A RECONFIGURABLE LINEAR MODEL FOR PBS VEHICLE DEVELOPMENT

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ABSTRACT

Traditional heavy vehicle legislation prescriptively regulates weights, dimensions, etc., whereas the PBS (Performance Based Standards) approach regulates vehicle safety performance. The Smart Truck Pilot Project in South Africa is tasked with evaluating the potential benefits of PBS regulation on the increase in transport efficiency, improvement in vehicle safety, reduction in the environmental impact and reduction in infrastructure damage. The flexibility in PBS allows for a design to optimally meet operator needs. The Smart Truck programme has shown that these benefits can be realised by adopting the PBS approach, however the development of a PBS heavy vehicle is associated with additional heavy vehicle dynamics analysis and design costs which can deter small operators. The University of Pretoria VDG (Vehicle Dynamics Group) has developed a reconfigurable multi-axle, multi-articulation heavy vehicle linear state space model that operators and designers can use in the early stages of development. This model can be used to conduct a feasibility study to determine if a PBS vehicle will have a positive ROI (Return on Investment) for the operator. Also, this model can be used in concept design to identify the necessary hardware (tyres, suspension, etc.) and evaluate the proposed vehicle's performance. The model does not require a vehicle dynamics specialist and can be used by the designers themselves. Further, the model can be operated in common coding languages (e.g. MATLAB, python), thus reducing the cost of PBS development. PBS vehicle development cost can be reduced by conducting the majority of the vehicle development (feasibility study and conceptual design) with this linear state space vehicle model, which is reasonably accurate to specify the vehicle hardware and parameters to meet the operator needs in the concept stage. The linear state space vehicle model can then be used to generate a non-linear multi-body model in Adams or TruckSim for the detailed design stage and the final PBS evaluation.

1. INTRODUCTION

In 2007 the Smart Truck Pilot Project was introduced in South Africa to determine the potential benefits of PBS (Performance Based Standard) regulation on the increase in heavy vehicle transport efficiency, improvement in vehicle safety, reduction in the environmental impact and reduction in infrastructure damage. To date there are 462 PBS vehicles in operation that have cumulatively travelled 242 017 819 km across South Africa. The Smart Truck Pilot Project reported a saving of 90 956 trips/year, thus saving R82.2 M/year in fuel costs, a reduction in greenhouse gas emissions of 16 649 tons CO_2/year, a reduction in road wear of R21 300 per vehicle/year and a 44% crashes/million km reduction in crashes (Nordengen, 2021).

Although, the Smart Truck Pilot Project has demonstrated that adopting PBS is beneficial to operators, PBS adoption is not wide-spread. Developing a PBS vehicle is costly and time consuming taking more than 2 years (Dessein, et al., 2012). The majority of this time is spent in the design iteration phase between operators and a vehicle dynamics specialist performing the PBS evaluation on the proposed designs. Kemp (2019) suggests that simplified tools be developed that operators and trailer manufacturers without specialised vehicle dynamics software and expertise can use to investigate whether a PBS vehicle will benefit the operator. Although, such a simplified tool cannot be used to perform a PBS evaluation in accordance with the standard's evaluation requirement, a simplified tool can be used for feasibility studies and early design stages with high probability that such a vehicle will meet the PBS standards.

Benade (2015) estimates that it costs R480 000 in consultation fees for a commercial car-carrier operator to conduct a PBS assessment on their designs. Benade (2015) proposed a pro-forma design estimated to cost R80 000 in consultation fees to reduce the PBS assessment costs. De Saxe (2012) developed a low-speed turning model to predict the low speed manoeuvrability of vehicle combination given its basic dimensions. Benade (2016) identified the New Zealand Land Transport Rule as a suitable simplified tool to estimate Static Roll Threshold (SRT) to potentially regulate the roll stability of heavy vehicles in South Arica. The need for this simplified tool is due to the fact that it's time consuming and costly to perform SRT tests through a multibody simulation software. Dessein (2012) developed a design routine that uses a new regression model to give a near optimal solution. Thereafter, a PBS evaluation is conducted to fine-tune the design until the vehicle is fully compliant. Although, these methods are not sufficient to perform PBS evaluations these models can be used by designers to predict the vehicle performance with acceptable error before contracting a PBS assessor to conduct a full PBS assessment.

