2	1	0	13
TL 1 axle spacing	0	0	0	0	0	1	0	1	0	4	2	5	8	1	8
TL 2 axle spacing	0	0	0	0	0	0	1	10	0	3	10	1	4	0	1
PM hitch height	0	0	0	0	8	2	3	1	0	0	0	0	0	0	1
TL 1 hitch height	0	0	0	0	5	0	7	0	0	0	0	0	0	0	0
PM hitch long. loc.	0	21	0	0	1	12	6	25	1	1	1	3	0	0	25
TL 1 hitch long. loc.	0	6	0	0	2	1	7	16	4	6	6	0	1	0	1
PM sprung mass	5	1	9	8	2	3	1	0	1	0	1	0	0	0	19
TL 1 sprung mass	6	5	12	10	2	1	0	4	2	0	0	0	0	0	1
TL 2 sprung mass	6	6	11	10	6	9	7	0	2	0	0	0	0	0	0
PM CG_x	0	5	0	0	0	2	2	2	0	0	0	0	0	0	6
TL 1 CG_x	0	10	0	0	4	1	39	3	0	0	0	1	1	0	1
TL 2 CG_x	0	2	0	0	7	6	4	4	0	1	0	1	1	0	0
PM CG_y	0	0	0	0	7	3	6	2	4	1	10	1	2	0	1
TL 1 CG_y	0	0	0	0	11	1	7	1	3	1	6	0	2	0	0
TL 2 CG_y	0	0	0	0	17	0	8	2	5	0	9	0	0	0	0
PM CG_z	0	0	0	0	4	1	1	1	1	0	0	0	0	0	0
TL 1 CG_z	0	0	0	0	11	0	3	2	0	0	0	0	0	0	0
TL 2 CG_z	0	0	0	0	19	1	10	2	1	0	0	0	0	0	0
PM I_{xx}	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0
TL 1 I_{xx}	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0
TL 2 I_{xx}	0	0	0	0	1	0	3	1	0	0	0	0	0	0	0
PM I_{yy}/I_{zz}	0	0	0	0	0	1	2	3	0	0	0	0	0	0	0
TL 1 I_{yy}/I_{zz}	0	0	0	0	0	3	3	7	0	0	0	0	0	0	0
TL 2 I_{yy}/I_{zz}	0	0	0	0	0	14	7	15	0	0	0	0	0	0	0
PM front overhang	0	0	0	0	0	0	0	0	2	25	0	89	6	1	0
TL 1 front overhang	0	0	0	0	0	0	0	0	0	0	0	0	100	100	0
TL 2 front overhang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TL 1 rear overhang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TL 2 rear overhang	0	0	0	0	0	0	0	0	17	0	54	0	0	0	0
PM reference height	0	0	0	0	0	0	0	0	59	6	0	24	4	0	0
TL 1 reference height	0	0	0	0	0	0	0	0	95	0	0	0	3	0	0
TL 2 reference height	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
PM vehicle width	0	0	0	0	0	0	0	0	59	22	0	100	50	4	0
TL 1 vehicle width	0	0	0	0	0	0	0	0	0	0	0	0	38	3	0
TL 2 vehicle width	0	0	0	0	0	0	0	0	45	0	100	0	0	0	0
TL 1 payload mass	100	100	100	100	100	40	47	36	15	11	2	4	5	1	20
TL 2 payload mass	67	59	100	100	13	27	6	25	20	6	2	1	1	0	1
TL 1 payload CG_x	0	18	0	0	9	0	12	6	1	0	0	1	1	0	1
TL 2 payload CG_x	0	3	0	0	11	11	13	9	0	1	0	1	2	0	1
TL 1 payload CG_y	0	0	0	0	75	1	8	4	16	4	26	1	9	1	0
TL 2 payload CG_y	0	0	0	0	94	0	24	12	29	2	28	0	2	1	0

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Table B.2: Complete CV matrix - tridem interlink (cont.)

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
TL 1 payload CG_z	0	0	0	0	**75**	7	**13**	9	2	0	1	0	0	0	0
TL 2 payload CG_z	0	0	0	0	**95**	6	9	**15**	9	0	1	0	0	0	0
TL 1 payload I_{xx}	0	0	0	0	1	0	**14**	0	0	0	0	0	0	0	0
TL 2 payload I_{xx}	0	0	0	0	1	1	**14**	2	1	0	0	0	0	0	0
TL 1 payload I_{yy}/I_{zz}	0	0	0	0	0	8	8	**22**	1	0	1	0	0	0	0
TL 2 payload I_{yy}/I_{zz}	0	0	0	0	1	**43**	**17**	**49**	1	0	1	0	0	0	0
St. unsprung mass	0	0	1	1	0	1	1	0	0	0	0	0	0	0	2
Dr. unsprung mass	2	4	3	3	0	1	0	2	0	0	0	0	0	0	1
Tl. unsprung mass	5	4	8	7	**16**	1	1	2	1	0	0	0	0	0	0
St. axle track	0	0	0	0	0	0	0	0	0	5	**17**	**79**	0	0	3
Dr. axle track	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0
Tl. axle track	0	0	0	0	**44**	1	4	4	4	0	0	0	0	0	0
St. axle centre height	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Dr. axle centre height	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. axle centre height	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
St. roll centre height	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0
Dr. roll centre height	0	0	0	0	**12**	0	2	6	1	1	0	1	1	0	**36**
Tl. roll centre height	0	0	0	0	8	3	6	2	3	0	0	0	0	0	0
St. roll steer coef.	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0
Dr. roll steer coef.	0	0	0	0	2	6	4	3	2	0	0	0	1	0	1
Tl. roll steer coef.	0	0	0	0	0	4	1	**21**	**18**	0	0	0	0	0	0
St. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. spin inertia	0	0	0	0	0	0	0	0	0	1	0	1	1	0	**22**
Tl. spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. wheel centre height	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
Dr. wheel centre height	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Tl. wheel centre height	0	0	0	0	4	0	1	1	1	0	0	0	0	0	0
St. aux. roll stiffness	0	0	0	0	3	0	2	0	0	0	0	0	0	0	0
Dr. aux. roll stiffness	0	0	0	0	**25**	2	8	1	2	0	1	1	0	0	1
Tl. aux. roll stiffness	0	0	0	0	**47**	**17**	**100**	**14**	**99**	0	9	0	1	0	0
St. damper	0	0	0	0	0	0	4	0	0	0	0	0	0	0	1
Dr. damper	0	0	0	0	0	0	4	1	2	0	0	0	0	0	0
Tl. damper	0	0	0	0	1	0	4	1	2	0	0	0	0	0	0
St. damper track	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Dr. damper track	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Tl. damper track	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. jounce / rebound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. jounce / rebound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. jounce / rebound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. spring	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0
Dr. spring	0	0	0	0	3	0	2	0	0	0	0	3	1	0	5
Tl. spring	0	0	0	0	7	1	8	1	1	0	0	0	1	0	0
St. spring track	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0
Dr. spring track	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0
Tl. spring track	0	0	0	0	2	0	7	1	2	0	0	0	0	0	0
Dr. dual spacing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Table B.2: Complete CV matrix - tridem interlink (cont.)

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
Tl. dual spacing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. eff. rolling radius	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. eff. rolling radius	7	0	1	4	0	0	0	0	0	0	0	0	0	0	0
Tl. eff. rolling radius	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. L for F_y & M_z	0	0	0	0	1	3	6	9	1	0	0	0	0	0	0
Tl. L for F_y & M_z	0	0	0	0	2	7	**11**	**21**	2	0	2	0	1	0	0
St. cornering stiffness	0	0	0	0	0	**19**	3	1	2	0	0	0	0	0	6
Dr. cornering stiffness	0	0	0	0	0	5	6	**32**	3	2	0	3	2	0	**19**
Tl. cornering stiffness	0	0	0	0	1	**13**	6	**94**	**22**	1	3	2	3	0	3
St. spring rate	0	0	0	0	1	0	1	1	1	0	0	2	0	0	1
Dr. spring rate	0	0	0	0	5	0	0	3	0	0	0	0	0	0	1
Tl. spring rate	0	0	0	0	**13**	6	**22**	2	3	0	0	0	0	0	0
St. unloaded radius	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Dr. unloaded radius	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. unloaded radius	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
St. wheel spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. wheel spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. wheel spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

B.3 Complete CV Matrix - Rigid Drawbar Combination

Table B.3: Complete CV matrix - rigid combination

VDP	STA	GRAa	GRAb	ACC	SRTt	SRTtrrcu	YDC	RA	HSTO	TASP	LSSP	TS	FS	STFD
PM wheelbase	0	28	0	0	8	0	43	21	25	10	49	70	54	32
DL wheelbase	0	0	0	0	1	0	2	4	3	3	42	0	5	1
TL wheelbase	0	0	0	0	17	12	44	55	31	17	100	63	4	4
PM axle spacing	0	0	0	0	0	0	0	0	0	0	1	2	0	2
DL axle spacing	0	0	0	0	0	0	2	1	2	0	5	0	7	2
TL axle spacing	0	0	0	0	0	0	0	1	5	0	4	0	1	1
PM hitch height	0	0	0	0	1	0	2	14	14	1	0	0	1	4
DL hitch height	0	0	0	0	5	2	2	1	2	1	0	0	0	0
PM hitch long. loc.	0	0	0	0	0	0	3	15	19	3	11	4	0	3
DL hitch long. loc.	0	0	0	0	3	2	18	6	4	2	3	1	1	4
PM sprung mass	3	1	6	4	0	0	3	1	1	0	1	1	1	18
DL sprung mass	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TL sprung mass	2	2	3	2	3	1	0	0	1	0	0	0	0	1
PM CG_x	0	6	0	0	0	0	2	1	0	0	2	1	1	9
DL CG_x	0	0	0	0	0	0	0	0	0	0	0	0	0	1
TL CG_x	0	0	0	0	6	3	1	4	1	0	0	0	0	1
PM CG_y	0	0	0	0	14	0	3	0	2	2	1	7	2	6
DL CG_y	0	0	0	0	1	0	0	0	0	0	0	0	0	0
TL CG_y	0	0	0	0	8	3	0	1	1	3	0	0	0	0
PM CG_z	0	0	0	0	5	0	0	1	0	1	0	0	0	0
DL CG_z	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TL CG_z	0	0	0	0	9	4	1	2	1	1	0	0	0	0
PM I_{xx}	0	0	0	0	0	0	0	2	3	1	0	0	0	0
DL I_{xx}	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TL I_{xx}	0	0	0	0	0	0	1	0	0	0	0	0	0	0
PM I_{yy}/I_{zz}	0	0	0	0	0	0	3	2	3	0	0	1	0	1
DL I_{yy}/I_{zz}	0	0	0	0	4	0	0	0	0	0	0	0	0	0
TL I_{yy}/I_{zz}	0	0	0	0	0	0	2	1	3	1	0	0	0	0
PM front overhang	0	0	0	0	0	0	0	0	0	1	18	0	100	0
TL front overhang	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PM rear overhang	0	0	0	0	0	0	0	0	0	0	0	91	0	0
TL rear overhang	0	0	0	0	0	0	0	0	0	11	0	100	0	0
PM reference height	0	0	0	0	0	0	0	0	0	63	4	9	23	0
TL reference height	0	0	0	0	0	0	0	0	0	66	0	0	0	0
PM vehicle width	0	0	0	0	0	0	0	0	0	50	13	49	85	0
TL vehicle width	0	0	0	0	0	0	0	0	0	28	0	0	0	0
PM payload mass	100	100	45	40	0	0	19	17	9	8	16	4	17	31
TL payload mass	67	36	100	100	18	79	100	100	65	14	7	0	5	5
PM payload CG_x	0	12	0	0	3	0	7	3	1	3	3	1	2	22
TL payload CG_x	0	0	0	0	18	9	4	2	4	1	1	0	2	2
PM payload CG_y	0	0	0	0	50	0	4	1	4	4	1	14	4	10
TL payload CG_y	0	0	0	0	85	40	2	5	9	30	2	39	0	0
PM payload CG_z	0	0	0	0	43	0	6	46	26	7	0	1	1	1
TL payload CG_z	0	0	0	0	82	100	32	23	30	16	0	0	0	0

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Table B.3: Complete CV matrix - rigid combination (cont.)

VDP	STA	GRAa	GRAb	ACC	SRTt	SRTtrrcu	YDC	RA	HSTO	TASP	LSSP	TS	FS	STFD
PM payload I_{xx}	0	0	0	0	0	0	**21**	**34**	**38**	**15**	0	0	0	0
TL payload I_{xx}	0	0	0	0	1	0	6	6	4	2	0	0	0	0
PM payload I_{yy}/I_{zz}	0	0	0	0	0	0	6	4	6	0	0	1	0	0
TL payload I_{yy}/I_{zz}	0	0	0	0	1	0	**13**	8	**19**	3	0	0	0	0
St. unsprung mass	1	0	1	0	0	0	1	0	0	0	1	0	1	2
Dr. unsprung mass	1	3	2	1	0	0	0	0	0	0	1	0	0	2
Tl. unsprung mass	3	3	5	4	**10**	5	0	1	1	0	0	0	0	1
St. axle track	0	0	0	0	0	0	0	0	0	0	4	0	**70**	**35**
Dr. axle track	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Tl. axle track	0	0	0	0	**36**	**17**	2	2	3	5	0	0	0	0
St. axle centre height	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Dr. axle centre height	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. axle centre height	0	0	0	0	1	1	0	1	0	0	0	0	0	0
St. roll centre height	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Dr. roll centre height	0	0	0	0	4	0	5	**11**	7	0	1	1	1	1
Tl. roll centre height	0	0	0	0	7	3	3	1	3	2	0	0	0	0
St. roll steer coef.	0	0	0	0	0	0	**10**	0	0	0	0	0	0	2
Dr. roll steer coef.	0	0	0	0	0	0	**25**	8	**21**	**12**	0	2	1	1
Tl. roll steer coef.	0	0	0	0	0	1	3	0	**15**	6	0	0	0	0
St. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. I_{xx}/I_{zz}	0	0	0	0	0	0	0	1	0	0	0	0	0	0
St. spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. spin inertia	0	0	0	0	5	**13**	0	0	0	0	0	0	0	0
St. wheel centre height	0	0	0	0	0	0	0	0	0	1	0	0	0	1
Dr. wheel centre height	0	0	0	0	0	0	1	0	0	0	0	0	1	1
Tl. wheel centre height	0	0	0	0	3	2	0	0	0	1	0	0	0	0
St. aux. roll stiffness	0	0	0	0	8	0	1	**11**	**11**	3	0	0	0	1
Dr. aux. roll stiffness	0	0	0	0	**77**	0	**46**	**68**	**100**	8	0	1	2	4
Tl. aux. roll stiffness	0	0	0	0	**100**	**46**	**28**	**70**	**22**	**100**	1	0	0	0
St. damper	0	0	0	0	0	0	1	1	2	1	0	0	0	3
Dr. damper	0	0	0	0	0	0	1	1	3	0	0	0	0	0
Tl. damper	0	0	0	0	1	0	1	**11**	1	0	0	0	0	0
St. damper track	0	0	0	0	0	0	0	1	1	0	0	0	0	0
Dr. damper track	0	0	0	0	0	0	0	1	1	0	0	0	0	0
Tl. damper track	0	0	0	0	0	0	1	0	0	0	0	0	0	0
St. jounce / rebound	0	0	0	0	0	0	1	4	2	1	0	0	0	0
Dr. jounce / rebound	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. jounce / rebound	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. spring	0	0	0	0	0	0	0	2	2	2	0	0	1	1
Dr. spring	0	0	0	0	1	0	1	9	9	1	0	0	2	2
Tl. spring	0	0	0	0	5	2	2	1	2	1	0	0	0	0
St. spring track	0	0	0	0	0	0	1	3	4	1	0	0	0	0
Dr. spring track	0	0	0	0	0	0	1	9	9	2	0	0	0	0
Tl. spring track	0	0	0	0	2	1	2	1	2	2	0	0	0	0
Dr. dual spacing	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. dual spacing	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Continued on next page

Table B.3: Complete CV matrix - rigid combination (cont.)

