# 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, $CO_2$ 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, $CO_2$ 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 influence of the vehicle 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).

$$CV = \frac{\sigma}{\mu} \times 100\% \tag{1}$$

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

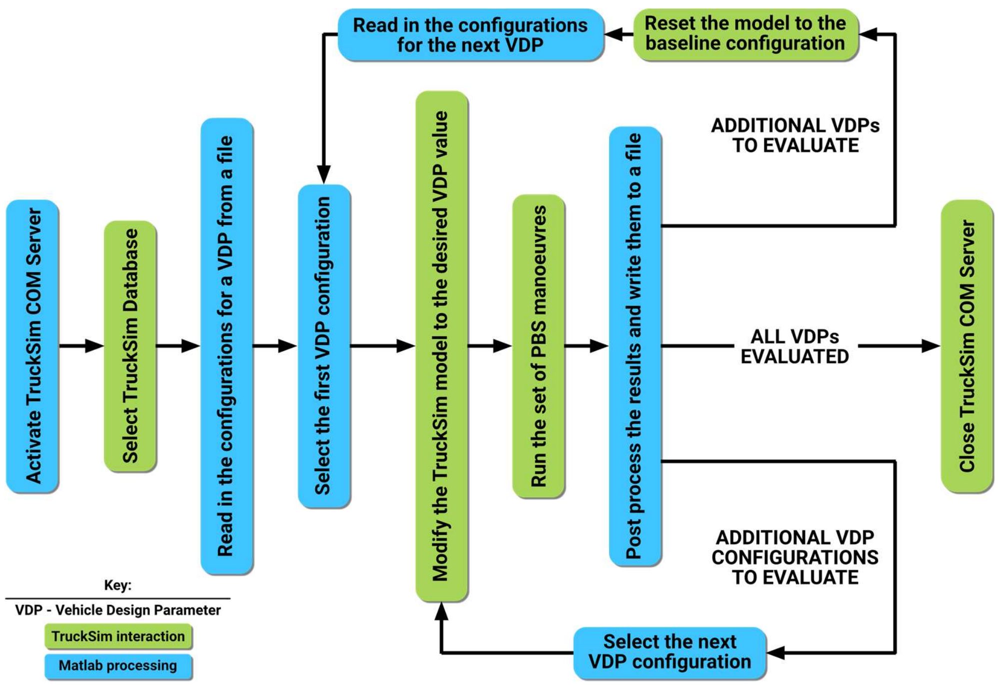


**Figure 1: TruckSim automation using the COM server**

## 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.

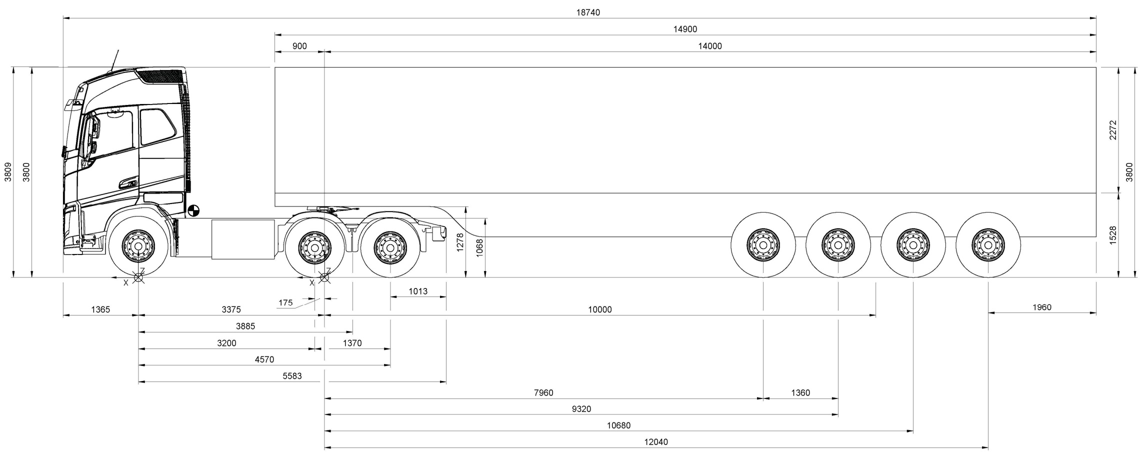


**Figure 2: Baseline quad-axle semi-trailer general arrangement drawing**

### 5.2 Baseline Tri-axle Interlink Combination

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

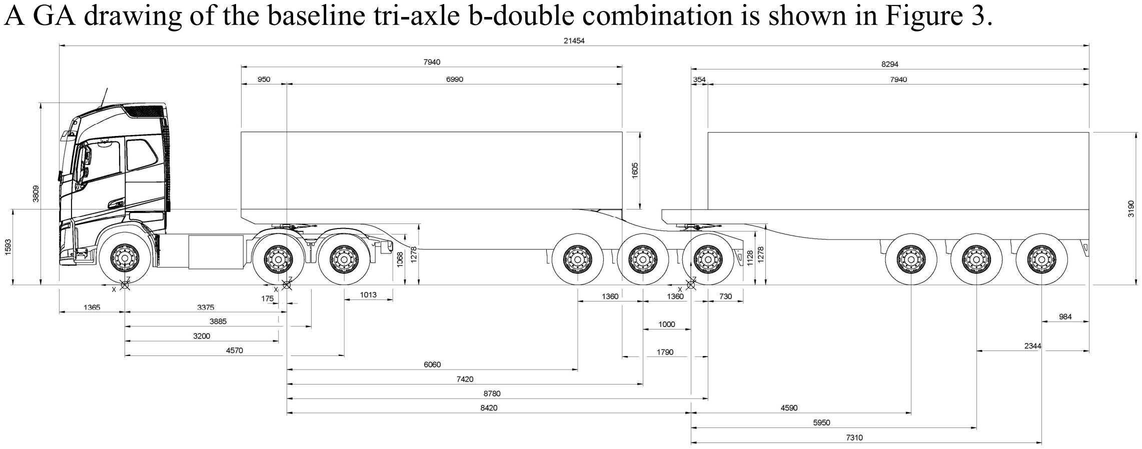


**Figure 3: Baseline tri-axle interlink general arrangement drawing**

### 5.3 Baseline Rigid Drawbar Combination

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

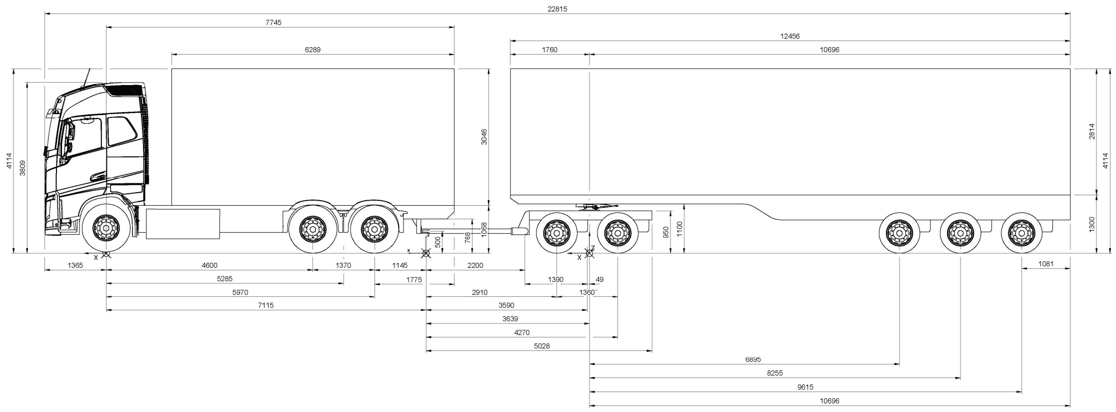


**Figure 4: Baseline rigid drawbar combination general arrangement drawing**

## 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 (Ixx) 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**

| | Quad-axle semi-trailer | | Tri-axle interlink | | | Rigid drawbar | | |
