

HEAVY VEHICLE SAFETY PERFORMANCE



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Abstract

Significant benefits have been realised in South Africa from adopting the PBS framework in the form of reduced fuel consumption, CO₂ emissions, road wear, trips and crashes. Three representative baseline PBS vehicles were developed (a quad-axle semitrailer, tri-axle interlink and rigid drawbar combination) and a set of ranges within which each vehicle design parameter (VDP) could be varied was developed. Each VDP for each baseline combination was varied in isolation to determine its effect on the vehicles PBS performance. The degree to which each VDP affected each performance measure in relation to each other is presented in a matrix for each of the baseline vehicles. The matrices indicate that the geometrical and inertial properties of the vehicle dominate vehicle performance and should be optimised before looking at suspension and tyre properties. The matrices yield insight into which VDPs have the most influence on each performance measure as well as which VDPs can be conservatively estimated in the absence of OEM data without significantly degrading the simulated vehicle performance.

Keywords: High productivity vehicles, Performance based standards, Technical research

1. Introduction

A performance based standards (PBS) approach to heavy vehicle design involves assessing vehicle safety performance through a set of performance measures (Arredondo 2012). The vehicle is required to perform standard road manoeuvres, during which these performance measures are evaluated through either physical testing or simulation. In addition, if a vehicle GCM (gross combination mass) exceeds the allowable maximum according to legislation, a bridge and road wear assessment must be conducted on the vehicle to ensure the vehicle impact on infrastructure is within suitable limits.

The PBS framework was adopted in South Africa in 2007. Since its inception, PBS vehicles have been monitored and data from their operation has been recorded. As of June 2017, over 100 million km was travelled by PBS vehicles within the South African road network. As of this date, there were 245 PBS vehicles in operation within 8 of the 9 Provinces in South Africa. Commodities transported include timber, fuel, beer and paper reels among others.

Monitoring data has been collected and analysed for the duration of the PBS pilot project. The data recorded as of June 2017 shows that PBS vehicles have significant benefits over their baseline equivalents. PBS vehicles require less trips to transport the same amount of payload which leads to reductions in fuel consumptions, CO₂ emissions and reduced road wear. PBS vehicles are recorded to be safer with a 39% reduction in crashes relative to their baseline equivalents (Nordengen et al. 2018).

The safety improvements realised by enforcing PBS compliance in South Africa are clear from the monitoring data collected during the pilot project. The PBS framework quantifies the safety performance of a heavy vehicle but does not provide direct insight on how to optimise performance within the framework.

The process of assessing and optimising a heavy vehicle within the PBS framework is costly and time consuming. 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. Gaining a better understanding of which vehicle design parameters (VDPs) have the largest influence on vehicle performance within the PBS framework will help assessors and designers focus on the design parameters that will most effectively improve vehicle performance for each PBS performance measure.

In addition, understanding which VDPs have a lower influence on vehicle performance will allow for conservative estimates to be made for these parameters without significantly degrading the simulated performance of the vehicle. This will help speed up PBS assessments where OEM (original equipment manufacturer) data is not readily supplied due to the red tape involved in distributing proprietary information which drastically affects the time required to complete an assessment.

2. Literature Review

The first step in optimisation is to determine which vehicle design parameters have the most influence on the vehicle performance. (Prem et al. 2002) conducted a study on the Australian heavy vehicle fleet to determine the influence of various design parameters on the PBS performance measures. A baseline configuration was chosen for a variety of vehicle configurations. The design parameters were then varied $\pm 20\%$ and the effects on each performance measure were tabulated, indicating the influence of each performance measure

using a scale with 4 discrete quantifiers (++ , + for improved performance and - , -- for degraded performance).

The study conducted by Prem et al. provides insight into how vehicle design parameters affect each performance measure within a small range of the baseline design parameters. The study does not consider a range according to the possible values of each design parameter. 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. In both cases, efforts put in to modifying such a parameter would be unproductive.

Heavy vehicle design parameters are well documented for overseas heavy vehicle fleets (US and Canada), with limited information available for the South African fleet. (Fancher et al. 1986) published a collection of heavy vehicle design parameters for the US heavy vehicle fleet including discussions on how certain vehicle design parameters affect vehicle performance. This data was collected in 1986 and is thus outdated, however is still a useful source to estimate approximate VDP ranges. A more recent collection of heavy vehicle design parameters is included in a review of truck characteristics performed by (Harwood et al. 2003) 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 notable resources for heavy vehicle design parameters and their influence on heavy vehicle performance include studies conducted by (Ervin and Guy 1986), (Wink, Bogard, and Karamihas 1995) and (Winkler, Gillespie, and Karamihas 2011).

3. Objectives

The purpose of this study is to provide insight into the relative effect of various design parameters of a collection of baseline heavy vehicle combinations on their safety performance within the PBS framework while considering unique ranges for each design parameter developed based on physical and legal constraints, published literature and OEM data.