VDP	STA	GRAa	GRAb	ACC	SRTt	SRTtrrcu	YDC	RA	HSTO	TASP	LSSP	TS	FS	STFD
St. eff. rolling radius	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. eff. rolling radius	5	0	1	3	0	0	0	0	0	0	0	0	0	0
Tl. eff. rolling radius	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. L for F_y & M_z	0	0	0	0	1	0	2	5	5	1	0	1	0	1
Tl. L for F_y & M_z	0	0	0	0	1	1	4	7	5	0	0	1	0	0
St. cornering stiffness	0	0	0	0	0	0	**96**	1	0	1	2	1	0	**100**
Dr. cornering stiffness	0	0	0	0	1	0	4	**19**	**30**	5	2	1	2	9
Tl. cornering stiffness	0	0	0	0	0	0	8	5	**34**	9	3	0	3	0
St. spring rate	0	0	0	0	0	0	0	1	0	2	0	0	1	0
Dr. spring rate	0	0	0	0	0	0	1	9	8	1	0	1	0	0
Tl. spring rate	0	0	0	0	**13**	6	4	1	5	4	0	0	0	0
St. unloaded radius	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. unloaded radius	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. unloaded radius	0	0	0	0	1	0	0	0	0	0	0	0	0	0
St. wheel spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. wheel spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. wheel spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0

B.4 Geometrical CV Matrices

The geometrical CV matrices containing all of the geometrical VDPs for each of the baseline combinations are included in Tables B.4 to B.6.

Table B.4: Geometrical CV matrix - quad semi-trailer

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
PM wheelbase	0	**63**	0	0	**16**	**57**	**14**	**77**	4	**31**	4	**63**	**16**	**19**	**100**
TL wheelbase	**100**	**100**	0	0	**100**	**100**	**100**	**100**	8	**100**	**44**	9	5	1	2
PM axle spacing	0	0	0	0	5	0	2	0	0	1	0	2	0	0	**14**
TL axle spacing	0	0	0	0	5	2	0	**15**	0	9	3	5	4	2	8
PM hitch height	0	0	0	0	**22**	0	2	3	0	0	0	0	0	0	1
PM hitch long. loc.	0	**35**	0	0	5	**12**	**12**	**42**	0	1	0	3	1	1	**24**
PM front overhang	0	0	0	0	0	0	0	0	3	**17**	0	**88**	3	**11**	0
TL front overhang	0	0	0	0	0	0	0	0	0	0	0	0	**100**	**100**	0
TL rear overhang	0	0	0	0	0	0	0	0	**30**	0	**100**	0	0	0	0
PM reference height	0	0	0	0	0	0	0	0	**76**	4	0	**23**	3	4	0
TL reference height	0	0	0	0	0	0	0	0	**100**	0	0	0	0	0	0
PM vehicle width	0	0	0	0	0	0	0	0	**77**	**15**	0	**100**	**37**	**22**	0
TL vehicle width	0	0	0	0	0	0	0	0	**59**	0	**17**	0	**25**	6	0

Table B.5: Geometrical CV matrix - tridem interlink

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
PM wheelbase	0	100	0	0	24	16	100	62	5	43	21	62	24	4	100
TL 1 wheelbase	0	26	0	0	34	8	36	17	0	34	5	1	5	0	0
TL 2 wheelbase	0	18	0	0	100	100	98	100	40	100	42	4	8	0	4
PM axle spacing	0	0	0	0	0	1	2	0	0	1	0	2	1	0	13
TL 1 axle spacing	0	0	0	0	3	1	1	1	0	4	2	5	8	1	8
TL 2 axle spacing	0	0	0	0	1	0	4	10	0	3	10	1	4	0	1
PM hitch height	0	0	0	0	71	2	14	1	0	0	0	0	0	0	1
TL 1 hitch height	0	0	0	0	46	0	35	0	0	0	0	0	0	0	0
PM hitch long. loc.	0	47	0	0	11	12	30	25	1	1	1	3	0	0	25
TL 1 hitch long. loc.	0	14	0	0	22	1	34	16	4	6	6	0	1	0	1
PM front overhang	0	0	0	0	0	0	0	0	2	25	0	89	6	1	0
TL 1 front overhang	0	0	0	0	0	0	0	0	0	0	0	0	100	100	0
TL 2 front overhang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TL 1 rear overhang	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TL 2 rear overhang	0	0	0	0	0	0	0	0	17	0	54	0	0	0	0
PM reference height	0	0	0	0	0	0	0	0	59	6	0	24	4	0	0
TL 1 reference height	0	0	0	0	0	0	0	0	95	0	0	0	3	0	0
TL 2 reference height	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
PM vehicle width	0	0	0	0	0	0	0	0	59	22	0	100	50	4	0
TL 1 vehicle width	0	0	0	0	0	0	0	0	0	0	0	0	38	3	0
TL 2 vehicle width	0	0	0	0	0	0	0	0	45	0	100	0	0	0	0

Table B.6: Geometrical CV matrix - rigid drawbar combination

VDP	STA	GRAa	GRAb	ACC	SRTt	SRTtrrcu	YDC	RA	HSTO	TASP	LSSP	TS	FS	STFD
PM wheelbase	0	100	0	0	48	1	98	37	81	15	49	70	54	100
DL wheelbase	0	0	0	0	4	2	4	8	9	5	42	0	5	4
TL wheelbase	0	0	0	0	100	100	100	100	100	25	100	63	4	12
PM axle spacing	0	0	0	0	0	0	0	0	0	0	1	2	0	8
DL axle spacing	0	0	0	0	0	0	4	2	5	0	5	0	7	5
TL axle spacing	0	0	0	0	1	1	0	1	17	0	4	0	1	3
PM hitch height	0	0	0	0	6	4	5	25	45	1	0	0	1	12
DL hitch height	0	0	0	0	27	19	4	1	6	1	0	0	0	0
PM hitch long. loc.	0	0	0	0	1	0	7	28	60	4	11	4	0	11
DL hitch long. loc.	0	0	0	0	18	17	40	11	14	3	3	1	1	12
PM front overhang	0	0	0	0	0	0	0	0	0	2	18	0	100	0
TL front overhang	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PM rear overhang	0	0	0	0	0	0	0	0	0	0	0	91	0	0
TL rear overhang	0	0	0	0	0	0	0	0	0	17	0	100	0	0
PM reference height	0	0	0	0	0	0	0	0	0	96	4	9	23	0
TL reference height	0	0	0	0	0	0	0	0	0	100	0	0	0	0
PM vehicle width	0	0	0	0	0	0	0	0	0	76	13	49	85	0
TL vehicle width	0	0	0	0	0	0	0	0	0	42	0	0	0	0

B.5 Inertial CV Matrices

The inertial CV matrices containing only the inertial VDPs for each of the baseline combinations are included in Tables B.7 to B.9.

Table B.7: Inertial CV matrix - quad semi-trailer

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
PM sprung mass	**23**	3	6	5	1	1	6	1	4	8	3	**23**	3	1	**69**
TL sprung mass	**85**	0	**22**	**20**	9	8	**18**	5	**17**	**10**	3	9	**10**	3	**22**
PM CG_x	0	**17**	0	0	0	0	6	3	1	8	2	6	1	1	**34**
TL CG_x	0	**85**	0	0	**12**	6	**67**	8	5	**35**	3	**68**	**11**	**12**	9
PM CG_y	0	0	0	0	5	5	5	3	**16**	**26**	**21**	**36**	**18**	**15**	4
TL CG_y	0	0	0	0	**14**	1	1	0	**34**	2	**35**	**10**	**35**	**27**	1
PM CG_z	0	0	0	0	4	1	7	1	2	0	0	2	0	0	1
TL CG_z	0	0	0	0	**22**	1	**27**	3	7	0	1	0	0	0	0
PM I_{xx}	0	0	0	0	0	0	2	0	1	0	0	2	0	0	2
TL I_{xx}	0	0	0	0	1	1	3	1	5	0	0	1	0	0	0
PM I_{yy}/I_{zz}	0	0	0	0	1	1	5	8	1	3	3	3	0	0	2
TL I_{yy}/I_{zz}	0	0	0	0	1	**19**	6	**38**	3	6	4	7	2	0	1
TL payload mass	**100**	**12**	**100**	**100**	**48**	**100**	**100**	**20**	**65**	**100**	**29**	**100**	**38**	**50**	**100**
TL payload CG_x	0	**100**	0	0	**12**	7	**28**	7	7	**41**	4	**78**	**13**	**14**	**12**
TL payload CG_y	0	0	0	0	**44**	4	**32**	0	**100**	5	**100**	**30**	**100**	**100**	1
TL payload CG_z	0	0	0	0	**100**	7	9	**20**	**42**	1	7	3	2	2	0
TL payload I_{xx}	0	0	0	0	2	1	2	1	5	0	0	2	0	0	0
TL payload I_{yy}/I_{zz}	0	0	0	0	1	**58**	**22**	**100**	7	**19**	**14**	**20**	6	1	3

Table B.8: Inertial CV matrix - tridem interlink

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
PM sprung mass	5	1	9	8	2	7	1	0	3	2	3	9	5	8	**99**
TL 1 sprung mass	6	5	**12**	**10**	2	1	1	8	5	4	1	2	4	1	8
TL 2 sprung mass	6	6	**11**	**10**	6	**22**	**15**	1	8	4	0	4	0	0	1
PM CG_x	0	5	0	0	0	5	4	3	1	2	1	1	5	1	**33**
TL 1 CG_x	0	**10**	0	0	4	1	**84**	5	1	2	1	**14**	7	3	3
TL 2 CG_x	0	2	0	0	7	**15**	8	9	2	7	0	**13**	**10**	3	3
PM CG_y	0	0	0	0	7	7	**13**	3	**13**	**12**	**35**	**24**	**24**	**17**	4
TL 1 CG_y	0	0	0	0	**11**	1	**15**	2	**10**	7	**22**	3	**20**	**11**	1
TL 2 CG_y	0	0	0	0	**17**	0	**18**	3	**17**	4	**31**	1	4	**10**	0
PM CG_z	0	0	0	0	4	2	2	1	3	0	0	2	0	0	1
TL 1 CG_z	0	0	0	0	**11**	1	7	4	2	0	1	1	0	0	0
TL 2 CG_z	0	0	0	0	**19**	2	**21**	4	5	0	1	0	0	0	0
PM I_{xx}	0	0	0	0	0	0	**29**	0	0	0	0	1	0	0	2
TL 1 I_{xx}	0	0	0	0	0	0	**10**	0	1	0	0	1	0	0	0
TL 2 I_{xx}	0	0	0	0	1	1	6	1	0	0	0	0	0	0	0
PM I_{yy}/I_{zz}	0	0	0	0	0	3	3	6	2	0	0	3	1	0	1
TL 1 I_{yy}/I_{zz}	0	0	0	0	0	8	7	**15**	1	0	1	1	1	0	0
TL 2 I_{yy}/I_{zz}	0	0	0	0	0	**33**	**15**	**29**	1	0	1	1	0	0	0
TL 1 payload mass	**100**	**100**	**100**	**100**	**100**	**92**	**100**	**73**	**52**	**100**	6	**100**	**59**	**100**	**100**
TL 2 payload mass	**67**	**59**	**100**	**100**	**13**	**62**	**13**	**51**	**69**	**58**	6	**21**	**16**	3	6
TL 1 payload CG_x	0	**18**	0	0	9	1	**25**	**13**	2	2	1	**26**	**15**	5	4
TL 2 payload CG_x	0	3	0	0	**11**	**25**	**27**	**18**	1	**13**	1	**24**	**19**	6	6
TL 1 payload CG_y	0	0	0	0	**75**	1	**16**	9	**56**	**39**	**93**	**15**	**100**	**66**	1
TL 2 payload CG_y	0	0	0	0	**94**	1	**51**	**24**	**100**	**18**	**100**	4	**25**	**67**	0
TL 1 payload CG_z	0	0	0	0	**75**	**16**	**28**	**18**	6	1	4	1	1	1	0
TL 2 payload CG_z	0	0	0	0	**95**	**13**	**20**	**30**	**31**	0	3	0	1	0	0
TL 1 payload I_{xx}	0	0	0	0	1	1	**30**	0	1	0	0	0	0	0	0
TL 2 payload I_{xx}	0	0	0	0	1	3	**30**	3	3	0	1	1	0	0	0
TL 1 payload I_{yy}/I_{zz}	0	0	0	0	0	**19**	**17**	**45**	3	2	2	3	3	1	1
TL 2 payload I_{yy}/I_{zz}	0	0	0	0	1	**100**	**36**	**100**	5	1	4	1	0	0	0

Table B.9: Inertial CV matrix - rigid drawbar combination

VDP	STA	GRAa	GRAb	ACC	SRTt	SRTtrrcu	YDC	RA	HSTO	TASP	LSSP	TS	FS	STFD
PM sprung mass	3	1	6	4	0	0	3	1	2	1	6	2	7	59
DL sprung mass	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TL sprung mass	2	2	3	2	3	1	0	0	1	2	1	0	1	2
PM CG_x	0	6	0	0	0	0	2	1	0	1	14	2	6	29
DL CG_x	0	0	0	0	0	0	0	0	0	0	1	0	1	2
TL CG_x	0	0	0	0	7	3	1	4	1	0	2	0	2	2
PM CG_y	0	0	0	0	16	0	3	0	3	7	4	18	12	20
DL CG_y	0	0	0	0	1	0	0	0	0	1	0	0	0	0
TL CG_y	0	0	0	0	9	3	0	1	1	10	1	0	0	0
PM CG_z	0	0	0	0	6	0	0	1	0	3	0	0	0	0
DL CG_z	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TL CG_z	0	0	0	0	11	4	1	2	2	2	0	0	0	0
PM I_{xx}	0	0	0	0	0	0	0	2	4	3	0	0	0	0
DL I_{xx}	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TL I_{xx}	0	0	0	0	1	0	1	0	1	1	0	0	0	0
PM I_{yy}/I_{zz}	0	0	0	0	0	0	3	2	5	1	0	2	1	3
DL I_{yy}/I_{zz}	0	0	0	0	5	0	0	0	0	0	0	0	0	0
TL I_{yy}/I_{zz}	0	0	0	0	0	0	2	1	4	2	0	0	0	0
PM payload mass	100	100	45	40	0	0	19	17	14	25	100	10	100	100
TL payload mass	67	36	100	100	22	79	100	100	100	45	42	0	30	16
PM payload CG_x	0	12	0	0	3	0	7	3	2	10	20	3	15	71
TL payload CG_x	0	0	0	0	21	9	4	2	6	2	10	0	9	5
PM payload CG_y	0	0	0	0	59	0	4	1	6	13	6	36	23	33
TL payload CG_y	0	0	0	0	100	40	2	5	14	100	14	100	0	1
PM payload CG_z	0	0	0	0	50	0	6	46	40	22	0	2	4	3
TL payload CG_z	0	0	0	0	97	100	32	23	47	52	1	0	0	0
PM payload I_{xx}	0	0	0	0	0	0	21	34	58	50	0	1	0	1
TL payload I_{xx}	0	0	0	0	1	0	6	6	7	6	0	0	0	0
PM payload I_{yy}/I_{zz}	0	0	0	0	0	0	6	4	9	1	0	3	1	2
TL payload I_{yy}/I_{zz}	0	0	0	0	1	0	13	8	29	10	0	0	1	0

B.6 Suspension CV Matrices

The suspension CV matrices containing only the suspension VDPs for each of the baseline combinations are included in Tables B.10 to B.12.