2. AIM OF PAPER

Develop a low-fidelity simplified reconfigurable multi-axle and multi-articulation heavy vehicle model capable of conducting PBS evaluations.

3. SCOPE OF PAPER

This paper gives a short discussion on the applicable PBS test conducted in this study. Thereafter, the development of a Linear State Space Heavy Vehicle Model (LSSHVM) in MATLAB is given. The accuracy of the linear state space model is evaluated by comparing the results of the linear state space model to an Adams View model with the same vehicle parameters.

4. PBS EVALUATION

PBS evaluation involves measuring the vehicle performance against 15 vehicle performance standards that can be performed through simulation or physical testing. This paper focuses on 7 of these standards; Swept Path maximum Width (SPW), Frontal Swing (FS), Tail Swing (TS), Rearward Amplification (RA), High Speed Transient Offtracking (HSTO), Yaw Damping Coefficient (YDC) and SRT.

5. LOW SPEED SWEPT PATH (LSSP)

The Low Speed Swept Path (LSSP) test evaluates whether a vehicle combination making a turn at an intersection will collide with others vehicles in adjacent lanes. This test measures the amount of road space a vehicle combination requires in a turn. The LSSP test has 6 measures; SPW, FS, TS, Maximum of Difference (MoD), Difference of Maximum (DoM) and Steer Tyre Friction Demand (STFD). This paper focuses on the SPW, FS and TS, which are sensitive to the unit's wheelbase and unit's frontal overhang and tail overhang. Increasing the unit's wheelbase or overhangs increases the amount of road space the vehicle requires in a turn (Australian National Transport Commission, 2008).

5.1 Static Roll Threshold (SRT)

The SRT measures the vehicle's propensity to rollover during a steady state turn. When travelling on a curved road, the vehicle experiences a lateral acceleration that causes an overturning moment. Rollover occurs when the overturning moment exceeds the vehicle's rollover stability threshold (Australian National Transport Commission, 2008). Increasing the vehicle's Centre of Gravity (CoG) height reduces the vehicle's SRT, while increasing the vehicle's wheel track increase the vehicle's SRT.

5.2 Rearward Amplification (RA) and High Speed Transcient Offtracking (HSTO)

Heavy vehicle combinations with articulation point(s) have a tendency of amplifying the lateral acceleration of the leading unit towards the last unit (Australian National Transport Commission, 2008). In an emergency single lane change manoeuvre this lateral acceleration amplification may lead to the last unit causing an accident by rolling over, or by offtracking from the path of the leading unit, risking the last unit colliding with other vehicles in adjacent lanes

RA is a measure of the likelihood of rollover of the last unit in an emergency manoeuvre. HSTO is a measure of the sway of the rear unit from the path of the tractor. Both RA and HSTO are improved by reducing the distance between the tractor's CoG to the hitch point, increasing the trailer's wheelbase and fitting tyres with a high cornering stiffness.

5.3 Yaw Damping Coefficient (YDC)

After a severe manoeuvre heavy vehicle combinations with articulation point(s) tend to experience sway oscillations that increases the driver's frequency of steering control movements. Vehicles that take a long time to settle increase the driver's workload and may lead to a rollover. YDC is a measure of how quickly yaw oscillations take to settle after a 'steer impulse' steering input. YDC is influenced by similar parameters that influence RA and HSTO (Australian National Transport Commission, 2008).

6. RECONFIGURABLE MULTI-AXLE, MULTI-ARTICULATION HEAVY VEHICLE LINEAR STATE SPACE MODEL

This chapter discusses the development of a linear state space model which can predict a multi-axle, multi-articulation heavy vehicle low speed, high speed and static roll threshold performance given basic vehicle parameters. The generalised model takes the lateral, yaw and roll dynamics of heavy vehicles into consideration as shown in Figure 1 to generate the dynamic equations of motion for a vehicle with arbitrary number of units, axles and articulation points.