4. Methodology

TruckSim[®] (version 2018.0) was used as the multibody vehicle dynamics simulation package to model the heavy vehicle combinations. The dynamic performance of each combination was evaluated within the PBS framework as adopted in South Africa in conjunction with a MATLAB[®] (version R2018a) post processor developed at Wits University.

Three representative baseline vehicles were developed using data collected from previously conducted PBS assessments. Physical and legal constraints, OEM data and literature from studies conducted on the design parameters of heavy vehicles was then used to develop a range of variation for each baseline VDP (Deiss 2018). A summary of the minimum and maximum values for each VDP with respect to the baseline VDP is included in Table 1 and Table 2.

A MATLAB[®] script was developed to automate the process of changing a VDP, simulating the combination performing the PBS manoeuvres and finally evaluating and recording the PBS performance. The process flow is detailed in Figure 1.

To quantify the sensitivity of the model to each VDP, the coefficient of variation (CV) as defined in Equation (1) was determined for each combination of VDP and performance

measure. The coefficient of variation is a dimensionless value that determines the spread of data about its mean. This facilitates the comparison of datasets where the units of measurement may differ (Soong 2004).

The CV for each performance measure was normalised with respect to the parameter with the highest CV , resulting in CV_n as per Equation (2).

$$CV = \frac{\sigma}{\mu} \times 100\% \quad (1)$$

$$CV_n = \frac{\left(\frac{\sigma}{\mu} \times 100\%\right)}{CV_{max}} \quad (2)$$

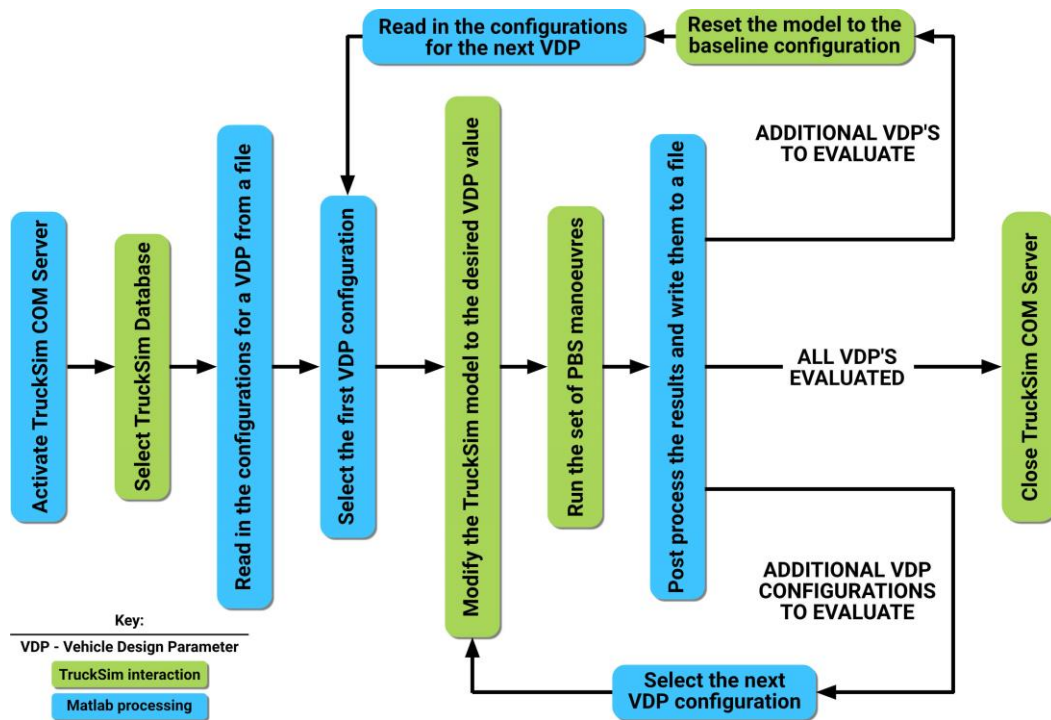


Figure 1: TruckSim automation using the COM server

5. Baseline Vehicles

Three baseline vehicles were developed to evaluate the effects of each VDP on different vehicle configurations. The baseline combinations developed are intended to model the envisioned PBS equivalents of South Africa's legal workhorse vehicles. A paper compiled by Nordengen (Nordengen 2008) highlights the legal workhorse vehicles in South Africa. It was determined that the four included combinations could be replaced by a quad-axle semi-trailer and tri-axle interlink combination each coupled to a 6x4 prime mover.

A rigid drawbar combination (truck and dog in Australian terminology) was selected as the third baseline vehicle since is one of the most popular PBS combinations in Australia (Grote 2017) which may lead to its adoption in South Africa as the PBS project progresses. This will

also provide insight into how the effect of a roll coupled (turntable) versus a non-roll coupled (pintle) articulation point affects the relative influence of the VDPs.

The same representative 6x4 prime mover was used for all baseline combinations with the wheelbase extended in the case of the rigid drawbar combination.