Table B.10: Suspension CV matrix - quad semi-trailer

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
St. unsprung mass	28	20	20	33	0	0	3	4	0	3	9	0	5	3	46
Dr. unsprung mass	72	100	59	72	0	3	13	15	1	7	29	0	10	7	29
Tl. unsprung mass	100	76	100	100	22	0	3	0	1	3	3	0	11	6	10
St. axle track	0	0	0	0	2	3	1	2	0	100	66	100	18	92	71
Dr. axle track	0	0	0	0	9	1	8	5	2	0	0	0	1	1	4
Tl. axle track	0	0	0	0	81	7	15	7	13	1	1	0	3	2	0
St. axle centre height	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0
Dr. axle centre height	0	0	0	0	3	0	1	1	0	0	0	0	0	0	1
Tl. axle centre height	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0
St. roll centre height	0	0	0	0	6	2	11	6	1	2	8	0	2	1	2
Dr. roll centre height	0	0	0	0	43	23	100	50	4	6	3	1	14	2	28
Tl. roll centre height	0	0	0	0	9	13	22	0	7	4	17	0	10	5	2
St. roll steer coef.	0	0	0	0	6	65	3	1	0	1	4	0	1	0	2
Dr. roll steer coef.	0	0	0	0	12	92	3	39	10	9	3	1	31	18	29
Tl. roll steer coef.	0	0	0	0	2	22	54	100	30	0	17	0	6	3	3
St. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
Dr. I_{xx}/I_{zz}	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Tl. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. spin inertia	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1
Dr. spin inertia	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2
Tl. spin inertia	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
St. wheel centre height	0	0	0	0	1	1	2	1	3	0	1	1	4	6	5
Dr. wheel centre height	0	0	0	0	2	2	1	2	0	5	31	1	23	23	2
Tl. wheel centre height	0	0	0	0	11	7	9	8	5	5	19	0	36	18	2
St. aux. roll stiffness	0	0	0	0	19	6	13	4	1	1	2	0	3	1	2
Dr. aux. roll stiffness	0	0	0	0	100	16	78	15	9	2	46	1	21	4	12
Tl. aux. roll stiffness	0	0	0	0	34	100	89	52	100	6	100	0	21	6	2
St. damper	0	0	0	0	3	0	2	3	1	0	1	0	0	0	22
Dr. damper	0	0	0	0	2	1	1	4	3	0	1	0	0	0	4
Tl. damper	0	0	0	0	5	0	14	3	2	0	0	0	0	0	2
St. damper track	0	0	0	0	0	0	1	1	0	0	0	0	0	0	5
Dr. damper track	0	0	0	0	0	0	1	1	0	0	0	0	0	0	2
Tl. damper track	0	0	0	0	0	0	9	2	0	0	0	0	0	0	2
St. jounce / rebound	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0
Dr. jounce / rebound	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
Tl. jounce / rebound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. spring	0	0	0	0	8	3	3	3	4	2	26	1	7	7	6
Dr. spring	0	0	0	0	11	13	23	17	0	21	43	4	100	100	100
Tl. spring	0	0	0	0	9	2	7	7	2	10	32	0	56	30	2
St. spring track	0	0	0	0	8	5	5	5	0	0	2	0	1	0	3
Dr. spring track	0	0	0	0	11	2	10	2	1	0	6	0	2	0	2
Tl. spring track	0	0	0	0	3	6	17	7	7	0	6	0	0	0	0

Table B.11: Suspension CV matrix - tridem interlink

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
St. unsprung mass	0	0	15	17	0	4	1	2	0	3	1	0	14	2	5
Dr. unsprung mass	40	95	33	40	0	4	0	10	0	6	0	0	14	5	4
Tl. unsprung mass	100	100	100	100	34	8	1	8	1	2	1	0	10	4	1
St. axle track	0	0	0	0	1	1	0	2	0	100	100	100	28	41	8
Dr. axle track	0	0	0	0	1	1	0	3	1	1	1	0	1	0	0
Tl. axle track	0	0	0	0	94	8	4	17	4	0	1	0	5	1	0
St. axle centre height	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
Dr. axle centre height	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. axle centre height	0	0	0	0	6	1	0	1	0	0	0	0	1	0	0
St. roll centre height	0	0	0	0	3	0	0	4	0	2	1	0	3	2	0
Dr. roll centre height	0	0	0	0	24	2	2	30	1	19	1	1	51	75	100
Tl. roll centre height	0	0	0	0	17	15	6	10	3	1	2	0	17	4	0
St. roll steer coef.	0	0	0	0	1	32	0	1	0	1	1	0	1	1	0
Dr. roll steer coef.	0	0	0	0	4	37	4	17	2	9	0	1	51	16	4
Tl. roll steer coef.	0	0	0	0	1	21	1	100	18	0	2	0	0	0	0
St. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Dr. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Tl. I_{xx}/I_{zz}	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0
St. spin inertia	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0
Dr. spin inertia	0	0	0	0	0	0	0	0	0	15	2	1	52	100	61
Tl. spin inertia	0	0	0	0	0	1	0	2	0	0	1	0	1	0	0
St. wheel centre height	0	0	0	0	1	0	0	0	1	1	0	1	4	5	1
Dr. wheel centre height	0	0	0	0	1	0	0	2	0	2	3	1	21	14	0
Tl. wheel centre height	0	0	0	0	8	2	1	3	1	1	1	0	29	7	0
St. aux. roll stiffness	0	0	0	0	7	3	2	1	0	1	0	0	4	1	1
Dr. aux. roll stiffness	0	0	0	0	53	10	8	7	2	5	7	1	29	3	1
Tl. aux. roll stiffness	0	0	0	0	100	100	100	66	100	6	53	0	46	7	0
St. damper	0	0	0	0	0	1	4	2	0	0	0	0	0	0	3
Dr. damper	0	0	0	0	0	0	4	3	2	0	1	0	1	0	1
Tl. damper	0	0	0	0	2	3	4	3	2	0	0	0	0	0	0
St. damper track	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1
Dr. damper track	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
Tl. damper track	0	0	0	0	1	2	0	2	0	0	0	0	0	0	0
St. jounce / rebound	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Dr. jounce / rebound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. jounce / rebound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. spring	0	0	0	0	2	1	0	1	1	1	0	1	7	5	1
Dr. spring	0	0	0	0	6	1	2	2	0	1	3	4	100	61	13
Tl. spring	0	0	0	0	15	6	8	3	1	4	1	0	74	14	0
St. spring track	0	0	0	0	3	2	0	2	0	1	1	0	1	0	0
Dr. spring track	0	0	0	0	5	1	1	1	0	1	1	0	4	0	0
Tl. spring track	0	0	0	0	5	1	7	7	2	0	2	0	3	0	0

Table B.12: Suspension CV matrix - rigid drawbar combination

VDP	STA	GRAa	GRAb	ACC	SRTt	SRTtrrcu	YDC	RA	HSTO	TASP	LSSP	TS	FS	STFD
St. unsprung mass	22	0	14	13	0	0	1	0	0	0	16	14	1	6
Dr. unsprung mass	26	94	33	37	0	0	1	0	0	0	18	9	0	6
Tl. unsprung mass	100	100	100	100	10	10	1	2	1	0	5	1	0	2
St. axle track	0	0	0	0	0	0	0	0	0	0	100	9	100	100
Dr. axle track	0	0	0	0	0	0	0	1	0	0	1	7	0	0
Tl. axle track	0	0	0	0	36	37	5	3	3	5	0	0	0	0
St. axle centre height	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Dr. axle centre height	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. axle centre height	0	0	0	0	1	1	0	1	0	0	0	0	0	0
St. roll centre height	0	0	0	0	0	0	1	1	1	0	0	8	0	0
Dr. roll centre height	0	0	0	0	4	0	12	15	7	0	16	53	2	4
Tl. roll centre height	0	0	0	0	7	7	7	1	3	2	2	2	0	0
St. roll steer coef.	0	0	0	0	0	0	22	0	0	0	0	3	0	4
Dr. roll steer coef.	0	0	0	0	0	0	54	12	21	12	8	100	1	2
Tl. roll steer coef.	0	0	0	0	0	1	8	1	15	6	3	1	0	1
St. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Dr. I_{xx}/I_{zz}	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. I_{xx}/I_{zz}	0	0	0	0	0	0	0	1	0	0	0	0	0	0
St. spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. spin inertia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. spin inertia	0	0	0	0	5	29	0	0	0	0	0	0	0	0
St. wheel centre height	0	0	0	0	0	0	0	0	0	1	1	9	1	3
Dr. wheel centre height	0	0	0	0	0	0	1	0	0	0	1	3	1	2
Tl. wheel centre height	0	0	0	0	3	3	0	0	0	1	0	1	0	0
St. aux. roll stiffness	0	0	0	0	8	0	2	15	11	3	0	14	0	2
Dr. aux. roll stiffness	0	0	0	0	77	1	100	97	100	8	3	68	2	12
Tl. aux. roll stiffness	0	0	0	0	100	100	61	100	22	100	21	1	0	0
St. damper	0	0	0	0	0	0	2	1	2	1	1	6	0	10
Dr. damper	0	0	0	0	0	0	2	2	3	0	0	6	0	1
Tl. damper	0	0	0	0	1	0	1	16	1	0	0	1	0	0
St. damper track	0	0	0	0	0	0	0	1	1	0	0	0	0	0
Dr. damper track	0	0	0	0	0	0	1	2	1	0	0	1	0	0
Tl. damper track	0	0	0	0	0	0	1	0	0	0	0	0	0	0
St. jounce / rebound	0	0	0	0	0	0	1	5	2	1	0	0	0	0
Dr. jounce / rebound	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tl. jounce / rebound	0	0	0	0	0	0	0	0	0	0	0	0	0	0
St. spring	0	0	0	0	0	0	1	3	2	2	2	8	1	3
Dr. spring	0	0	0	0	1	1	2	13	9	1	0	25	3	5
Tl. spring	0	0	0	0	5	5	5	2	2	1	1	1	0	0
St. spring track	0	0	0	0	0	0	2	5	4	1	0	16	0	1
Dr. spring track	0	0	0	0	0	0	3	12	9	2	0	14	0	1
Tl. spring track	0	0	0	0	2	3	4	1	2	2	0	0	0	0

B.7 Tyre CV Matrices

The tyre CV matrices containing only the tyre VDPs for each of the baseline combinations are included in Tables B.13 to B.15.

Table B.13: Tyre CV matrix - quad semi-trailer

VDP	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
Dr. dual spacing	0	-	0	0	1	0	0	0	0	0	0	1	0	1	0
St. eff. rolling radius	0	-	0	0	0	0	0	0	0	0	0	1	0	0	0
Dr. eff. rolling radius	100	-	100	100	0	0	0	0	0	0	4	1	0	0	0
Tl. eff. rolling radius	0	-	0	0	0	0	0	0	0	0	0	0	0	0	0
Dr. L for F_y & M_z	0	-	0	0	82	2	27	8	0	7	35	10	5	2	1
Tl. L for F_y & M_z	0	-	0	0	38	6	42	17	1	17	100	13	17	3	2
St. cornering stiffness	0	-	0	0	16	100	5	2	4	12	91	12	17	7	32
Dr. cornering stiffness	0	-	0	0	55	2	94	61	27	90	35	100	100	100	100
Tl. cornering stiffness	0	-	0	0	16	15	100	100	100	100	45	76	99	99	14
St. spring rate	0	-	0	0	18	1	0	2	7	1	30	57	4	16	5
Dr. spring rate	0	-	0	0	100	1	11	5	3	10	78	18	16	24	3
Tl. spring rate	0	-	0	0	44	3	22	2	18	13	46	1	20	19	0
St. unloaded radius	0	-	0	0	2	0	0	0	3	0	3	14	2	4	1
Dr. unloaded radius	0	-	0	0	2	0	1	0	0	6	27	15	8	14	1
Tl. unloaded radius	0	-	0	0	52	1	1	1	3	37	77	4	11	11	1
St. wheel spin inertia	0	-	0	0	2	0	0	0	0	0	3	1	0	0	0
Dr. wheel spin inertia	0	-	0	0	2	0	0	0	0	0	5	0	0	0	0
Tl. wheel spin inertia	0	-	0	0	1	0	0	0	0	0	4	2	0	0	0

Table B.14: Tyre CV matrix - tridem interlink

VDP	**STA**	**GRAa**	**GRAb**	**ACC**	**SRTt**	**YDC**	**RA**	**HSTO**	**TASP**	**LSSP**	**TS**	**FS**	**MoD**	**DoM**	**STFD**
Dr. dual spacing	0	-	0	0	0	0	0	0	0	0	2	2	0	0	0
Tl. dual spacing	0	-	0	0	1	0	0	0	0	0	1	1	0	0	0
St. eff. rolling radius	0	-	0	0	0	0	0	0	0	1	1	1	0	0	0
Dr. eff. rolling radius	100	-	100	100	0	0	0	0	0	0	5	1	0	0	1
Tl. eff. rolling radius	0	-	0	0	0	0	0	0	0	0	1	1	0	0	0
Dr. L for F_y & M_z	0	-	0	0	5	16	26	9	3	6	13	2	5	3	2
Tl. L for F_y & M_z	0	-	0	0	19	37	50	22	7	14	56	4	20	10	1
St. cornering stiffness	0	-	0	0	1	100	13	1	7	10	10	10	7	4	30
Dr. cornering stiffness	0	-	0	0	4	26	28	33	14	100	3	100	89	40	100
Tl. cornering stiffness	0	-	0	0	9	71	26	100	100	35	100	64	100	100	14
St. spring rate	0	-	0	0	10	2	3	1	6	4	5	60	4	16	6
Dr. spring rate	0	-	0	0	40	2	0	3	2	4	8	18	11	20	3
Tl. spring rate	0	-	0	0	100	35	100	2	15	3	13	2	1	3	1
St. unloaded radius	0	-	0	0	0	0	0	0	3	1	3	15	1	4	1
Dr. unloaded radius	0	-	0	0	0	0	0	0	1	2	2	14	7	13	1
Tl. unloaded radius	0	-	0	0	17	1	0	0	2	3	2	2	8	4	0
St. wheel spin inertia	0	-	0	0	0	0	0	0	0	1	9	1	0	0	0
Dr. wheel spin inertia	0	-	0	0	0	0	0	0	0	2	11	2	0	0	0
Tl. wheel spin inertia	0	-	0	0	0	1	0	0	1	0	2	1	0	0	0