Assumptions:

- Vehicle parameters are constant and the forward speed is constant.
- Small slip angles and small articulation angles.
- Pitch and bounce is negligible.
- Linear lateral tyre stiffness, linear hitch stiffness and linear suspension system.
- Tyres maintain contact with the road and tyres on the same axle have the same slip angle (bicycle model approach).
- Load transfer, vertical tyre stiffness and aerodynamics are ignored.
- The steer tyre angle is used as system input (steering system gearing is ignored).

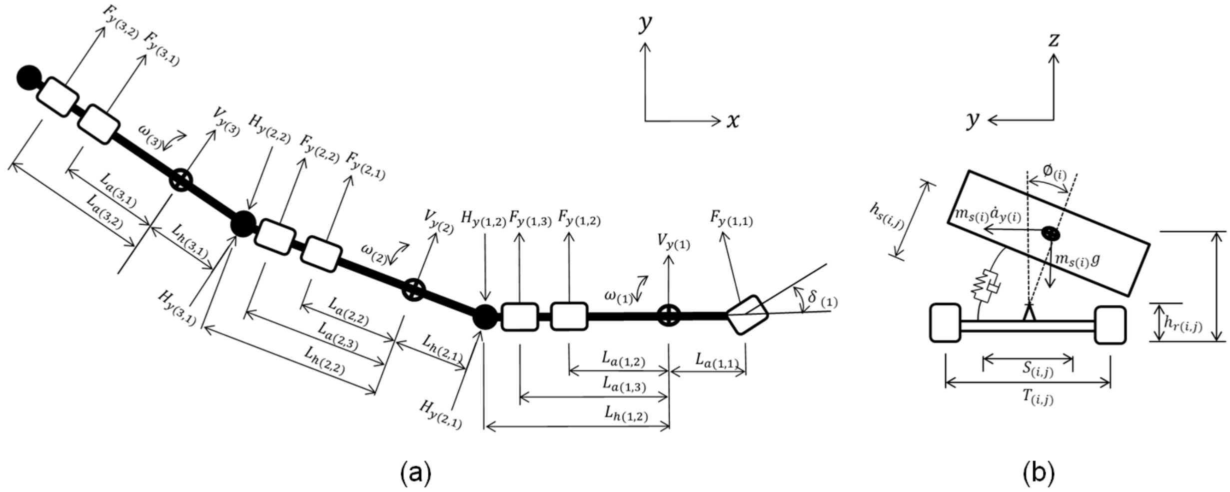

Figure 1: Linear single track multi-axle, multi-articulation heavy vehicle model (a) Lateral and yaw plane (b) Roll plane

The generalised equations of motion defining the lateral, yaw and roll motions of the vehicle are given in Equations 1, 2 and 3, respectively The units are connected together by the hitch points which have kinematic relationship defined by Equation 4.The leading unit's sideslip angle (β) is defined by Equation 5, the subsequent units' sideslip angle is given by Equation 6. The tyre's slip angle (α) is given by Equation 7 and the linearised lateral tyre forces are defined by Equation 8. These equations are then combined to create a linear state space model with 5 state (x) and input (u) per unit represented by Equation 10 and Equation 11, respectively. The model states include each unit's lateral velocity ($V_{y(i)}$), yaw angle ($\omega_{(i)}$), yaw angular velocity ($\dot{\omega}_{(i)}$), roll angle ($\emptyset_{(i)}$) and roll angular velocity ($\dot{\emptyset}_{(i)}$). Subscripts i and j represent the unit number and axle number, respectively. Variables where the subscript is a non-positive integer are reduced to zero. Important vehicle parameters included in the state space model are defined in Table 1.

$$m_{(i)}\left(\dot{V}_{y(i)} + V_x\dot{\omega}_{(i)}\right) = \sum_{j=1}^{J} F_{y(i,j)} + H_{y(i,i-1)} - H_{y(i,i+1)} \tag{1}$$

$$I_{zz(i)}\ddot{\omega}_{(i)} = \sum_{j=1}^{J} F_{y(i,j)}\, L_{a(i,j)} + H_{y(i-1)}L_{h(i-1)} + H_{y(i)}L_{h(i)} \tag{2}$$