5.1 Baseline Quad-axle Semi-trailer Combination

A GA (general arrangement) of the quad-axle semi-trailer is provided in Figure 2.

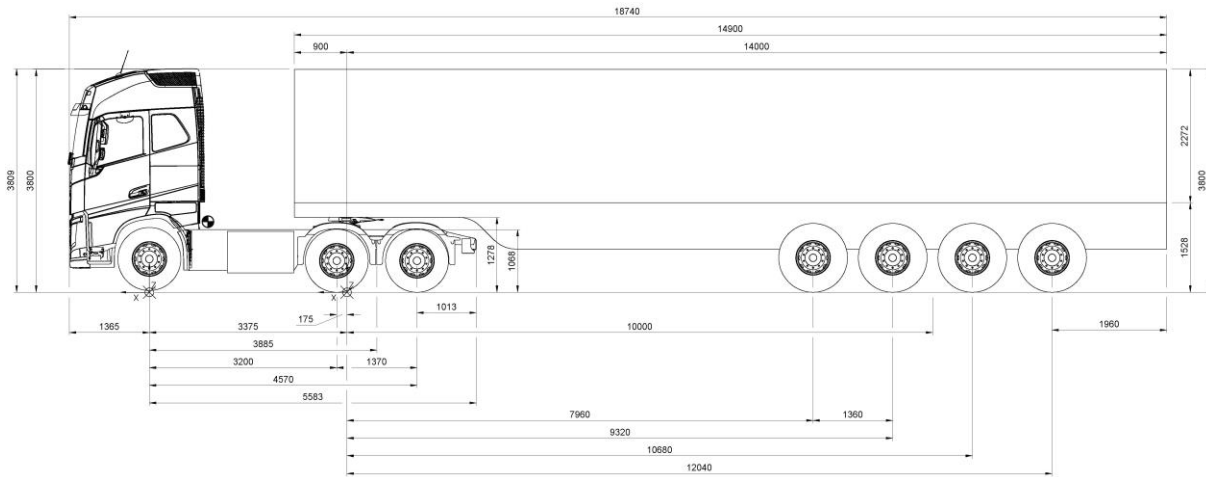


Figure 2: Baseline quad-axle semi-trailer general arrangement drawing

5.2 Baseline Tri-axle Interlink Combination

A GA drawing of the baseline tri-axle b-double combination is shown in Figure 3.

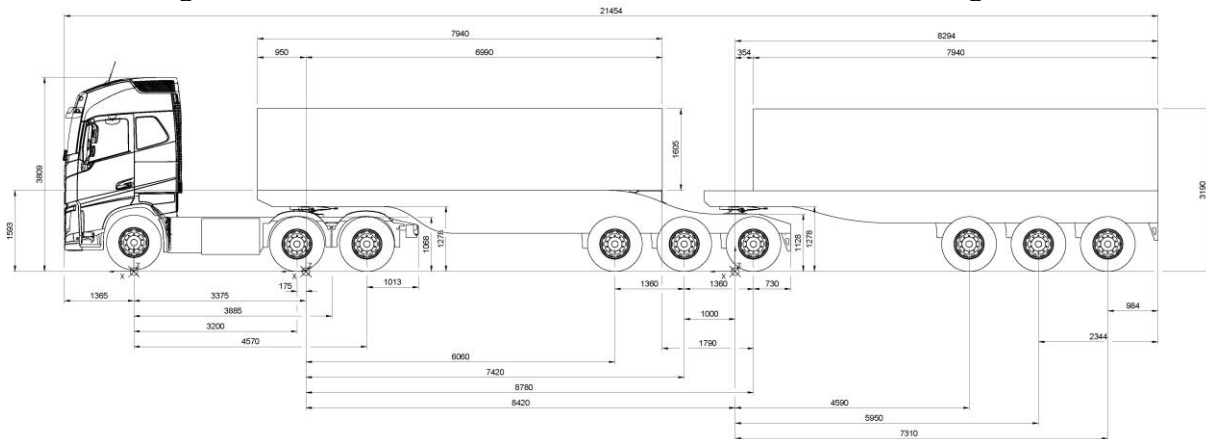


Figure 3: Baseline tri-axle interlink general arrangement drawing

5.3 Baseline Rigid Drawbar Combination

A GA drawing for the baseline rigid drawbar combination is provided in Figure 4.