Table B.15: Tyre CV matrix - rigid drawbar combination

VDP	**STA**	**GRAa**	**GRAb**	**ACC**	**SRTt**	**SRTtrrcu**	**YDC**	**RA**	**HSTO**	**TASP**	**LSSP**	**TS**	**FS**	**STFD**
Dr. dual spacing	0	-	0	0	0	0	0	0	0	0	0	1	0	0
Tl. dual spacing	0	-	0	0	0	0	0	0	0	0	0	0	0	0
St. eff. rolling radius	0	-	0	0	0	0	0	0	0	0	0	0	0	0
Dr. eff. rolling radius	100	-	100	100	0	0	0	0	0	1	0	0	1	0
Tl. eff. rolling radius	0	-	0	0	1	0	0	0	0	0	0	0	0	0
Dr. L for F_y & M_z	0	-	0	0	9	8	2	27	15	11	12	92	8	1
Tl. L for F_y & M_z	0	-	0	0	11	15	4	36	15	4	11	100	7	0
St. cornering stiffness	0	-	0	0	0	0	100	3	1	12	54	83	13	100
Dr. cornering stiffness	0	-	0	0	8	5	4	100	87	55	69	58	74	9
Tl. cornering stiffness	0	-	0	0	3	5	8	26	100	100	100	4	100	0
St. spring rate	0	-	0	0	2	0	0	3	1	21	2	8	35	0
Dr. spring rate	0	-	0	0	1	2	1	46	22	12	3	70	8	0
Tl. spring rate	0	-	0	0	100	100	4	7	15	48	0	2	0	0
St. unloaded radius	0	-	0	0	0	0	0	1	0	5	1	7	9	0
Dr. unloaded radius	0	-	0	0	1	1	0	1	1	2	0	4	11	0
Tl. unloaded radius	0	-	0	0	7	7	0	0	0	2	0	0	0	0
St. wheel spin inertia	0	-	0	0	0	0	0	0	0	0	0	0	0	0
Dr. wheel spin inertia	0	-	0	0	0	0	0	0	0	0	0	0	0	0
Tl. wheel spin inertia	0	-	0	0	1	0	0	0	0	1	0	0	0	0

C NTC Validation

This appendix includes a set of validation results comparing the PBS performance of the NTC combinations determined by UMTRIs Yaw/Roll program against the TruckSim® 2018 software package.

The results obtained from TruckSim® 2018 are overlaid onto the available UMTRIs yaw/roll results from Prem et al. [22].

C.1 NTC B-Double Validation

The NTC B-double validation graphs are presented in Sections C.1.1 to C.1.4.