$$\begin{aligned}\left(I_{xx(i)} + m_{s(i)} h_{s(i)}{}^2\right)\ddot{\emptyset}_{(i)} + \sum_{j=1}^{J} k_{s(i,j)}\dot{\emptyset}_{(i)} + \sum_{j=1}^{J} K_{s(i,j)}\emptyset_{(i)} \\ = H_{y(i,i-1)}h_{h(i,i-1)} + H_{y(i,i+1)}h_{h(i,i+1)} + m_{s(i)} g h_{s(i)}\left(\emptyset_{(i)} + \theta\right) \\ - m_{s(i)}\left(\dot{V}_{y(i)} + V_x \dot{\omega}_{(i)}\right)h_{s(i)} + K_{h(i-1,i)}\left(\emptyset_{(i-1)} - \emptyset_{(i)}\right) \\ - K_{h(i,i+1)}\left(\emptyset_{(i)} - \emptyset_{(i+1)}\right)\end{aligned} \quad (3)$$

$$\dot{V}_{y(i)} + V_x\dot{\omega}_{(i)} - \ddot{\omega}_{(i)}L_{h(i)} = \dot{V}_{y(i+1)} + V_x\dot{\omega}_{(i+1)} - \ddot{\omega}_{(i+1)}L_{h(i+1)} \qquad \text{for } i = 1,2,\dots,n-1 \quad (4)$$

$$\beta_{(i=1)} = \frac{V_{y(i)}}{V_x} \quad (5)$$

$$\beta_{(i=2,3,\dots,I)} = \beta_{(i-1)} + \left(\omega_{(i-1)} - \omega_{(i)}\right) + \frac{L_{h(i-1,2)}\dot{\omega}_{(i-1)}}{V_x} - \frac{L_{h(i,1)}\dot{\omega}_{(i)}}{V_x} \quad (6)$$

$$\alpha_{(i,j)} = \delta_{(i,j)} - \beta_{(i)} - \frac{L_{a(i,j)}\dot{\omega}_{(i)}}{V_x} \quad (7)$$

$$F_{(i,j)} = C_{\alpha(i,j)}\left[\alpha_{(i,j)}\right] \quad (8)$$

$$\dot{X} = AX + BU \quad (9)$$

$$X = [x_1, x_2, \dots, x_I]^T \qquad \text{, where } x_i = \left[V_{y(i)}, \omega_{(i)}, \dot{\omega}_{(i)}, \emptyset_{(i)}, \dot{\emptyset}_{(i)}\right] \quad (10)$$

$$U = [u_1, u_2, \dots, x_I]^T \qquad \text{, where } u_{(i)} = \left[\delta_{(i,1)}, \delta_{(i,2)}, \dots, \delta_{(i,J)}\right] \quad (11)$$

Table 1: Vehicle parameters

m	Total mass	m_s	Sprung mass
V_x	Longitudinal velocity	H_y	Hitch lateral force
I_{zz}	Yaw moment of inertia	I_{xx}	Roll moment of inertia
θ	Tilt table angle	g	Gravitational acceleration
L_a	Displacement from the CoG to the axle	C_α	Tyre cornering stiffness
L_h	Displacement from the CoG to the hitch	K_s	Equivalent roll stiffness
h_s	Displacement from the CoG to the roll centre	k_s	Equivalent roll damping
h_h	Displacement from the hitch to the roll centre	K_h	Equivalent hitch stiffness

7. SIMPLIFIED HEAVY VEHICLE MODEL PERFORMACE AND RESULTS

The generalised equations are used to generate a 7 axles (1 steer axle and 8 non-steer-axle) B-double heavy vehicle model for this study. The simplified model has 15 states and 1 input represented by Equation 12 and Equation 13, respectively. The same vehicle parameters are used to create an Adams View model which is used to evaluate the linear model's accuracy when performing 5 PBS tests; LSSP RA, HSOT, YDC and SRT.