|---|---|---|---|---|---|---|---|---|
| Parameter | Tractor | Quad-axle semi-trailer | Tractor | Interlink leader | Interlink follower | Rigid | Dolly | Tridem semi-trailer |
| **Vehicle unit** | | | | | | | | |
| **Wheelbase** | 79/112 | 80/100 | 79/112 | 95/103 | 75/108 | 84/111 | 79/135 | 73/108 |
| **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** | 67/100 | 24/100 | 67/100 | 40/100 | 36/100 | 71/100 | 88/100 | 66/100 |
| **CGx** | 80/120 | 70/130 | 80/120 | 70/130 | 70/130 | 80/120 | 90/110 | 70/130 |
| **CGy** | †[2] | † | † | † | † | † | † | † |
| **CGz** | 89/118 | 63/100 | 89/118 | 72/114 | 67/106 | 98/129 | 100/121 | 85/135 |
| **Ixx** | 70/130 | 55/145 | 70/130 | 55/145 | 55/145 | 70/130 | 80/120 | 55/145 |
| **Iyy/Izz** | 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 | 0/612 | 0/144 | 0/144 | 0/612 | x | 0/112 |
| **Payload** | | | | | | | | |
| **Payload 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 |
| **Ixx** | x | 50/150 | x | 50/150 | 50/150 | 50/150 | x | 50/150 |
| **Iyy/Izz** | 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**