C.1.1 B-double Pulse Steer

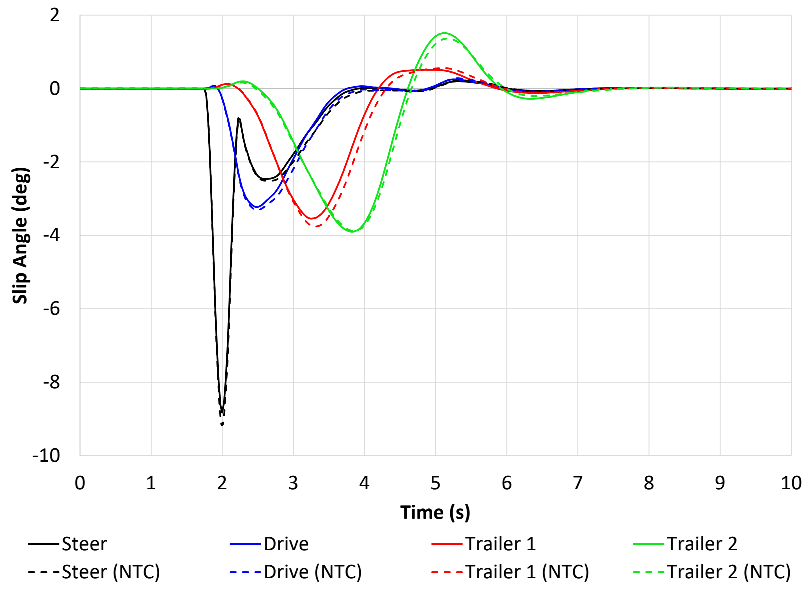

Figure C.1: Tyre slip angles from the B-double pulse steer simulations

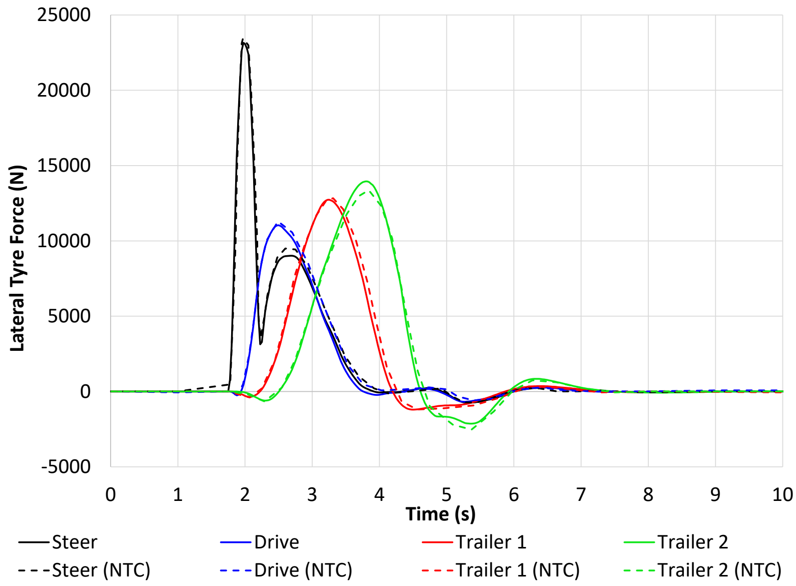

Figure C.2: Lateral tyre forces from the B-double pulse steer simulations

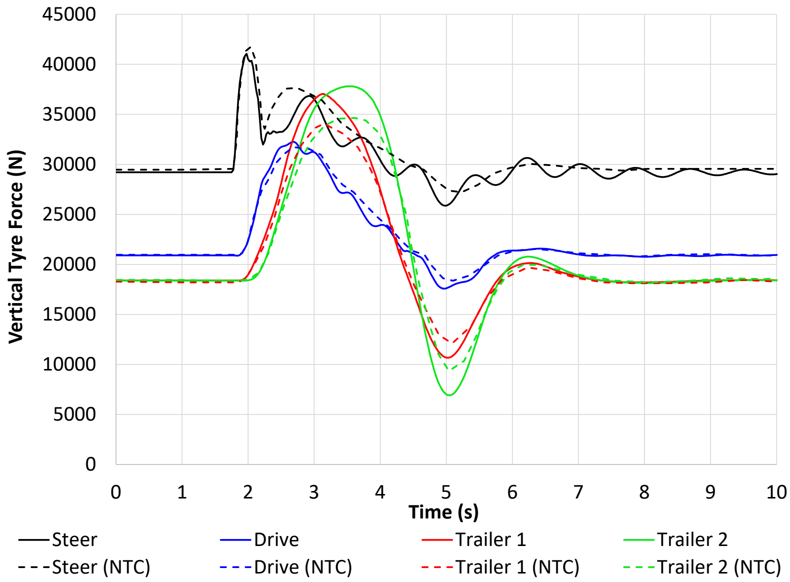

Figure C.3: Vertical tyre forces from the B-double pulse steer simulations

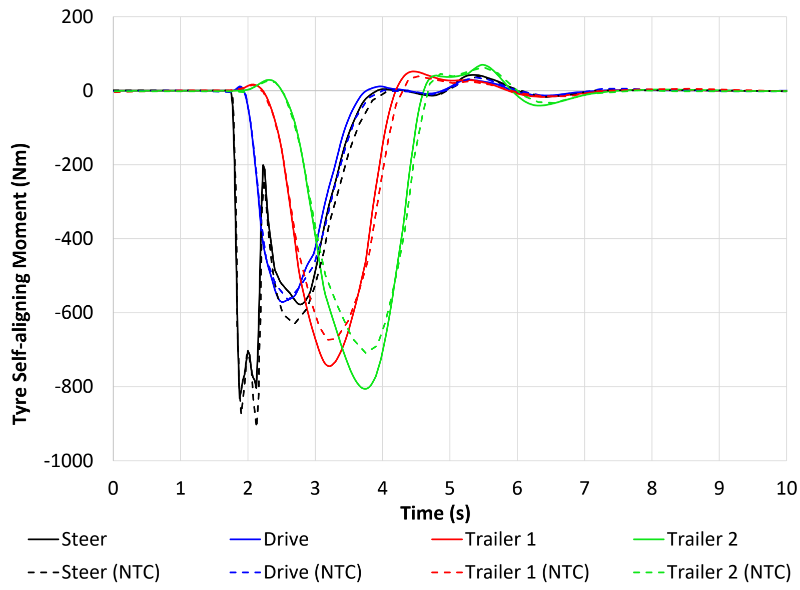

Figure C.4: Self-aligning moments from the B-double pulse steer simulations

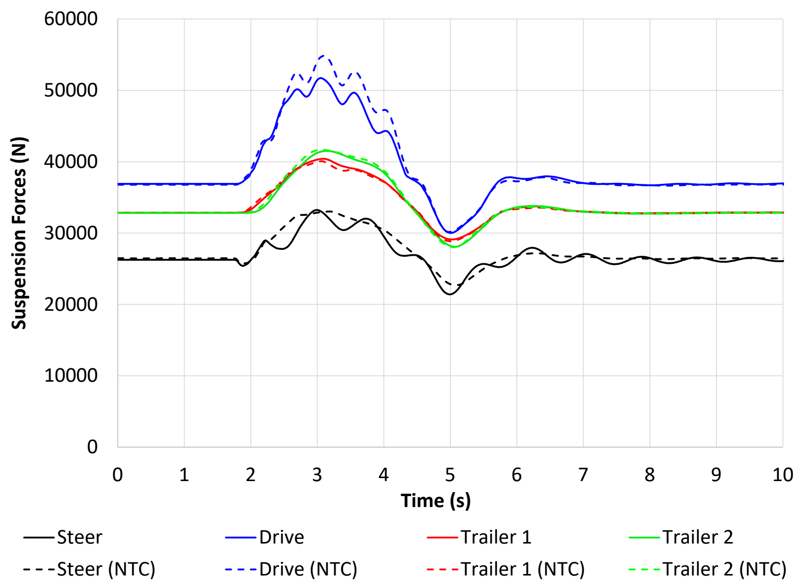

Figure C.5: Suspension forces from the B-double pulse steer simulations

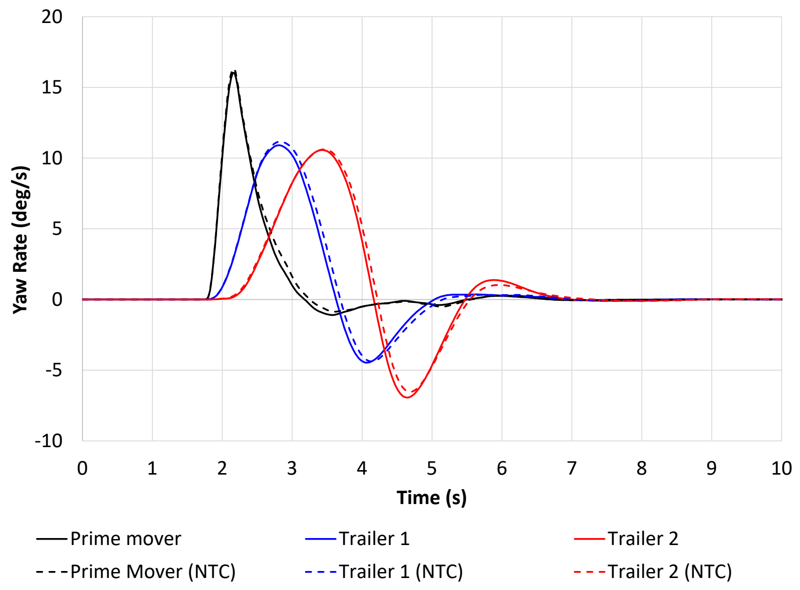

Figure C.6: Yaw rates from the B-double pulse steer simulations

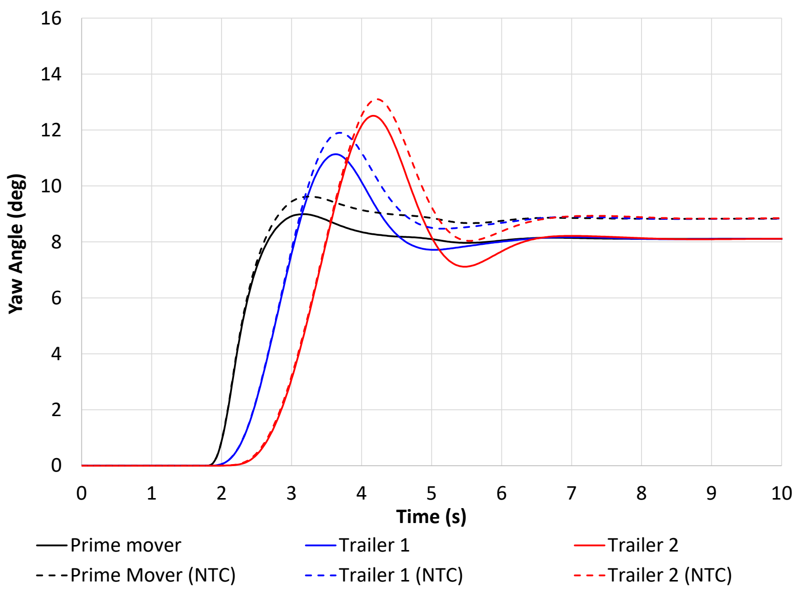

Figure C.7: Yaw angles from the B-double pulse steer simulations

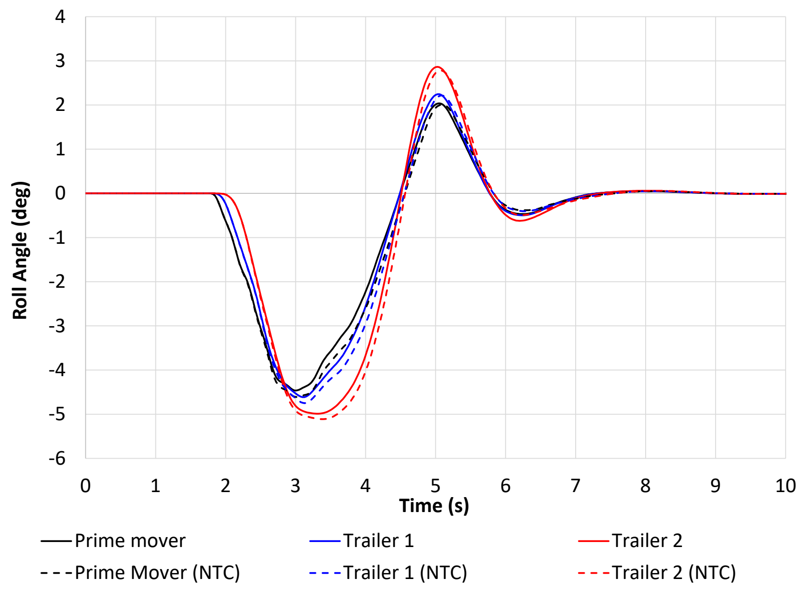

Figure C.8: Roll angles from the B-double pulse steer simulations

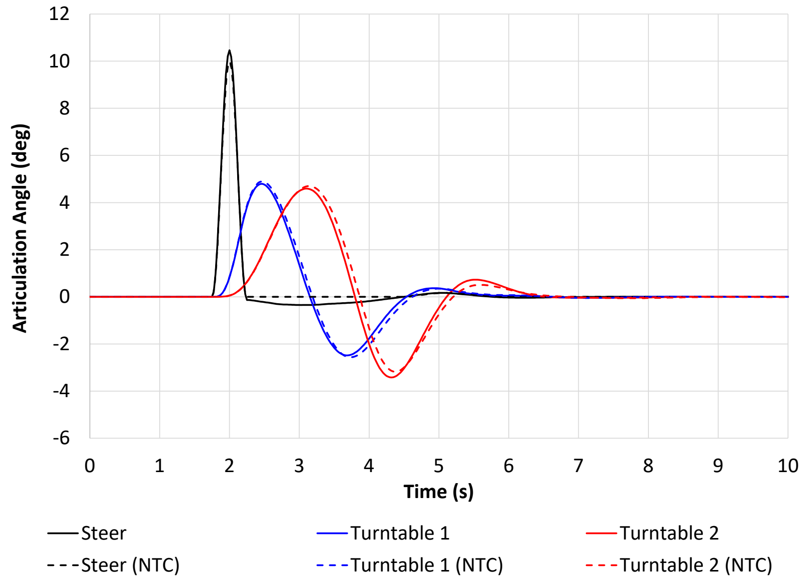

Figure C.9: Articulation angles from the B-double pulse steer simulations

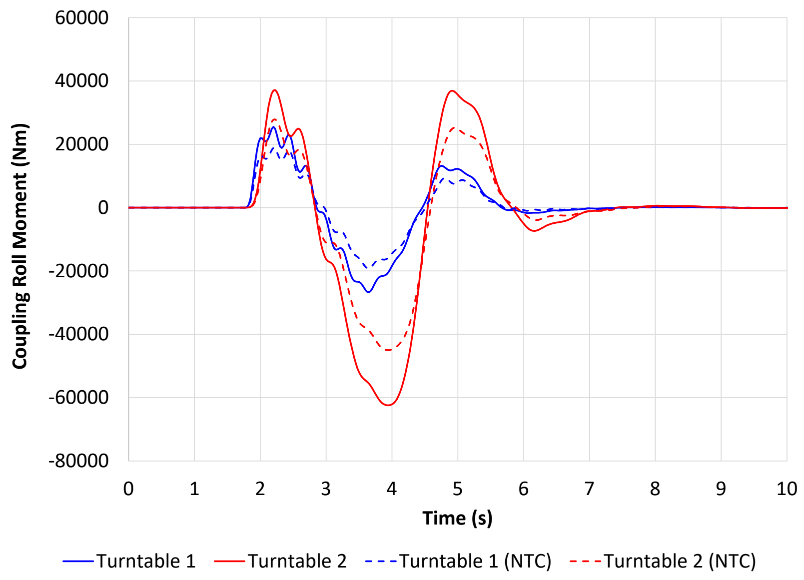

Figure C.10: Coupling roll moments from the B-double pulse steer simulations

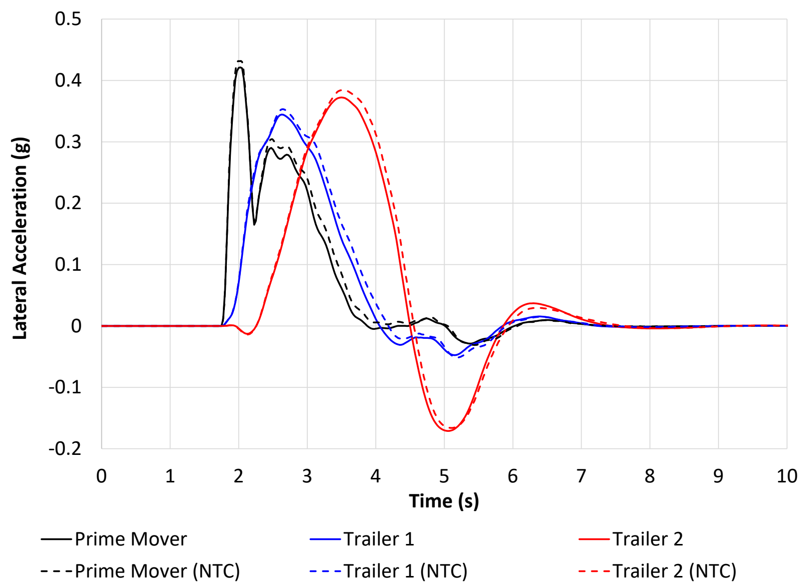

Figure C.11: Lateral accelerations from the B-double pulse steer simulations

C.1.2 B-double Step Steer

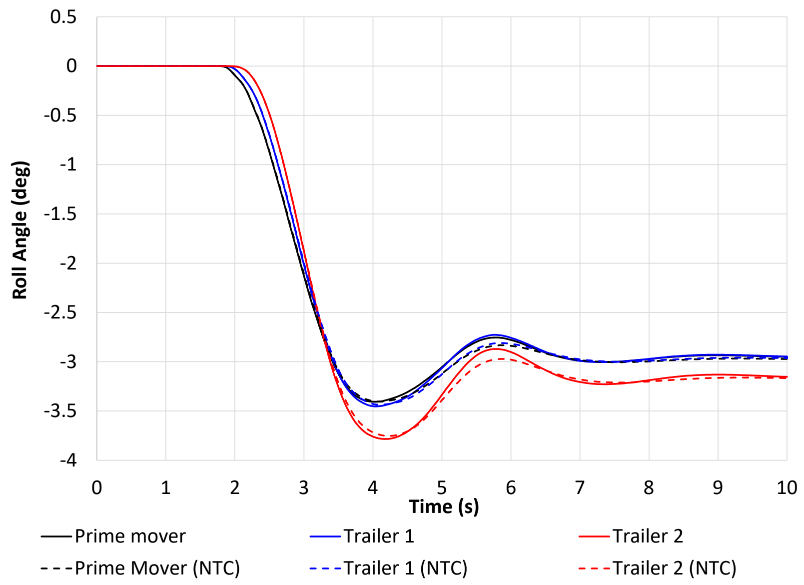

Figure C.12: Roll angle from the B-double step steer simulations

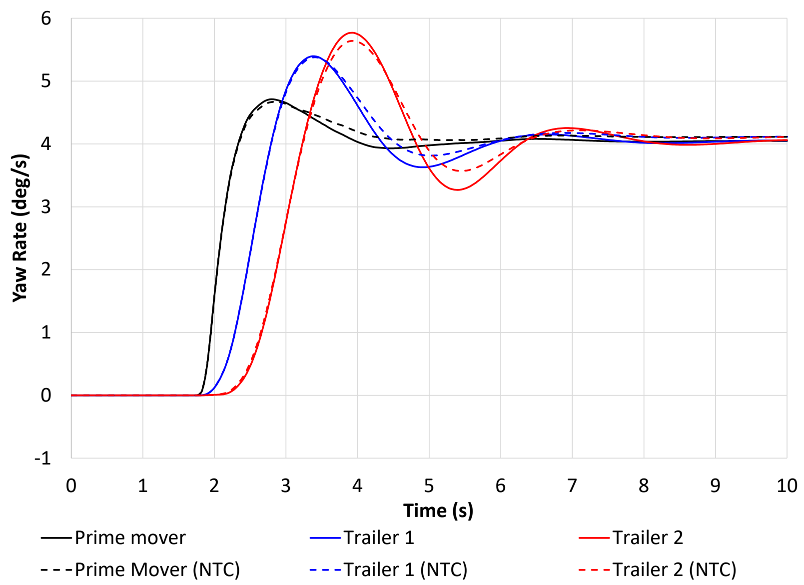

Figure C.13: Yaw rates from the B-double step steer simulations

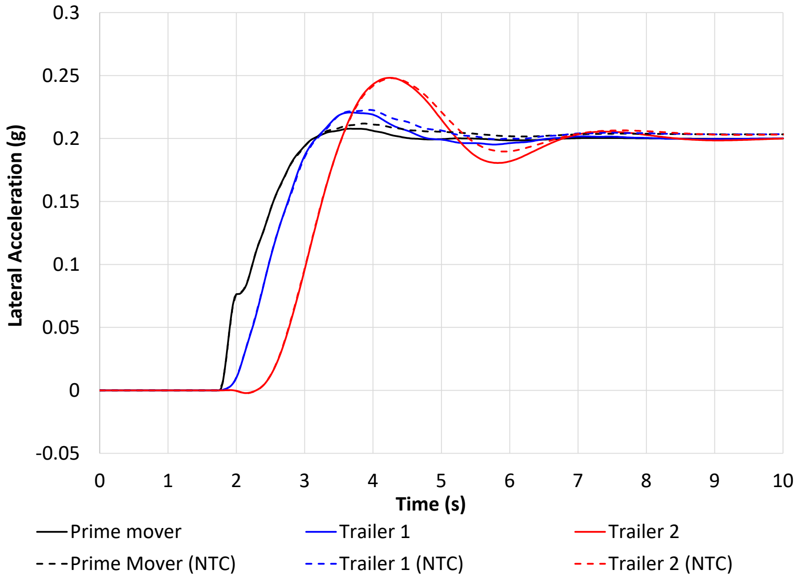

Figure C.14: Lateral accelerations from the B-double step steer simulations

C.1.3 B-double Lane Change

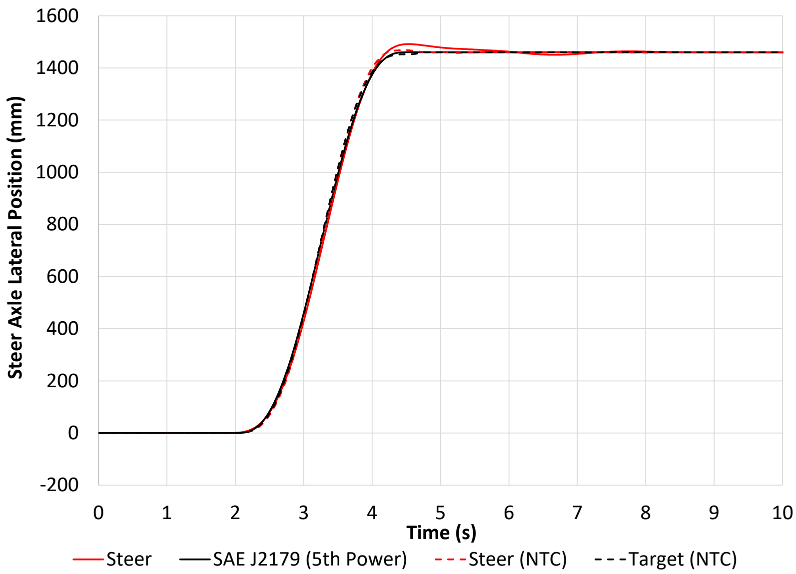

Figure C.15: Steer axle lateral position from the B-double lane change simulations

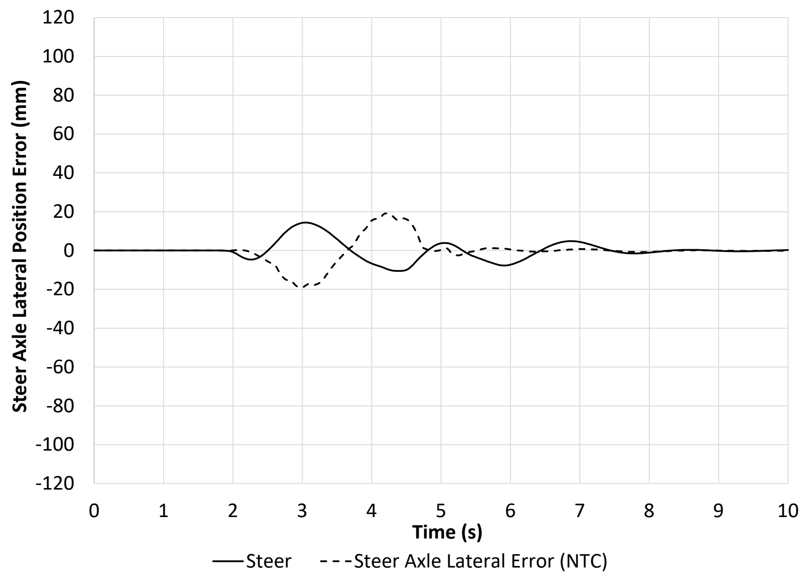

Figure C.16: Steer axle lateral position error from the B-double lane change simulations

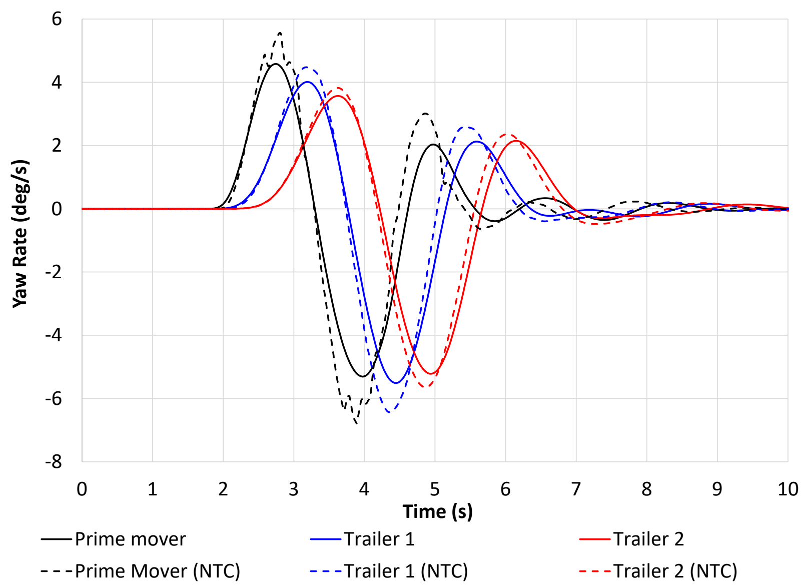

Figure C.17: Yaw rates from the B-double lane change simulations

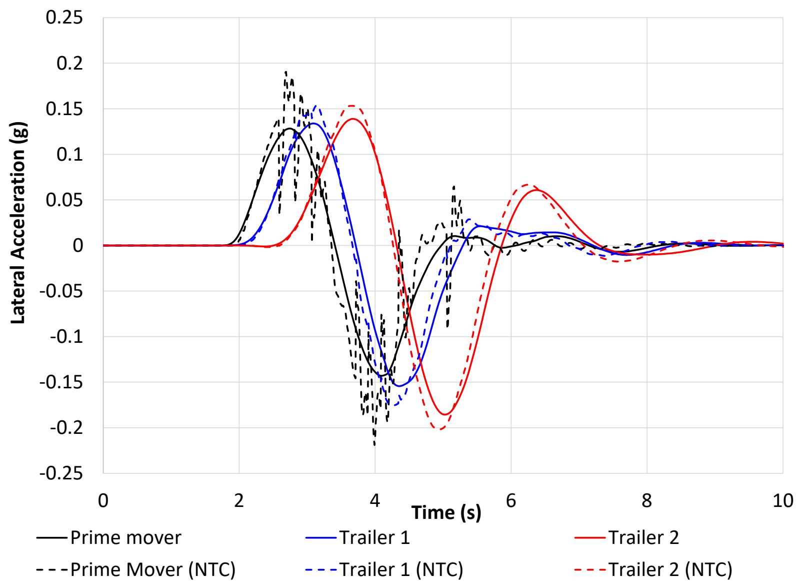

Figure C.18: Lateral accelerations from the B-double lane change simulations

C.1.4 B-double Low-speed 90° Turn

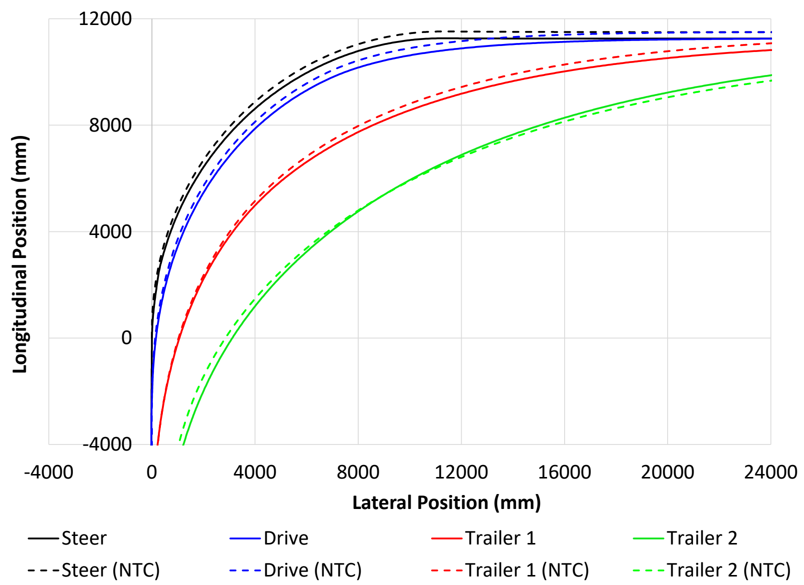

Figure C.19: Trajectories from the B-double low-speed 90° turn simulations

C.2 Truck-trailer Validation

The NTC truck-trailer validation graphs are presented in Sections C.2.1 to C.2.4.