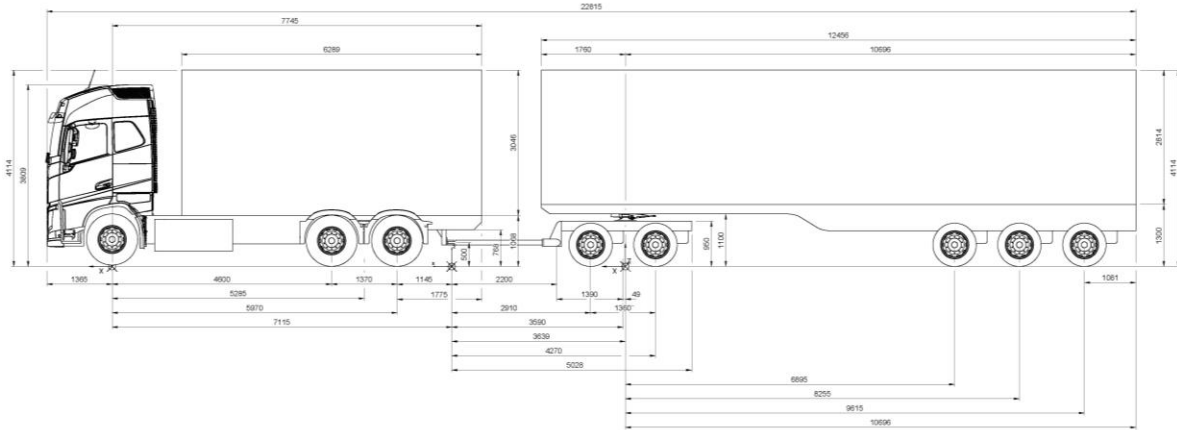


Figure 4: Baseline rigid drawbar combination general arrangement drawing

6. Results and Discussion

To concisely present the ranges of each vehicle design parameter, Table 1 and Table 2 summarise the range of each of the vehicle design parameters evaluated. In each cell, the minimum and maximum value as a percentage of the baseline value is presented as min% / max%. Cells that are highlighted have an impact of at least 10% relative to the most influential VDP for any performance measure.

Table 3 to Table 5 present the CV matrix for each of the baseline combinations. For brevity, only design parameters that have at least 10% influence relative to the highest impact parameter have been included.

The most influential design parameters for each performance measure have been highlighted and are represented by a value of 100. The influence of any other design parameters for a performance measure are presented as a % influence relative to the most influential parameter.

The design parameter range and influence of the vehicle units and payloads are displayed in Table 1. The inertial and geometrical properties of each baseline vehicle dominate the overall vehicle performance. This is attributed to the fact that these parameters have the largest scope to vary as well as being highly influential on overall vehicle performance. It is indicative of the fact that tweaking suspension design parameters while a parameter such as the wheelbase is not in optimal placement may lead to a safe combination, however safety could be improved by a greater extent by getting the wheelbase correct.

The inertial properties were varied to consider vehicle performance from the unladen to the laden condition and thus evaluates a wide range of vehicle loading conditions. The importance of getting correct payload properties is clear. The analysis highlights that the moment of inertia properties of the sprung masses have a relatively lower influence (in particular the roll moment of inertia (I_{xx}) which is likely due to the lower variation allowed based on the fact that vehicle structures and payloads are generally symmetrical about the longitudinal axis and have less scope to vary) on overall vehicle performance compared to their physical location or mass.

Table 1: Design parameter range and influence – vehicle units and payloads

Parameter	Quad-axle semi-trailer		Tri-axle interlink			Rigid drawbar		
	Tractor	Quad-axle semi-trailer	Tractor	Interlink leader	Interlink follower	Rigid	Dolly	Tridem semi-trailer
Vehicle unit								
Wheelbase	79/112	75/100	79/112	95/103	73/108	84/111	79/135	71/108
Axle spacing	88/102	88/136	88/102	88/136	88/136	88/102	88/132	88/136
Hitch height	85/106	x ¹	85/106	90/106	x	60/184	88/123	x
Hitch offset	95/115	x	95/115	94/104	x	92/110	93/104	x
Sprung mass	53/100	24/100	53/100	40/100	36/100	71/100	88/100	66/100
CGx	80/120	70/130	80/120	70/130	70/130	70/130	90/110	70/130
CGy	† ²	†	†	†	†	†	†	†
CGz	89/118	63/100	89/118	72/114	67/106	98/129	100/121	85/135
lxx	70/130	55/145	70/130	55/145	55/145	70/130	80/120	55/145
lyy/lzz	60/140	50/150	60/140	50/150	50/150	60/140	70/130	50/150
Front overhang	95/133	0/200	95/133	0/189	100/-131	95/133	x	0/102
Rear overhang	x	0/306	x	100/72	0/363	0/143	x	0/458
Width	89/104	92/100	89/104	92/100	92/100	89/104	x	92/100
Reference point height	0/612	0/121	0/114	0/144	0/144	0/612	x	0/112
Payload								
Sprung mass	x	0/100	x	0/100	0/100	0/100	x	0/100
CGx	x	89/111	x	87/113	91/109	93/107	x	87/113
CGy	x	†	x	†	†	†	x	†
CGz	x	78/140	x	70/104	70/104	45/119	x	53/117
lxx	x	60/140	x	60/140	60/140	40/160	x	60/140
lyy/lzz	x	40/160	x	40/160	40/160	40/160	x	40/160

With sufficient testing it could be confirmed that approximate estimates for moment of inertia using basic geometrical assumptions reasonably predict overall vehicle performance without the need for complex 3D CAD (computer aided design) models. If this is indeed the case, then this would significantly reduce the time and effort required to predict vehicle performance. A simple GA drawing could be used by an inexperienced user to reasonably predict vehicle performance.