| | Quad-axle semi-trailer | | | Tri-axle interlink | | | Rigid drawbar | | |
|---|---|---|---|---|---|---|---|---|---|
| **Parameter** | **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 | †[4] | -114/657 | 0/230 | † | -26/147 | 0/230 | † | -26/147 |
| **Axle roll/yaw inertia** | 100/117 | 100/115 | 100/119 | 100/117 | 100/115 | 100/118 | 100/117 | 100/115 | 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** | 73/107 | 80/104 | 72/105 | 73/107 | 80/104 | 74/111 | 73/107 | 80/104 | 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 fy mz** | x | 0/100 | 0/100 | x | 0/100 | 0/100 | x | 0/100 | 0/100 |
| **Lateral tyre force** | 100/180 | 100/180 | 100/173 | 100/180 | 100/180 | 100/180 | 100/180 | 100/180 | 97/161 |
| **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**

| | VDP Description | STA | GRAa | GRAb | ACC | SRTt | YDC | RA | HSTO | TASP | LSSP | TS | FS | MoD | DoM | STFD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vehicle unit VDPs | 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 offset | 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 CGx | 0 | 10 | 0 | 0 | 0 | 0 | 5 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 7 |
| | TL CGx | 0 | 49 | 0 | 0 | 12 | 6 | 55 | 8 | 2 | 1 | 0 | 2 | 1 | 1 | 2 |
| | TL CGy | 0 | 0 | 0 | 0 | 14 | 1 | 0 | 0 | 11 | 0 | 3 | 0 | 4 | 2 | 0 |
| | TL CGz | 0 | 0 | 0 | 0 | 22 | 1 | 22 | 3 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| | TL Iyy / Izz | 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 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 |
| | 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 |
| Payload VDPs | TL payload mass | 56 | 7 | 100 | 100 | 48 | 100 | 82 | 20 | 21 | 2 | 2 | 3 | 4 | 3 | 22 |
| | TL payload CGx | 0 | 57 | 0 | 0 | 12 | 7 | 23 | 7 | 2 | 1 | 0 | 2 | 1 | 1 | 2 |
| | TL payload CGy | 0 | 0 | 0 | 0 | 44 | 4 | 26 | 0 | 33 | 0 | 8 | 1 | 11 | 6 | 0 |
| | TL payload CGz | 0 | 0 | 0 | 0 | 100 | 7 | 7 | 20 | 14 | 0 | 1 | 0 | 0 | 0 | 0 |
| | TL payload Iyy / Izz | 0 | 0 | 0 | 0 | 1 | 58 | 18 | 100 | 2 | 0 | 1 | 1 | 1 | 0 | 1 |
| Suspension VDPs | 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 | 0 | 0 | 0 | 0 | 2 | 11 | 0 | 7 | 3 | 0 | 0 | 0 | 0 | 0 | 1 |
| | Tl. roll steer | 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 |
| Tyre VDPs | Dr. eff. rolling radius | 15 | 0 | 1 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Tl. lag fy mz | 0 | 0 | 0 | 0 | 2 | 4 | 14 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | St. lateral force | 0 | 0 | 0 | 0 | 1 | 65 | 2 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 7 |
| | Dr. lateral force | 0 | 0 | 0 | 0 | 2 | 1 | 31 | 49 | 6 | 1 | 0 | 3 | 2 | 1 | 21 |
| | Tl. lateral force | 0 | 0 | 0 | 0 | 1 | 10 | 33 | 81 | 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.