C.2.1 Truck-trailer Pulse Steer

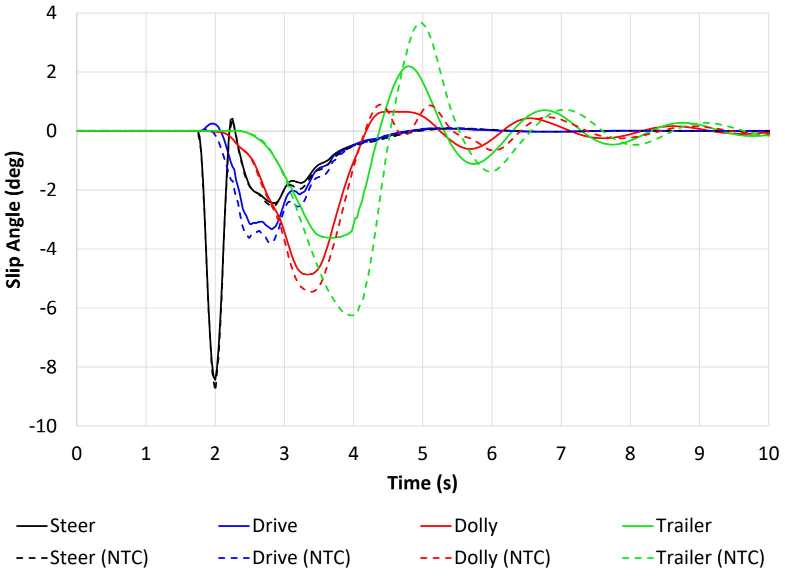

Figure C.20: Tyre slip angles from the truck-trailer pulse steer simulations

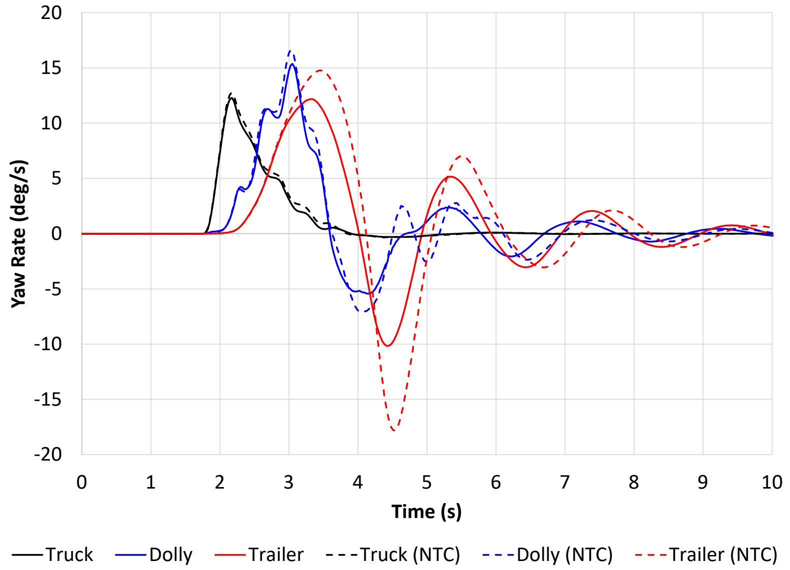

Figure C.21: Yaw rates from the truck-trailer pulse steer simulations

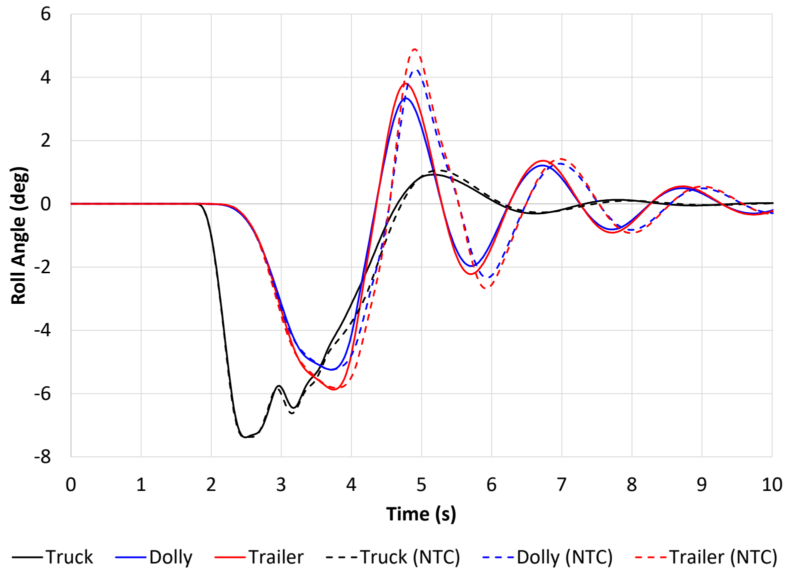

Figure C.22: Roll angles from the truck-trailer pulse steer simulations

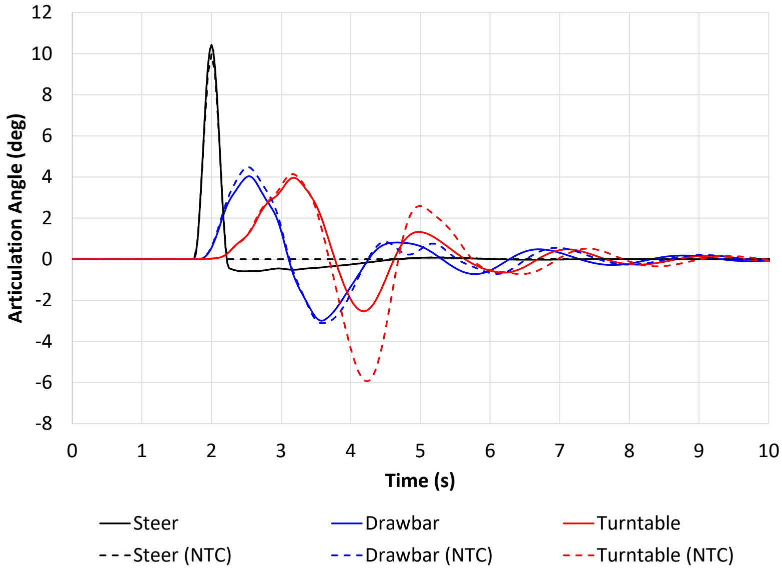

Figure C.23: Articulation angles from the truck-trailer pulse steer simulations

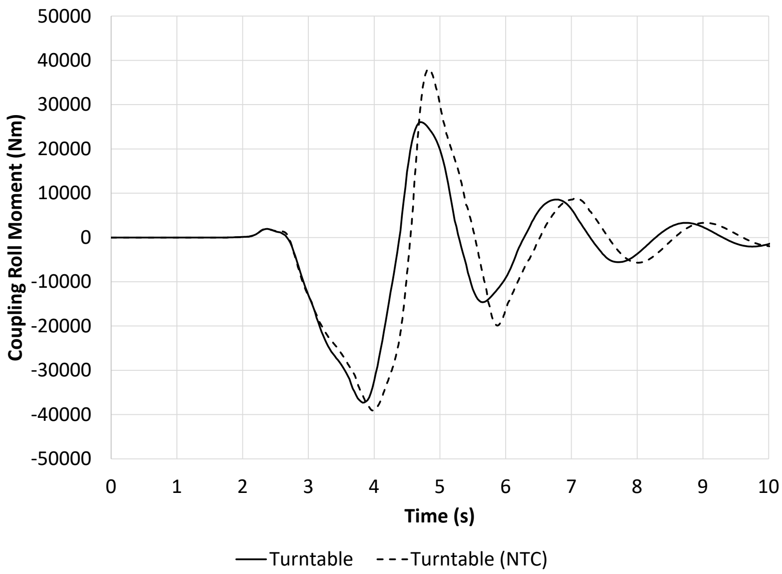

Figure C.24: Turntable coupling roll moments from the truck-trailer pulse steer simulations

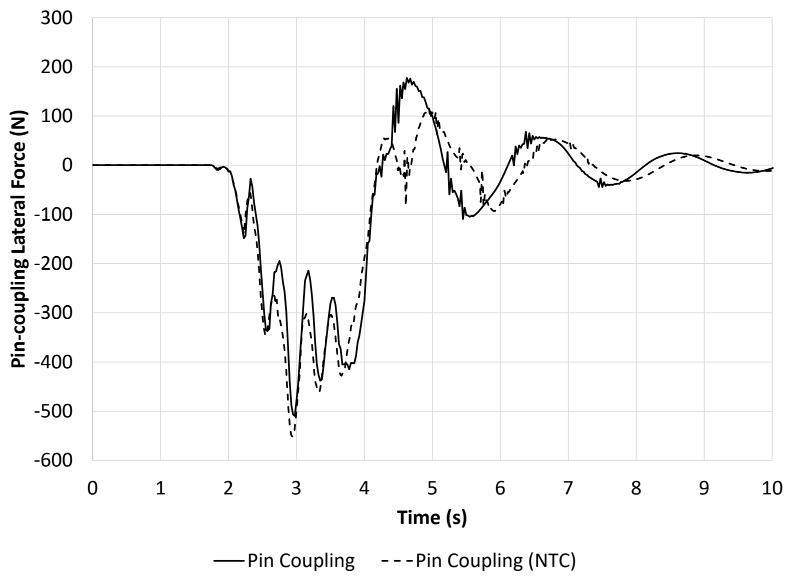

Figure C.25: Pin coupling lateral forces from the truck-trailer pulse steer simulations

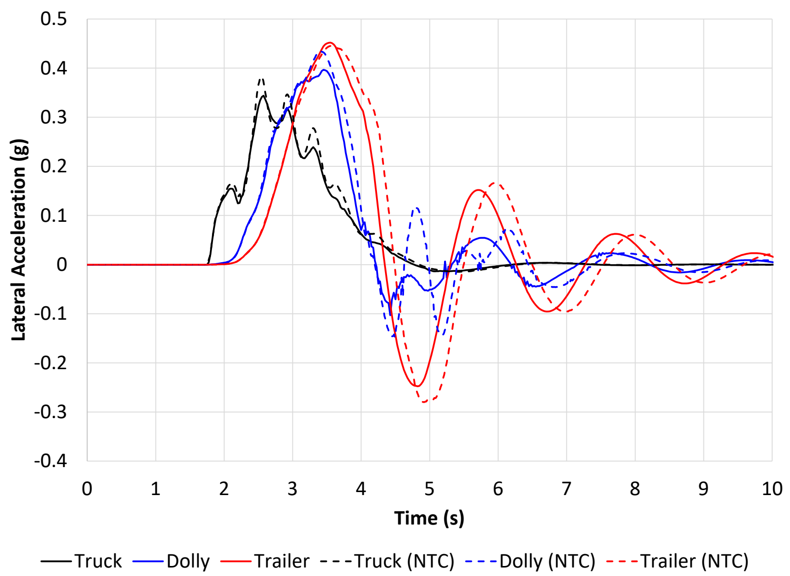

Figure C.26: Lateral accelerations from the truck-trailer pulse steer simulations