The design parameter range and influence of the suspension and tyres is displayed in Table 2. The relatively lower impact of the suspension parameters indicates that using a simplified generic suspension could be used to generate a predictive model that would yield reasonable overall vehicle performance within the PBS framework. This presents the opportunity to develop a lightweight model that could easily be used by an end-user to approximate the performance of a heavy vehicle within the PBS framework. To further extend the model, the most influential suspension parameters namely axle track, auxiliary roll stiffness, roll centre height, roll steer and tyre lateral force could be added to improve the accuracy of the model.

A model generated with these basic inputs would allow individuals with little technical experience to reasonably predict overall vehicle performance within the PBS framework without the need for complex calculations and extensive data acquisition.

¹ x – parameter not evaluated

² † – +/- 10% of vehicle width (250 mm for tractor, 260 mm for all other units)

It becomes important to model accurate VDPs for a combination that is performing close to the PBS limits. However, a simple predictive model ignoring the less influential parameters will allow for quick preliminary assessment of a vehicles PBS performance, lead to more optimal designs and limit the amount of redesign involved due to intelligent design decisions being made before the combination ever reaches the assessor.

Table 2: Design parameter range and influence – suspension and tyres

Parameter	Quad-axle semi-trailer			Tri-axle interlink			Rigid drawbar		
	Steer Axle	Drive Axles	Trailer Axles	Steer Axle	Drive Axles	Trailer Axles	Steer Axle	Drive Axles	* Trailer Axles ³
Suspension kinematics									
Axle track	92/108	98/105	93/102	92/108	98/105	95/103	92/108	98/105	90/100
Axle centre height	88/112	88/112	89/111	88/112	88/112	88/112	88/112	88/112	85/115
Roll centre height	-95/476	-31/100	-110/175	-95/476	-31/100	-110/175	-95/476	-31/100	-110/175
Roll steer	0/230	†	-114/657	0/230	†	-26/147	0/230	†	-26/147
Axle roll/yaw inertia	99/117	99/115	99/119	99/117	99/115	100/118	99/117	99/115	100/119
Axle spin inertia	100/1000	100/1000	100/1000	100/1000	100/1000	100/1000	100/1000	100/1000	100/1000
Unsprung mass	67/107	69/104	71/125	67/107	69/104	89/111	67/107	69/104	70/112
Wheel centre height	100/104	100/104	100/105	100/104	100/104	100/104	100/104	100/104	100/105
Suspension compliance									
Auxiliary roll stiffness	36/170	11/169	9/146	36/170	11/169	9/146	36/170	11/169	9/146
Damper model	13/250	13/250	13/250	13/250	13/250	13/250	13/250	13/250	13/250
Damper track	68/100	67/110	72/139	68/100	67/110	88/158	68/100	67/110	88/158
Jounce / rebound stop	22/123	18/100	18/100	22/123	18/100	18/100	22/123	18/100	18/100
Spring vertical stiffness	68/128	42/126	62/186	68/128	42/126	62/186	68/128	42/126	62/186
Spring track	96/141	89/146	60/115	96/141	89/146	67/120	96/141	89/146	67/120
Tyre properties									
Dual tyre spacing	x	100/101	x	x	100/101	100/101	x	100/101	100/102
Effective rolling radius	99/103	99/103	99/104	99/103	99/103	99/103	99/103	99/103	99/103
Tyre lag	x	0/100	0/100	x	0/100	0/100	x	0/100	0/100
Lateral tyre force	100/150	100/150	100/135	100/150	100/150	100/150	100/150	100/150	100/135
Vertical tyre spring rate	57/118	57/118	65/104	57/118	57/118	57/118	57/118	57/118	59/113
Unloaded radius	98/100	98/100	98/100	98/100	98/100	98/100	98/100	98/100	98/100
Tyre spin moment of inertia	58/117	58/117	50/100	58/117	58/117	58/117	58/117	58/117	65/130

The most critical tyre property is noted as the lateral tyre force. This highlights that to accurately predict heavy vehicle performance, correct lateral tyre force curves are required. Tyre manufactures do not typically make their tyre performance curves available to the public or

³ The dolly vehicle unit was assumed to have the same axles as the trailer for all vehicle configurations

⁴ † Baseline value is 0 deg/deg, min = 0.04 deg/deg with a max of -0.23 deg/deg

assessors, thus conservative tyre models are often used as required by the NTC rules should the real tyre performance curves not be available. It would be beneficial to accurately measure tyre lateral cornering stiffness curves to predict actual vehicle performance. This would allow for more productive vehicles to be developed without being restricted by poor predicted performance because of the need to use conservative lateral tyre force curves.