## Table 4: Tri-axle interlink relative performance CV matrix

| | VDP Description | STA | GRAa | GRAb | ACC | SRTt | YDC | RA | HSTO | TASP | LSSP | TS | FS | MoD | DoM | STFD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vehicle unit VDPs | 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 offset | 0 | 21 | 0 | 0 | 1 | 12 | 6 | 25 | 1 | 1 | 1 | 3 | 0 | 0 | 25 |
| | TL 1 hitch offset | 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 CGx | 0 | 10 | 0 | 0 | 4 | 1 | 39 | 3 | 0 | 0 | 0 | 1 | 1 | 0 | 1 |
| | PM CGy | 0 | 0 | 0 | 0 | 7 | 3 | 6 | 2 | 4 | 1 | 10 | 1 | 2 | 0 | 1 |
| | TL 1 CGy | 0 | 0 | 0 | 0 | 11 | 1 | 7 | 1 | 3 | 1 | 6 | 0 | 2 | 0 | 0 |
| | TL 2 CGy | 0 | 0 | 0 | 0 | 17 | 0 | 8 | 2 | 5 | 0 | 9 | 0 | 0 | 0 | 0 |
| | TL 1 CGz | 0 | 0 | 0 | 0 | 11 | 0 | 3 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | TL 2 CGz | 0 | 0 | 0 | 0 | 19 | 1 | 10 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | PM Ixx | 0 | 0 | 0 | 0 | 0 | 0 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | TL 2 Iyy / Izz | 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 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 |
| | 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 |
| Payload VDPs | 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 CGx | 0 | 18 | 0 | 0 | 9 | 0 | 12 | 6 | 1 | 0 | 0 | 1 | 1 | 0 | 1 |
| | TL 2 payload CGx | 0 | 3 | 0 | 0 | 11 | 11 | 13 | 9 | 0 | 1 | 0 | 1 | 2 | 0 | 1 |
| | TL 1 payload CGy | 0 | 0 | 0 | 0 | 75 | 1 | 8 | 4 | 16 | 4 | 26 | 1 | 9 | 1 | 0 |
| | TL 2 payload CGy | 0 | 0 | 0 | 0 | 94 | 0 | 24 | 12 | 29 | 2 | 28 | 0 | 2 | 1 | 0 |
| | TL 1 payload CGz | 0 | 0 | 0 | 0 | 75 | 7 | 13 | 9 | 2 | 0 | 1 | 0 | 0 | 0 | 0 |
| | TL 2 payload CGz | 0 | 0 | 0 | 0 | 95 | 6 | 9 | 15 | 9 | 0 | 1 | 0 | 0 | 0 | 0 |
| | TL 1 payload Ixx | 0 | 0 | 0 | 0 | 1 | 0 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | TL 2 payload Ixx | 0 | 0 | 0 | 0 | 1 | 1 | 14 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | TL 1 payload Iyy / Izz | 0 | 0 | 0 | 0 | 0 | 8 | 8 | 22 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| | TL 2 payload Iyy / Izz | 0 | 0 | 0 | 0 | 1 | 43 | 17 | 49 | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| Suspension VDPs | 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 | 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 |
| | Tl. unsprung mass | 5 | 4 | 8 | 7 | 16 | 1 | 1 | 2 | 1 | 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 |
| Tyre VDPs | 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. spring rate | 0 | 0 | 0 | 0 | 13 | 6 | 22 | 2 | 3 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 5: Rigid drawbar relative performance CV matrix**

| | VDP Description | STA | GRAa | GRAb | ACC | SRTt | SRTtrrcu | YDC | RA | HSTO | TASP | LSSP | TS | FS | STFD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vehicle unit VDPs | 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 offset | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 15 | 19 | 3 | 11 | 4 | 0 | 3 |
| | DL hitch offset | 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 CGy | 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 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 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 |
| Payload VDPs | 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 CGx | 0 | 12 | 0 | 0 | 3 | 0 | 7 | 3 | 1 | 3 | 3 | 1 | 2 | 22 |
| | TL payload CGx | 0 | 0 | 0 | 0 | 18 | 9 | 4 | 2 | 4 | 1 | 1 | 0 | 2 | 2 |
| | PM payload CGy | 0 | 0 | 0 | 0 | 50 | 0 | 4 | 1 | 4 | 4 | 1 | 14 | 4 | 10 |
| | TL payload CGy | 0 | 0 | 0 | 0 | 85 | 40 | 2 | 5 | 9 | 30 | 2 | 39 | 0 | 0 |
| | PM payload CGz | 0 | 0 | 0 | 0 | 43 | 0 | 6 | 46 | 26 | 7 | 0 | 1 | 1 | 1 |
| | TL payload CGz | 0 | 0 | 0 | 0 | 82 | 100 | 32 | 23 | 30 | 16 | 0 | 0 | 0 | 0 |
| | PM payload Ixx | 0 | 0 | 0 | 0 | 0 | 0 | 21 | 34 | 38 | 15 | 0 | 0 | 0 | 0 |
| | TL payload Iyy / Izz | 0 | 0 | 0 | 0 | 1 | 0 | 13 | 8 | 19 | 3 | 0 | 0 | 0 | 0 |
| Suspension VDPs | 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 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 0 | 0 | 0 | 0 | 2 |
| | Dr. roll steer | 0 | 0 | 0 | 0 | 0 | 0 | 25 | 8 | 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 |
| | Tl. unsprung mass | 3 | 3 | 5 | 4 | 10 | 5 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| | 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 |
| Tyre VDPs | St. lateral force | 0 | 0 | 0 | 0 | 0 | 0 | 96 | 1 | 0 | 1 | 2 | 1 | 0 | 100 |
| | Dr. lateral force | 0 | 0 | 0 | 0 | 1 | 0 | 4 | 19 | 30 | 5 | 2 | 1 | 2 | 9 |
| | Tl. lateral force | 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 |

## 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.globaltrailermag.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/Austroads 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.