C.2.2 Truck-trailer Step Steer

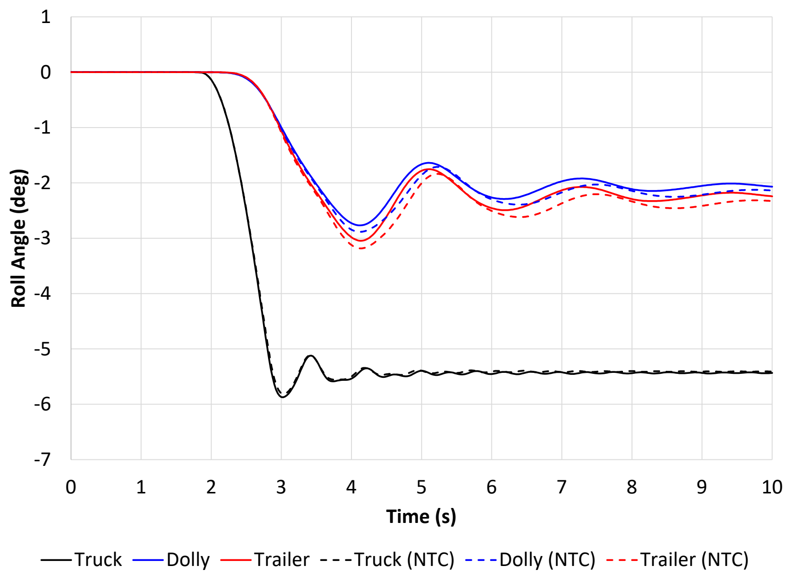

Figure C.27: Roll angles from the truck-trailer step steer simulations

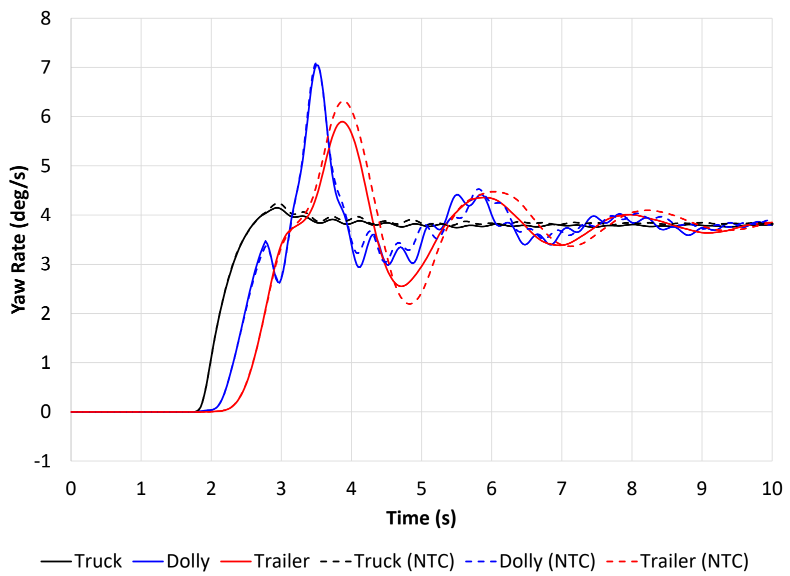

Figure C.28: Yaw rates from the truck-trailer step steer simulations

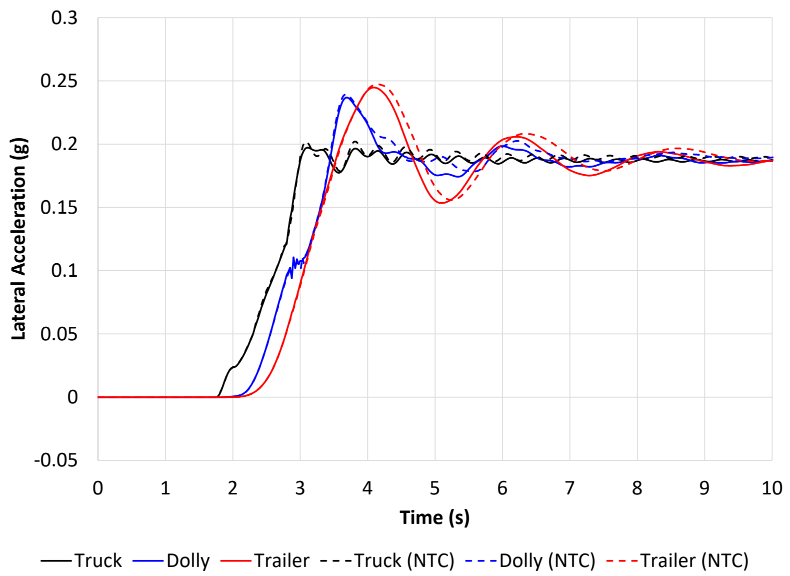

Figure C.29: Lateral accelerations from the truck-trailer step steer simulations

C.2.3 Truck-trailer SAE Lane Change

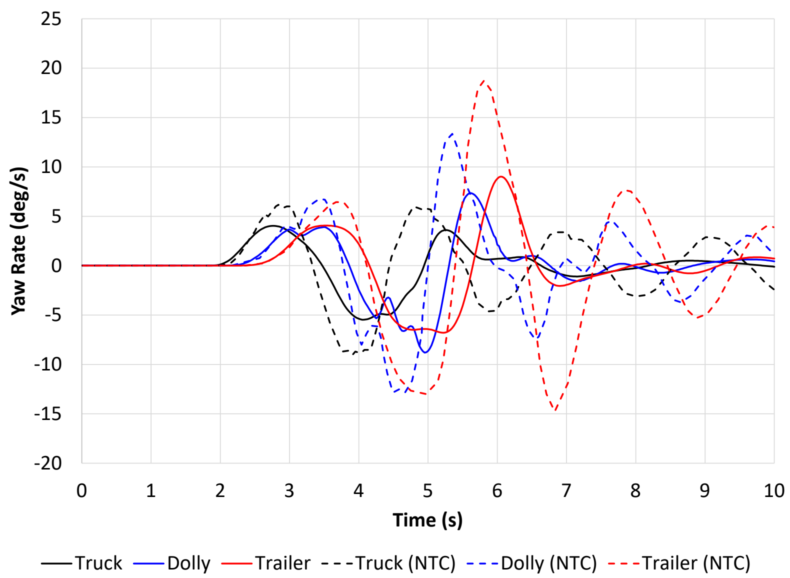

Figure C.30: Yaw rates from the truck-trailer SAE lane change simulations

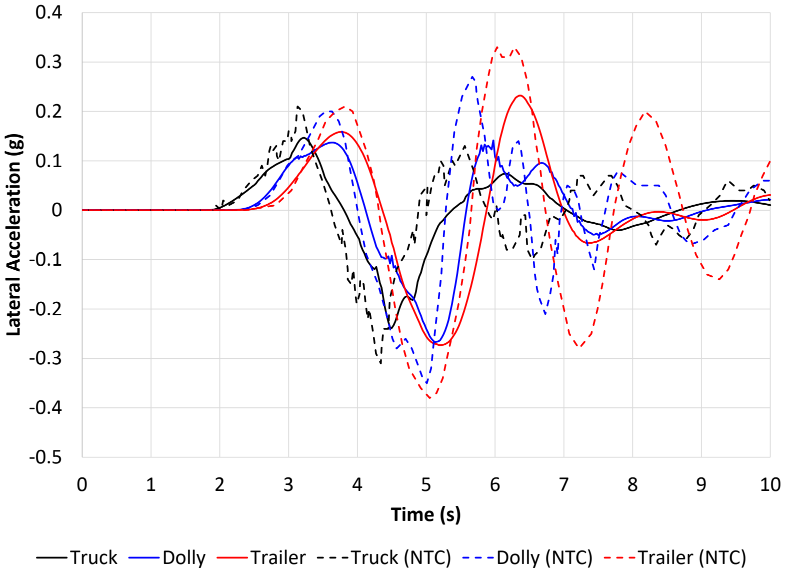

Figure C.31: Lateral accelerations from the truck-trailer SAE lane change simulations

C.2.4 Truck-trailer Low-speed 90° Turn

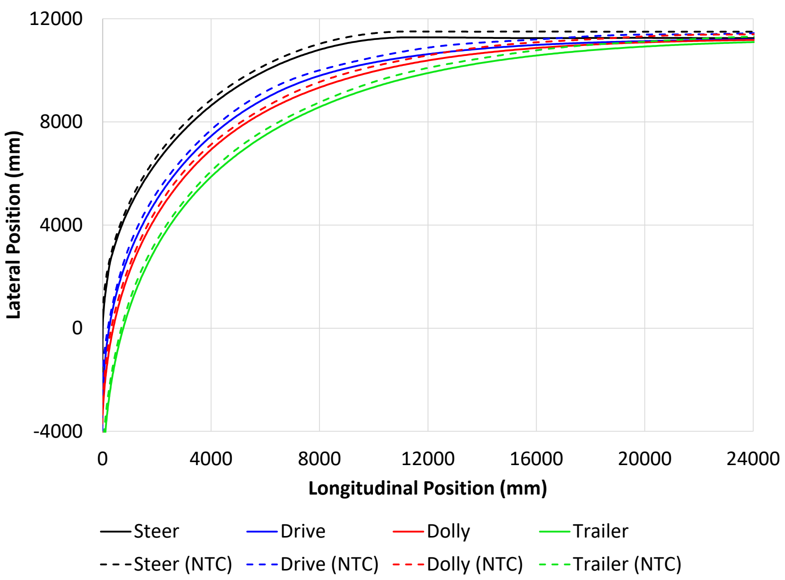

Figure C.32: Trajectories from the truck-trailer low-speed 90° turn simulations

D Manufacturer Data

The sections that follow contain data that has been consolidated from data books published from OEMs in the public domain. This data has been used in aid of determining reasonable ranges of design parameters where applicable in Section 6.

D.1 BPW Rigid Axles

The data included in the BPW rigid axles catalogue has been consolidated into Tables D.1 to D.5.

Table D.1: BPW rigid axles with 300 mm drum brake

OEM Description	Permitted axle load up to 105 km/h (kg)	Tyres	Track width (SP) (mm)	Spring centre (FM) (mm)	Axle cross section (mm)	Tyre size	Tyre example	Overall width (P) (mm)	Axle weight (kg)
NHSF 6410	6,400	Single	2010	1300	120	15"/17.5"/19.5"	10 R152)	2277	270
NHSF 6410	6,400	Single	2195	1500	120	15"/17.5"/19.5"	10 R152)	2462	278
NHZF 6410	6,400	Twin	1830	980	120	15"/17.5"/19.5"	215/75 R17.5	2317	266
NHZF 6410	6,400	Twin	1950	1100	120	15"/17.5"/19.5"	215/75 R17.5	2437	271
NHZF 9010	9000	Twin	1830	980	120	15"/17.5"/19.5"	235/75 R17.5	2365	285
NHZF 9010	9000	Twin	1900	1100	120	15"/17.5"/19.5"	235/75 R17.5	2435	287
NHZF 9010	9000	Twin	1950	1100	120	15"/17.5"/19.5"	235/75 R17.5	2485	289
NHZF 9010	9000	Twin	1995	1100	120	15"/17.5"/19.5"	235/75 R17.5	2530	316
NHZF 10010	10,000	Twin	1830	980	120	15"/17.5"/19.5"	235/75 R17.5	2365	294
NHZF 10010	10,000	Twin	1880	980	120	15"/17.5"/19.5"	235/75 R17.5	2415	297
NHZF 10010	10,000	Twin	1880	1100	120	15"/17.5"/19.5"	235/75 R17.5	2415	297
NHZF 10010	10,000	Twin	1950	1100	120	15"/17.5"/19.5"	235/75 R17.5	2485	302
NHZF 10010	10,000	Twin	1995	1100	120	15"/17.5"/19.5"	235/75 R17.5	2530	304
NHZF 12010	12000	Twin	1830	980	120	15"/17.5"/19.5"	235/75 R17.5	2365	308
NHZF 12010	12000	Twin	1880	980	120	15"/17.5"/19.5"	235/75 R17.5	2415	312
NHZF 12010	12000	Twin	1950	1000	120	15"/17.5"/19.5"	235/75 R17.5	2485	317
NHZF 12010	12000	Twin	1950	1100	120	15"/17.5"/19.5"	235/75 R17.5	2485	317
NHZF 12010	12000	Twin	1995	1100	120	15"/17.5"/19.5"	235/75 R17.5	2530	320

Table D.2: BPW rigid axles with 360 mm drum brake

OEM Description	Permitted axle load up to 105 km/h (kg)	Tyres	Track width (SP) (mm)	Spring centre (FM) (mm)	Axle cross section (mm)	Tyre size	Tyre example	Overall width (P) (mm)	Axle weight (kg)
KHSF 9008	9000	Single	2045	1300	120 x 10	19.5"	425/55 R19.5	2475	303
KHSF 9010/3	9000	Single	2040	1300	120 x 10	19.5"	425/55 R19.5	2470	306
KHZF 9008	9000	Twin	1835	980	120 x 10	19.5"	265/70 R19.5	2420	295
KHSF 9008	9000	Single	1965	1200	120 x 10	19.5"	425/55 R19.5	2395	300
KHSF 9008	9000	Single	2005	1250	120 x 10	19.5"	425/55 R19.5	2435	301
KHZF 10008-15	10000	Twin	1930	980	120 x 15	19.5"	265/70 R19.5	2515	341
KHZF 11010-15	11000	Twin	1830	980	120 x 15	19.5"	265/70 R19.5	2415	326
KHZF 11008-15	11000	Twin	1930	1100	120 x 15	19.5"	265/70 R19.5	2515	340
KHZF 11010-15	11000	Twin	1930	1100	120 x 15	19.5"	265/70 R19.5	2515	331
KHZF 12008-15	12000	Twin	1930	1100	120 x 15	19.5"	285/70 R19.5	2530	342
KHZF 12010-15	12000	Twin	1930	1100	120 x 15	19.5"	285/70 R19.5	2530	336

Table D.3: BPW rigid axles with 420 mm drum brake

OEM Description	Permitted axle load up to 105 km/h (kg)	Tyres	Track width (SP) (mm)	Spring centre (FM) (mm)	Axle cross section (mm)	Tyre size	Tyre example	Overall width (P) (mm)	Axle weight (kg)
HSF 6510	6500	Single	2040	1300	120 x 10	20"/22.5"	10 R20	2335	280
HSF 6508	6500	Single	2045	1300	120 x 10	20"/22.5"	10 R20	2340	278
HSF 9010	9000	Single	2040	1200	120 x 10	20"/22.5"/24"	385/65 R22.5	2435	291
HSF 9010	9000	Single	2040	1300	120 x 10	20"/22.5"/24"	385/65 R22.5	2435	291
HSF 9010	9000	Single	2040	1300	120 x 10	20"/22.5"/24"	385/65 R22.5	2435	289
HSF 9010	9000	Single	2040	1300	120 x 10	20"/22.5"/24"	385/65 R22.5	2435	288
HSF 9010	9000	Single	2095	1300	120 x 10	20"/22.5"/24"	385/65 R22.5	2490	293
HSF 9010	9000	Single	2095	1300	120 x 10	20"/22.5"/24"	385/65 R22.5	2490	292
HSF 9010	9000	Single	2140	1400	120 x 10	20"/22.5"/24"	385/65 R22.5	2535	294
HSF 9010	9000	Single	2140	1400	120 x 10	20"/22.5"/24"	385/65 R22.5	2535	295
HSF 9010	9000	Single	2040	1200	120 x 10	20"/22.5"/24"	385/65 R22.5	2435	328
HSF 9010	9000	Single	2040	1300	120 x 10	20"/22.5"/24"	385/65 R22.5	2435	328
HZF 9010-15	9000	Twin	1820	900	120 x 15	20"/22.5"/24"	10 R22.5	2385	313
HZF 9010-15	9000	Twin	1820	980	120 x 15	20"/22.5"/24"	10 R22.5	2385	313
HSF 10110-15	10000	Single	2040	1200	120 x 15	20"/22.5"/24"	425/65 R22.5	2475	358
HSF 11010	11000	Single	2040	1300	150 x 10	20"/22.5"/24"	445/65 R22.5	2505	353
HZF 11010	11000	Twin	1820	900	150 x 10	20"/22.5"/24"	11 R22.5	2425	352
HZF 11010	11000	Twin	1820	980	150 x 10	20"/22.5"/24"	11 R22.5	2425	352
HSF 12010	12000	Single	2040	1300	150 x 10	20"/22.5"/24"	445/65 R22.5	2505	365
HZF 12010-16	12000	Twin	1820	900	150 x 16	20"/22.5"/24"	12 R22.5	2495	380
HZF 12010-16	12000	Twin	1820	980	150 x 16	20"/22.5"/24"	12 R22.5	2495	380
HZF 14010-1	14000	Twin	1820	900	150 x 16	20"/22.5"/24"	12 R20	2500	442