Table 3: Quad-axle semi-trailer relative performance CV matrix

Description	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
Vehicle unit design parameters															
PM ⁵ wheelbase	0	45	0	0	3	29	9	42	4	24	4	63	16	19	100
TL wheelbase	100	100	0	0	23	100	96	100	9	100	50	14	7	3	4
PM axle spacing	0	0	0	0	1	0	1	0	0	1	0	2	0	0	14
PM hitch offset	0	25	0	0	1	6	7	23	0	1	0	3	1	1	24
PM sprung mass	8	1	6	5	1	0	3	1	1	0	0	1	0	0	15
TL sprung mass	30	0	22	20	9	6	9	3	5	0	0	0	1	0	5
TL CGx ⁶	0	35	0	0	12	5	34	5	2	1	0	2	1	1	2
PM CGy	0	0	0	0	11	8	100	5	11	1	3	2	4	2	1
TL CGy	0	0	0	0	26	2	0	0	22	0	6	1	8	3	0
TL CGz	0	0	0	0	22	1	14	2	2	0	0	0	0	0	0
TL Iyy/Izz ⁷	0	0	0	0	1	14	3	26	1	0	0	0	0	0	0
PM front overhang	0	0	0	0	0	0	0	0	3	14	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 pt. height	0	0	0	0	0	0	0	0	76	3	0	23	3	4	0
TL reference pt. height	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
PM width	0	0	0	0	0	0	0	0	77	12	0	100	37	22	0
TL width	0	0	0	0	0	0	0	0	59	0	17	0	25	6	0
Payload design parameters															
TL payload mass	35	5	100	100	48	73	50	13	21	2	2	3	4	3	22
TL payload CGx	0	41	0	0	12	5	14	5	2	1	0	2	1	1	2
TL payload CGy	0	0	0	0	81	7	16	1	66	0	18	2	24	9	1
TL payload CGz	0	0	0	0	100	5	4	14	14	0	1	0	0	0	0
TL payload Iyy / Izz	0	0	0	0	1	43	11	68	2	0	1	1	1	0	1
Suspension design parameters															
St. ⁸ axle track	0	0	0	0	0	0	0	0	0	3	1	79	0	1	3
TL axle track	0	0	0	0	16	1	1	1	5	0	0	0	0	0	0
TL roll steer	0	0	0	0	0	2	4	12	10	0	0	0	0	0	0
Dr. aux. roll stiffness	0	0	0	0	19	1	6	2	3	0	0	1	0	0	1
TL aux. roll stiffness	0	0	0	0	7	8	7	6	35	0	1	0	0	0	0
Tyre design parameters															
St. tyre lateral force	0	0	0	0	1	48	1	1	1	0	0	0	0	0	7
Dr. tyre lateral force	0	0	0	0	2	1	19	34	6	1	0	3	2	1	21
TL tyre lateral force	0	0	0	0	1	7	20	56	23	1	0	2	2	1	3

There are differences in the relative influence of various VDPs between the three baseline configurations. This indicates that the CV matrix is sensitive to the baseline vehicle design. However, there are clear similarities between the three matrices; the geometrical and inertial properties are consistently more influential than the suspension properties; auxiliary roll stiffness, axle track and roll steer are influential suspension properties and lateral tyre force is the most influential tyre property.

⁵ PM – Prime mover; TL – Trailer; TL 1 – Lead trailer; TL 2 – Follower trailer; DL - Dolly

⁶ CGx – Longitudinal centre of gravity; CGy – Lateral centre of gravity; CGz – Vertical centre of gravity

⁷ Ixx – roll moment of inertia; Iyy – pitch moment of inertia; Izz – yaw moment of inertia