$$X = \left[V_{y(1)}, \omega_{(1)}, \dot{\omega}_{(1)}, \emptyset_{(1)}, \dot{\emptyset}_{(1)}, V_{y(2)}, \omega_{(2)}, \dot{\omega}_{(2)}, \emptyset_{(2)}, \dot{\emptyset}_{(2)}, V_{y(3)}, \omega_{(3)}, \dot{\omega}_{(3)}, \emptyset_{(3)}, \dot{\emptyset}_{(3)}\right]^T \tag{12}$$

$$U = \delta_{(1,1)} \tag{13}$$

7.1 Low Speed Swept Path

Calculating the simplified model's displacement by directly integrating the longitudinal and lateral velocity results in the units drifting slightly apart at the end of the manoeuvre. Further, this integration error increases as the number of articulation points increase. To reduce this drift the hitch point velocities are integrated to calculate the hitch point displacements instead. Then, the hitch point displacements and units' yaw angles are used to calculate the units' CoG displacements. It can be seen in Figure 2 that the simplified model estimates SPW, FS and TS with a 5%, 57% and 25% error. Although, the simplified model over estimates the FS and TS measures the simplified model can give guidance to designers in the early design stages of possible areas of concern. It should be noted that although the FS and TS error percentages are larger, the error magnitudes are small. Therefore, the overhang design modifications that will be required in the detailed design to ensure the proposed design complies with the standards will be minimal.