Table D.4: BPW rigid axles with 370 mm disc brake

OEM Description	Permitted axle load up to 105 km/h (kg)	Tyres	Track width (SP) (mm)	Spring centre (FM) (mm)	Axle cross section (mm)	Tyre size	Tyre example	Overall width (P) (mm)	Axle weight (kg)
SKHBF 9010	9000	Single	2040	1300	120 x 10	22"	385/65 R22	2440	275
SKHBF 9010	9000	Single	2040	1200	120 x 10	22"	385/65 R22	2440	275
SKHBF 9010	9000	Single	2095	1300	120 x 10	22"	385/65 R22	2495	278
SKHBF 9010	9000	Single	2140	1400	120 x 10	22"	385/65 R22	2540	279
SKHSF 9008	9000	Single	2045	1300	120 x 10	19.5"	425/55 R19.5	2470	254
SKHSF 9008	9000	Single	2045	1200	120 x 10	19.5"	425/55 R19.5	2470	254
SKHSF 9010	9000	Single	2040	1300	120 x 10	22.5"	385/65 R22.5	2440	265
SKHSF 9010	9000	Single	2040	1200	120 x 10	22.5"	385/65 R22.5	2440	265
SKHSF 9010	9000	Single	2095	1300	120 x 10	22.5"	385/65 R22.5	2495	268
SKHSF 9010	9000	Single	2140	1300	120 x 10	22.5"	385/65 R22.5	2540	269
SKHSF 9010	9000	Single	2140	1400	120 x 10	22.5"	385/65 R22.5	2540	269
SKHSF 9008	9000	Single	2005	1100	120 x 15	19.5"	425/55 R19.5	2430	275
SKHSF 9010	9000	Single	2000	1100	120 x 15	22.5"	385/65 R22.5	2400	286
SKHZF 9008	9000	Twin	1885	980	120 x 15	19.5"	265/70 R19.5	2465	270
SKHZF 9008	9000	Twin	1925	980	120 x 15	19.5"	265/70 R19.5	2505	272
SKHZF 9010	9000	Twin	1880	980	120 x 15	22.5"	10 R22.5	2425	280
SKHSF 10010	10000	Single	2040	1300	120 x 15	19.5"	445/65 R19.5	2505	302
SKHZF 10008	10000	Twin	1880	980	120 x 15	19.5"	265/70 R19.5	2460	290
SKHZF 10008	10000	Twin	1920	980	120 x 15	19.5"	265/70 R19.5	2500	292
SKHZF 10008	10000	Twin	1970	1100	120 x 15	19.5"	265/70 R19.5	2550	294
SKHZF 10008	10000	Twin	1920	1100	120 x 15	19.5"	265/70 R19.5	2500	292

Table D.5: BPW axles with 430 mm disc brake

OEM Description	Permitted axle load up to 105 km/h (kg)	Tyres	Track width (SP) (mm)	Spring centre (FM) (mm)	Axle cross section (mm)	Tyre size	Tyre example	Overall width (P) (mm)	Axle weight (kg)
SHBF 9010	9000	Single	2040	1300	120 x 10	22.5"	385/65 R22.5	2440	286
SHBF 9010	9000	Single	2040	1200	120 x 10	22.5"	385/65 R22.5	2440	286
SHBF 9010	9000	Single	2095	1300	120 x 10	22.5"	385/65 R22.5	2495	288
SHBF 9010	9000	Single	2140	1400	120 x 10	22.5"	385/65 R22.5	2540	289
SHSF 9010	9000	Single	2040	1300	120 x 10	22.5"	385/65 R22.5	2440	277
SHSF 9010	9000	Single	2040	1200	120 x 10	22.5"	385/65 R22.5	2440	277
SHSF 9010	9000	Single	2095	1300	120 x 10	22.5"	385/65 R22.5	2495	279
SHSF 9010	9000	Single	2140	1300	120 x 10	22.5"	385/65 R22.5	2540	281
SHSF 9010	9000	Single	2140	1400	120 x 10	22.5"	385/65 R22.5	2540	281
SHSF 9010	9000	Single	2040	1100	120 x 15	22.5"	385/65 R22.5	2440	300
SHZF 9010	9000	Twin	1880	980	120 x 15	22.5"	10 R22.5	2450	292
SHSF 101102	10000	Single	2040	1200	120 x 15	22.5"	425/65 R22.5	2480	317
SHSF 101102	10000	Single	2040	1300	120 x 15	22.5"	425/65 R22.5	2480	317
SHZF 10110	10000	Twin	1820	980	120 x 15	22.5"	11 R22.5	2430	306
SHZF 10110	10000	Twin	1850	980	120 x 15	22.5"	11 R22.5	2460	308
SHZF 10110	10000	Twin	1880	980	120 x 15	22.5"	11 R22.5	2490	309
SHSF 12010	12000	Single	2040	1160	150 x 16	22.5"	445/65 R22.5	2510	352
SHZF 12010	12000	Twin	1820	900	150 x 16	22.5"	12 R22.5	2460	339
SHZF 12010	12000	Twin	1840	900	150 x 16	22.5"	12 R22.5	2480	340
SHZF 12010	12000	Twin	1880	980	150 x 16	22.5"	12 R22.5	2520	343

D.2 Tyre Spring Rate

The OEM data for the tyre sizes used for the baseline combinations with calculated spring rates (assuming linear behaviour) is provided in Tables D.6 to D.8.

Table D.6: Spring rate approximation for 445/65 R22.5 tyres

Manufacturer	Model	Pressure (bar)	Number of tyres	Axle load (kg)	Unladen radius (mm)	Laden radius (mm)	Load per tyre (kg)	Deflection (mm)	Spring rate (N/mm)
Bridgestone	R244	9	2	11600	582	533	5800	48.26	1179
Bridgestone	M854	9	2	11600	583	536	5800	46.99	1211
Bridgestone	L315	8.3	2	11200	589	544	5600	45.72	1202
Goodyear	RHT/MST II	5	2	7250	575	529	3625	46.00	773.1
Goodyear	RHT/MST II	9	2	11600	575	529	5800	46.00	1237
Michelin	XZY TL	7	2	9020	587	534	4510	53.00	834.8
Michelin	XZY TL	9	2	11600	587	534	5800	53.00	1074
				Min. (mm)	575			**Min. Singles (N/mm)**	773.1
				Max. (mm)	589			**Max. Singles (N/mm)**	1237

Table D.7: Spring rate approximation for 315/80 R22.5 tyres

Manufacturer	Model	Pressure (bar)	Number of tyres	Axle load (kg)	Unladen radius (mm)	Laden radius (mm)	Load per tyre (kg)	Deflection (mm)	Spring rate (N/mm)
Bridgestone	M860A	9	2	9080	544	505	4540	38	1169
Bridgestone	M843	9	2	8250	550	511	4125	39	1028
Goodyear	LHS II+	5	2	5240	544	505	2620	38	674.6
Goodyear	LHS II+	8.5	2	8000	538	500	4000	38	1033
Goodyear	Ultragrip coach	5	2	4910	544	505	2455	38	632.1
Goodyear	Ultragrip coach	8.5	2	7500	538	500	3750	38	968.1
Michelin	XZA2 Energy TL	6.5	2	6270	548	507	3135	41	750.1
Michelin	XZA2 Energy TL	8	2	7500	548	507	3750	41	897.3
Michelin	XDY TL	6.5	2	6270	548	506	3135	42	732.2
Michelin	XDY TL	8	2	7500	548	506	3750	42	875.9
Michelin	Ice Grip TL	6.5	2	6270	548	504	3135	44	699.0
Michelin	Ice Grip TL	8	2	7570	548	504	3785	44	843.9
Bridgestone	M860A	9	4	16480	544	505	4120	38	1061
Bridgestone	M843	9	4	15000	550	511	3750	39	934.4
Goodyear	RHD II+	5	4	8770	544	505	2193	38	564.5
Goodyear	RHD II+	8.5	4	13400	538	500	3350	38	864.8
Goodyear	MSS II	5	4	8770	544	505	2193	38	564.5
Goodyear	MSS II	8.5	4	13400	538	500	3350	38	864.8
Michelin	XZA2 Energy TL	6.5	4	11090	548	507	2773	41	663.4
Michelin	XZA2 Energy TL	8	4	13400	548	507	3350	41	801.5
Michelin	XDY TL	6.5	4	11090	548	506	2773	42	647.6
Michelin	XDY TL	8	4	13400	548	506	3350	42	782.5
Michelin	Ice Grip TL	6.5	4	11090	548	504	2773	44	618.1
Michelin	Ice Grip TL	8	4	13400	548	504	3350	44	746.9
				Min. (mm)	538			**Min. Singles (N/mm)**	632.1
				Max. (mm)	550			**Max. Singles (N/mm)**	1169
								Min. Duals (N/mm)	564.5
								Max. Duals (N/mm)	1061

Table D.8: Spring rate approximation for 285/70 R19.5 tyres

Manufacturer	Model	Pressure (bar)	Number of tyres	Axle load (kg)	Unladen radius (mm)	Laden radius (mm)	Load per tyre (kg)	Deflection (mm)	Spring rate (N/mm)
Bridgestone	R227F	8.6	2	6300	448	414	3150	34.29	901.2
Bridgestone	M729F	8.6	2	5800	450	414	2900	35.56	800.0
Goodyear	RHT II	5	2	4190	448	408	2095	39.50	520.3
Goodyear	RHT II	9	2	6700	448	408	3350	39.50	832.0
Goodyear	RHS II	5	2	3750	448	413	1875	34.50	533.2
Goodyear	RHS II	9	2	6000	448	413	3000	34.50	853.0
Michelin	XZA TL	6	2	4320	456	413	2160	42.50	498.6
Michelin	XZA TL	8	2	5800	456	413	2900	42.50	669.4
Michelin	XTA TL	6.5	2	4940	456	409	2470	46.50	521.1
Michelin	XTA TL	8.5	2	6300	456	409	3150	46.50	664.5
Michelin	XTE2 TL	6.5	2	4900	456	409	2450	46.50	516.9
Michelin	XTE2 TL	9	2	6700	456	409	3350	46.50	706.7
Bridgestone	R227F	8.6	4	11600	448	414	2900	34.29	829.7
Bridgestone	M729F	8.6	4	10900	450	414	2725	35.56	751.8
Goodyear	RHT II	5	4	7880	448	408	1970	39.50	489.3
Goodyear	RHT II	9	4	12600	448	408	3150	39.50	782.3
Goodyear	RHS II	5	4	7000	448	413	1750	34.50	497.6
Goodyear	RHS II	9	4	11200	448	413	2800	34.50	796.2
Michelin	XZA TL	6	4	8200	456	413	2050	42.50	473.2
Michelin	XZA TL	8	4	10900	456	413	2725	42.50	629.0
Michelin	XTA TL	6.5	4	9090	456	409	2273	46.50	479.4
Michelin	XTA TL	8.5	4	11600	456	409	2900	46.50	611.8
Michelin	XTE2 TL	6.5	4	9000	456	409	2250	46.50	474.7
Michelin	XTE2 TL	9	4	12300	456	409	3075	46.50	648.7
				Min. (mm)	448			**Min Singles (N/mm)**	498.6
				Max. (mm)	456			**Max Singles (N/mm)**	901.2
								Min Duals (N/mm)	473.2
								Max Duals (N/mm)	829.7

E Anonymised PBS Data

E.1 Trailer and Dolly Units

To gain insight into existing variations in design, data was extracted from South African PBS assessments and anonymised for presentation in this research. The data extracted includes the wheelbase, sprung mass, CG_z as well as a normalised mass metric.

The normalised mass is calculated as the ratio of the sprung mass to the wheelbase in kg/m. The minimum normalised mass was scaled with the baseline vehicles to determine a reasonable minimum for the sprung mass of the trailers used in the baselines considering a wide range of commodities transported in a combination of similar configuration. The normalised mass was calculated for the dolly using the ratio of the sprung mass to the axle spread.

Table E.1: Anonymised trailer CG_z and normalised sprung masses

Trailer type	**Wheelbase (m)**	**Sprung mass (kg)**	CG_z **(m)**	(R_{sw}) **(kg/m)**
Auger Bulker	9.440	7180	1.902	761
Baseline tridem interlink follower	5.950	4167	1.912	700
Baseline tridem interlink leader	7.420	4632	1.777	624
Baseline quad semi-trailer	10.410	10410	2.025	1000
Baseline tridem semi-trailer	8.255	3150	1.500	382
Bottom dumper leader	8.850	5040	1.494	569
Bottom dumper leader	8.100	4230	1.645	522
Flat deck semi-trailer	5.400	3085	1.480	571
Flat deck semi-trailer follower	5.530	3510	1.400	635
Flat deck semi-trailer follower	7.329	3320	1.384	453
Flat deck semi-trailer leader	7.590	4810	1.400	634
Flat deck semi-trailer leader	6.670	2729	1.289	409
Semi-trailer - timber	9.785	4965	1.300	507
Semi-trailer - timber	12.600	3150	1.280	250
Side tipper follower	5.200	4010	1.605	771
Side tipper follower	5.200	4010	1.605	771
Side tipper follower	5.950	4167	1.912	700
Side tipper leader	8.250	4460	1.530	541
Side tipper leader	8.250	4400	1.533	533
Side tipper leader	8.250	4460	1.530	541
Side tipper leader	7.420	4632	1.777	624
Side tipper follower	5.350	3950	1.615	738
Step-deck semi-trailer	7.175	4666	1.600	650
Tanker - cement powder	8.770	4026	1.788	459
Tanker - fuel	9.686	5212	1.324	538
Tanker semi-trailer	9.686	5212	1.324	538
Tautliner follower	8.200	3860	1.646	471
Tautliner leader	9.085	4360	1.366	480
Tautliner semi-trailer follower	6.478	3890	1.650	600
Tautliner semi-trailer leader	7.960	3510	1.400	441
Timber semi-trailer	8.255	3022	1.500	366
		Minimum	1.280	250
		Maximum	2.025	1000

Table E.2: Anonymised dolly CG_z and normalised sprung masses

Trailer type	**Axle spread (m)**	**Sprung mass (kg)**	CG_z **(m)**	(R_{sa}) **(kg/m)**
Baseline rigid drawbar dolly	1.360	453	0.868	333
Dolly	2.720	1435	1.000	528
Dolly	2.720	800	1.050	294
		Minimum	0.868	294
		Maximum	1.050	528

E.2 Prime Mover Units

A similar table was extracted for the prime mover units, using the wheelbase once again to normalise the sprung mass to find a reasonable minimum.

Table E.3: Anonymised prime mover CG_z and normalised sprung masses

Category	**Axle arrangement**	**Wheelbase (m)**	**Sprung mass (kg)**	CG_z **(mm)**	R_{sw} **(kg/m))**
Baseline tractor	6x4	3.885	6598	1.204	1698
Baseline rigid	6x4	5.285	6698	1.017	1267
Tractor	6x4	3.975	5507	1.150	1385
Tractor	6x4	3.9	4974	1.070	1275
Tractor	6x4	3.975	5641	1.426	1419
Tractor	6x4	3.975	5507	1.150	1385
Tractor	6x4	3.9	4974	1.070	1275
Tractor	6x4	3.885	5370	1.180	1382
Tractor	6x4	3.885	6134	1.150	1579
Tractor	6x4	3.885	5967	1.200	1536
Tractor	6x4	3.885	6550	1.200	1686
Tractor	6x4	3.975	5507	1.150	1385
Tractor	6x4	3.9	5279	1.070	1354
Tractor	6x4	3.9	4445	1.370	1140
Rigid	6x4	5.285	5770	1.000	1092
Rigid	6x4	5.2	4974	1.070	957
Rigid	6x4	5.175	5655	1.008	1093
Rigid	6x4	6.685	6030	1.315	902
			Minimum (tractor)	1.070	1140
			Maximum (tractor)	1.426	1698
			Minimum (rigid)	1.000	902
			Maximum (rigid)	1.315	1267