⁸ St. – Steer axle; Dr. – Drive axle; TL. – Trailer axle

Table 4: Tri-axle interlink relative performance CV matrix

Description	STA	GRAa	GRAb	ACC	SRTt	YDC	RA	HSTO	TASP	LSSP	TS	FS	MoD	DoM	STFD
Vehicle unit design parameters															
PM wheelbase	0	43	0	0	2	16	20	62	5	43	21	62	24	4	100
TL 1 wheelbase	0	11	0	0	2	8	7	17	0	34	5	1	5	0	0
TL 2 wheelbase	0	8	0	0	7	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
PM hitch offset	0	21	0	0	1	12	6	25	1	1	1	3	0	0	25
TL 1 hitch offset	0	6	0	0	1	1	7	16	4	6	6	0	1	0	1
PM sprung mass	5	1	9	8	1	3	1	0	1	0	1	0	0	0	19
TL 1 mass	6	5	12	10	1	1	0	4	2	0	0	0	0	0	1
TL 2 mass	6	6	11	10	4	9	7	0	2	0	0	0	0	0	0
TL 1 CGx	0	10	0	0	2	1	39	3	0	0	0	1	1	0	1
PM CGy	0	0	0	0	8	10	73	3	8	3	25	2	5	0	1
TL 1 CGy	0	0	0	0	12	1	17	2	6	2	15	0	4	0	0
TL 2 CGy	0	0	0	0	20	0	15	3	10	1	23	0	1	0	0
TL 2 CGz	0	0	0	0	12	1	10	2	1	0	0	0	0	0	0
PM ix	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0
TL 2 lyy / lzz	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 RP height	0	0	0	0	0	0	0	0	95	0	0	0	3	0	0
TL 2 RP 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 width	0	0	0	0	0	0	0	0	0	0	0	0	38	3	0
TL 2 width	0	0	0	0	0	0	0	0	45	0	100	0	0	0	0
Payload design parameters															
TL 1 payload mass	100	100	100	100	63	40	47	36	15	11	2	4	5	1	20
TL 2 payload mass	67	59	100	100	8	27	6	25	20	6	2	1	1	0	1
TL 1 payload CGx	0	18	0	0	6	0	12	6	1	0	0	1	1	0	1
TL 2 payload CGx	0	3	0	0	7	11	13	9	0	1	0	1	2	0	1
TL 1 payload CGy	0	0	0	0	78	6	38	8	32	8	40	1	19	1	0
TL 2 payload CGy	0	0	0	0	100	7	27	21	57	4	47	0	4	1	0
TL 1 payload CGz	0	0	0	0	47	7	13	9	2	0	1	0	0	0	0
TL 2 payload CGz	0	0	0	0	60	6	9	15	9	0	1	0	0	0	0
TL 1 payload lxx	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0
TL 2 payload lxx	0	0	0	0	1	1	10	1	1	0	0	0	0	0	0
TL 1 payload lyy / lzz	0	0	0	0	0	8	8	22	1	0	1	0	0	0	0
TL 2 payload lyy / lzz	0	0	0	0	0	43	17	49	1	0	1	0	0	0	0
Suspension design parameters															
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	28	1	4	4	4	0	0	0	0	0	0
Dr. roll centre height	0	0	0	0	7	0	2	6	1	1	0	1	1	0	36
Tl. roll steer	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	16	2	8	1	2	0	1	1	0	0	1
Tl. aux. roll stiffness	0	0	0	0	30	17	100	14	99	0	9	0	1	0	0
Tyre design parameters															
Tl. lag fy mz	0	0	0	0	2	7	11	21	2	0	2	0	1	0	0
St. lateral force	0	0	0	0	0	19	3	1	2	0	0	0	0	0	6
Dr. lateral force	0	0	0	0	0	5	6	32	3	2	0	3	2	0	19
Tl. lateral force	0	0	0	0	1	13	6	94	22	1	3	2	3	0	3
Tl. tyre spring rate	0	0	0	0	8	6	22	2	3	0	0	0	0	0	0

Table 5: Rigid drawbar relative performance CV matrix

Description	STA	GRAa	GRAb	ACC	SRTt	SRTtrrcu	YDC	RA	HSTO	TASP	LSSP	TS	FS	STFD
Vehicle unit design parameters														
PM wheelbase	0	28	0	0	8	0	43	17	25	10	45	70	54	32
DL wheelbase	0	0	0	0	1	0	2	4	3	3	39	0	5	1
TL wheelbase	0	0	0	0	15	13	71	100	30	23	100	70	5	6
DL axle spacing	0	0	0	0	0	0	2	1	2	0	5	0	7	2
PM hitch height	0	0	0	0	1	0	2	12	14	1	0	0	1	4
PM hitch offset	0	0	0	0	0	0	3	13	19	3	10	4	0	3
DL hitch offset	0	0	0	0	3	2	18	5	4	2	3	1	1	4
PM sprung mass	3	1	6	4	0	0	3	1	1	0	1	1	1	18
PM CGx	0	9	0	0	1	0	3	1	0	1	2	1	1	15
PM CGy	0	0	0	0	13	0	6	1	4	4	1	15	4	12
TL CGy	0	0	0	0	13	7	1	1	1	6	0	0	0	0
PM front overhang	0	0	0	0	0	0	0	0	0	1	16	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	3	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	12	49	85	0
TL vehicle width	0	0	0	0	0	0	0	0	0	28	0	0	0	0
Payload design parameters														
PM payload CGx	0	12	0	0	2	0	7	3	1	3	3	1	2	22
TL payload CGx	0	0	0	0	16	9	4	2	4	1	1	0	2	2
PM payload CGy	0	0	0	0	47	0	18	1	8	9	2	35	9	23
TL payload CGy	0	0	0	0	100	71	4	5	11	64	4	43	0	0
PM payload CGz	0	0	0	0	39	0	6	38	26	7	0	1	1	1
TL payload CGz	0	0	0	0	74	100	32	19	30	16	0	0	0	0
PM payload lxx	0	0	0	0	0	0	23	31	43	18	0	0	0	0
TL payload lyy / lzz	0	0	0	0	1	0	13	6	17	2	0	0	0	0
PM payload mass	100	100	45	40	0	0	19	14	9	8	14	4	17	31
TL payload mass	67	36	100	100	17	79	100	84	65	14	6	0	5	5
Suspension design parameters														
St. axle track	0	0	0	0	0	0	0	0	0	0	4	0	70	35
TL axle track	0	0	0	0	33	17	2	2	3	5	0	0	0	0
St. roll steer	0	0	0	0	0	0	10	0	0	0	0	0	0	2
Dr. roll steer	0	0	0	0	0	0	25	7	21	12	0	2	1	1
TL roll steer	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	7	0	1	9	11	3	0	0	0	1
Dr. aux roll stiffness	0	0	0	0	70	0	46	57	100	8	0	1	2	4
TL aux roll stiffness	0	0	0	0	91	46	28	59	22	100	1	0	0	0
Tyre design parameters														
St. tyre lateral force	0	0	0	0	0	0	96	1	0	1	2	1	0	100
Dr. tyre lateral force	0	0	0	0	1	0	4	16	30	5	2	1	2	9
TL tyre lateral force	0	0	0	0	0	0	8	4	34	9	3	0	3	0
TL tyre spring rate	0	0	0	0	12	6	4	1	5	4	0	0	0	0