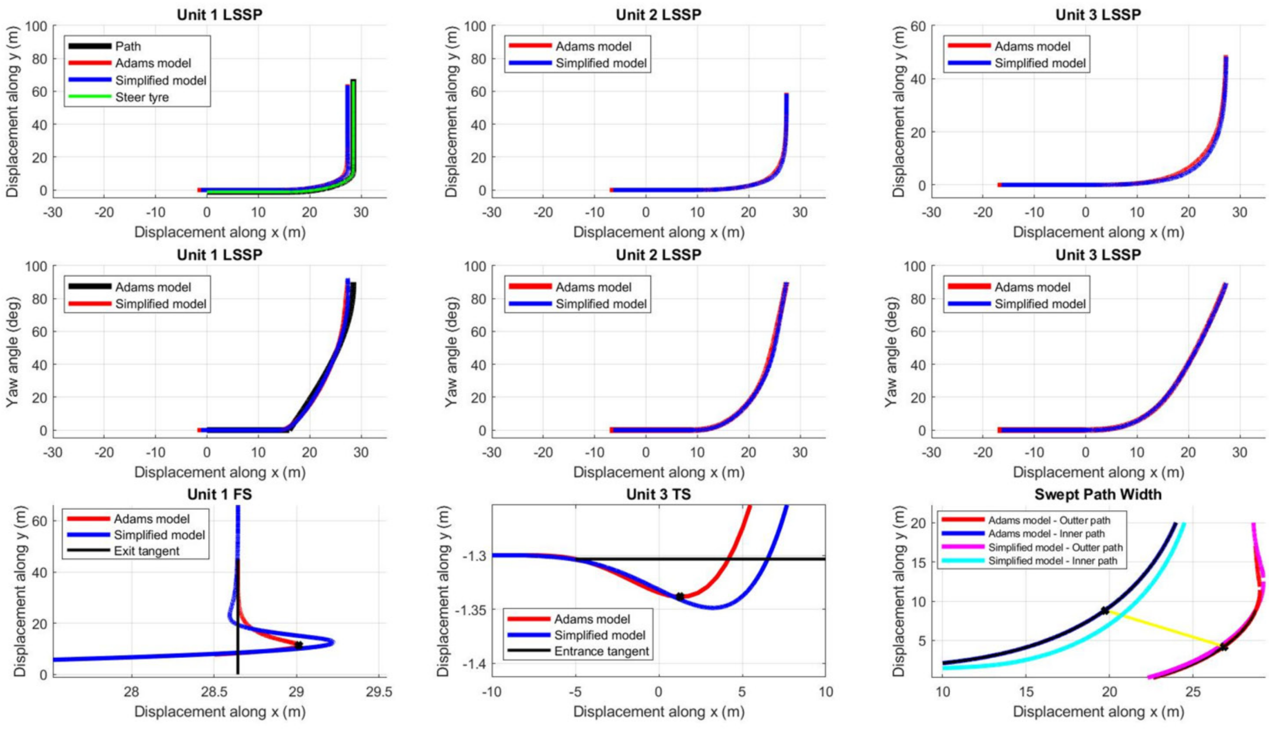

Figure 2: Low Speed Swept Path

7.2 Rearward Amplification and High Speed Transcient Offtracking

The simplified model underestimates the HSTO performance by 83%. The Adams model experiences more sway from the path, in comparison to the simplified model as shown in Figure 3. This is due to the linear tyre simplification resulting in the simplified model experiencing slightly higher lateral tyre forces (more grip) than the Adams model. Even at side slip angle less than 1 degree the linear tyre assumption slightly diverges from the non-linear tyre within an acceptable range. Also, the linear tyre is more responsive, because the tyre relaxation length is not included in the simplified model. Notwithstanding the simplified model overestimating the lateral acceleration experienced by each unit by approximately 15%, the simplified model is able to estimate the RA with a 5% error.

Although the simplified model underestimates the HSTO and RA performance, the simplified model can be used to verify if the proposed vehicle configuration will be capable of performing a single lane change without rolling over. If the simplified model cannot perform a single lane change then the vehicle configuration will definitely fail the HSTO and RA test when simulated in Adams. Failing the tests with the simplified model allows designer to make design iterations to the vehicle configuration until the proposed vehicle is able to pass the HSTO and RA, before the non-linear PBS evaluation is conducted. Thus, reducing the amount of time and cost of consulting a vehicle dynamics specialist.

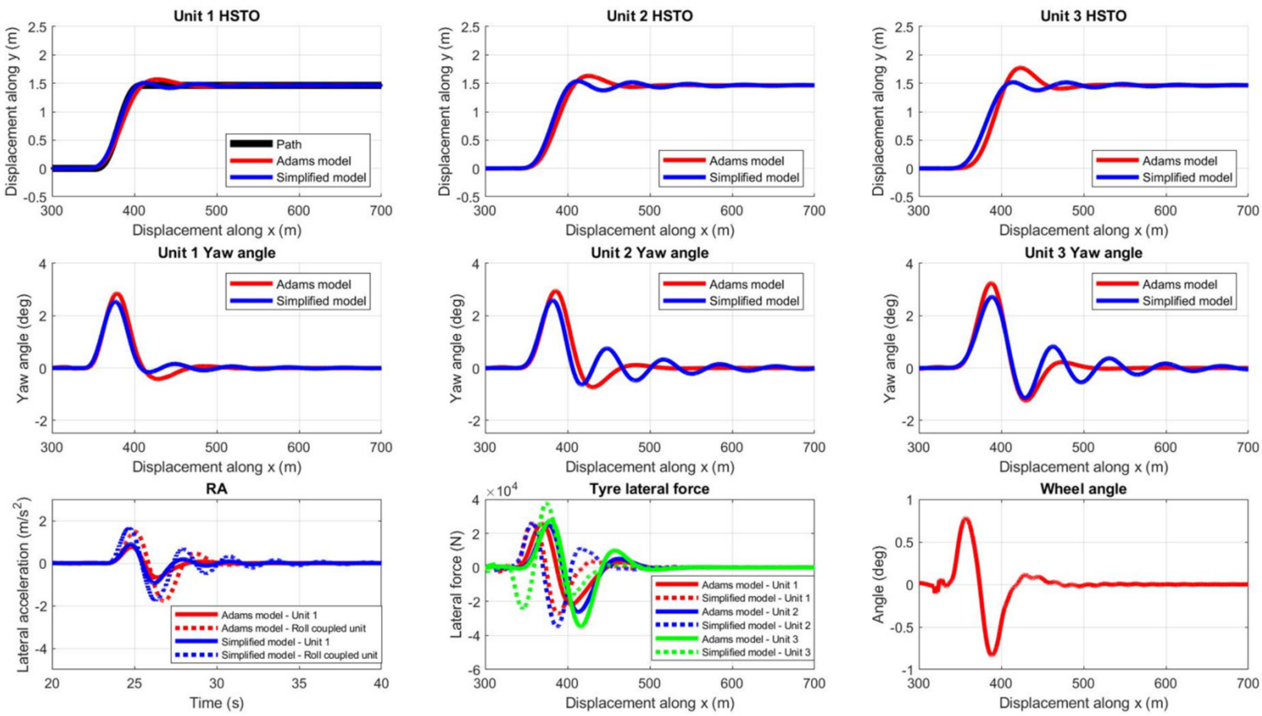

Figure 3: High Speed Off-Tracking and Rearward Amplification

7.3 Yaw Damping Coefficient

The simplified model achieved a 33% YDC error. The simplified model underestimates the lateral displacement and yaw response of the vehicle to a ‘Steer Impulse’ as shown in Figure 4. The simplified model yaw oscillations take a longer time to settle. Nevertheless, the simplified model indicates that the yaw oscillations decay overtime.