7. Conclusions and Recommendations

Should a vehicle fail a performance measure, the normalised CV matrices can be used to determine which design parameters (those with a high CV_n value) should be varied to redesign the vehicle to improve or optimise this performance measure.

A multibody dynamic model is only as accurate as the inputs of the model; but contacting OEMs to acquire all the required parameters for a complete model is time-consuming. In some cases, the information required is proprietary and the OEM is not able to divulge the required information, necessitating assumptions to be made. The CV matrix can be used to determine which parameters need to be either accurately sourced from the OEMs or estimated conservatively should an OEM not be able to divulge the required parameter details (those with a high CV_n value). Conversely the parameters with a low CV_n value can be safely approximated as their influence is relatively low.

The results of this study will assist in the development of simplified models to predict and optimise heavy vehicle safety performance. The CV matrix could be used as a guide to which design parameters should be included in the development of these simplified models. The design parameter ranges were chosen to be representative of the possible design modifications on the baseline vehicle. The coefficient of variation is sensitive to the range of values evaluated for each design parameter as well as the design of the baseline vehicle which limits the results from being universally true. However, similarities between the three matrices highlight the VDPs that are consistently influential on vehicle performance and provide guidance as to which VDPs should be focused on when optimising vehicle design within the PBS framework.

8. References

- Arredondo, J. 2012. “Innovative and High Productivity Vehicles: The PBS Scheme in Australia from 2007 to 2011.” International Symposium on Heavy Vehicle Transport Technology (HVTT12).
- Deiss, Jarryd Andre. 2018. “Relative Influence of High Capacity Vehicle Design Parameters (Unpublished Master’s Thesis).” University of the Witwatersrand.
- Ervin, RD and Yoram Guy. 1986. The Influence of Weights and Dimensions on the Stability and Control of Heavy Duty Trucks in Canada Final Report Volume I - Technical Report (UMTRI-86-35/I).
- Fancher, Paul S., Robert D. Ervin, Christopher B. Winkler, and Thomas D. Gillespie. 1986. A Factbook of the Mechanical Properties of the Components for Single-Unit and Articulated Heavy Trucks (UMTRI-86-12).
- Grote, Sebastian. 2017. “Beyond the Hype.” Global Trailer Issue 32, 45–47. Retrieved (www.globaltrailer.com).
- Harwood, Douglas D., Darren J. Torbic, Karen R. Richard, William D. Glauz, and Lily Elefteriadou. 2003. Review of Truck Characteristics as Factors in Roadway Design.
- Nordengen, Paul A. 2008. OECD Report: South Africa Truck Descriptions.
- Nordengen, Paul A., Christopher C. de Saxe, Robert Berman, Anton Steenkamp, and Jarryd Andre Deiss. 2018. “Improving Heavy Vehicle Safety and Road Transport Efficiency: A Performance-Based Standards Approach in South Africa.” Pp. 1–8 in Proceedings of 7th Transport Research Arena TRA 2018.
- Prem, Hans, John de Pont, Bob Pearson, and John McLean. 2002. Performance Characteristics of the Australian Heavy Vehicle Fleet (Performance Based Standards – NRTC/Austroroads Project A3 and A4), Working Paper – February 2002.
- Soong, T. T. 2004. Fundamentals of Probability and Statistics for Engineers. John Wiley & Sons, Ltd.
- Wink, Scott Bogard, and Steve Karamihas. 1995. Parameter Measurement of a Highway Tractor and Semitrailer (UMTRI-95-47).
- Winkler, Christopher B., Thomas D. Gillespie, and Steve Karamihas. 2011. Mechanics of Heavy Duty Truck Systems. UMTRI.