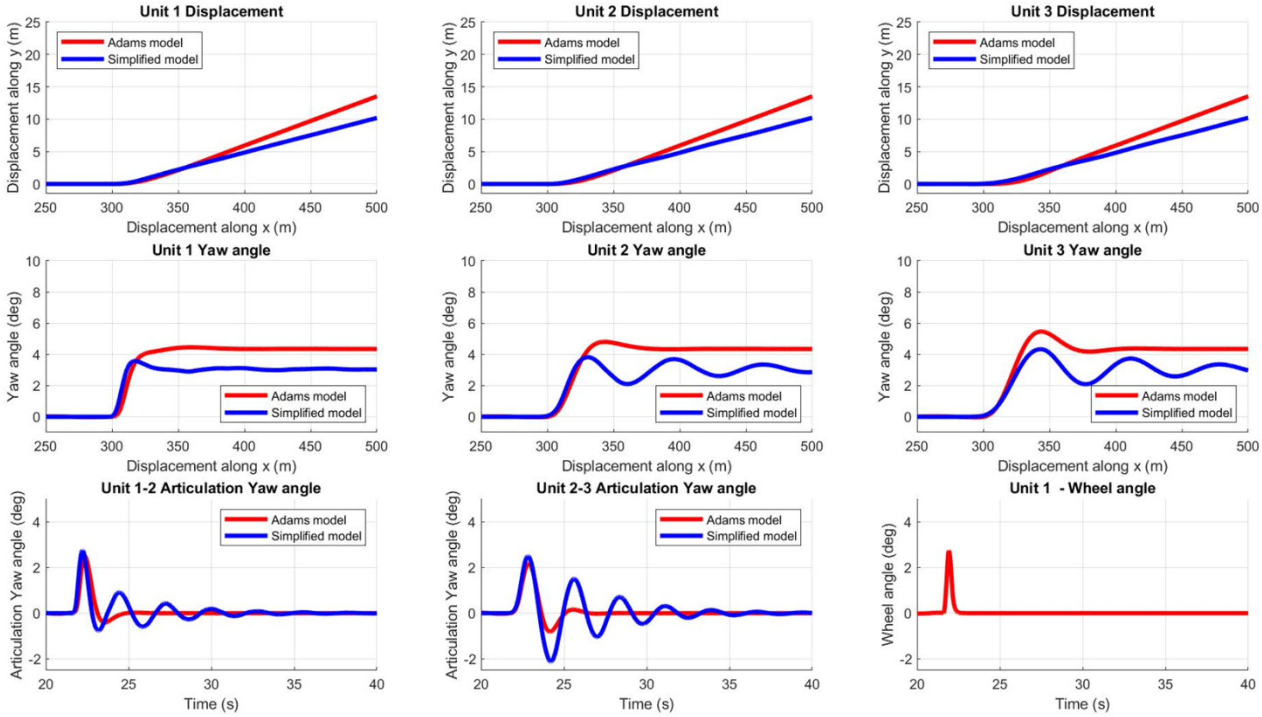

Figure 4: Yaw Damping Coefficient

7.4 Static Roll Threshold

The simplified model is modified to include a roll angle on the axle relative to the ground, to represent the tilt table used to perform the SRT test. The simplified model is able to predict the point of roll over with a 5% roll coupled lateral error as shown in Figure 5. After a tilt table angle on 10º the non-linear Adams model rolls more than the simplified model. However the points of roll are the same for both models. The CoG height and the vehicle's wheel track width are the main contributor to SRT, compared to the no load transfer, linear suspension system and vertical tyre stiffness assumptions.

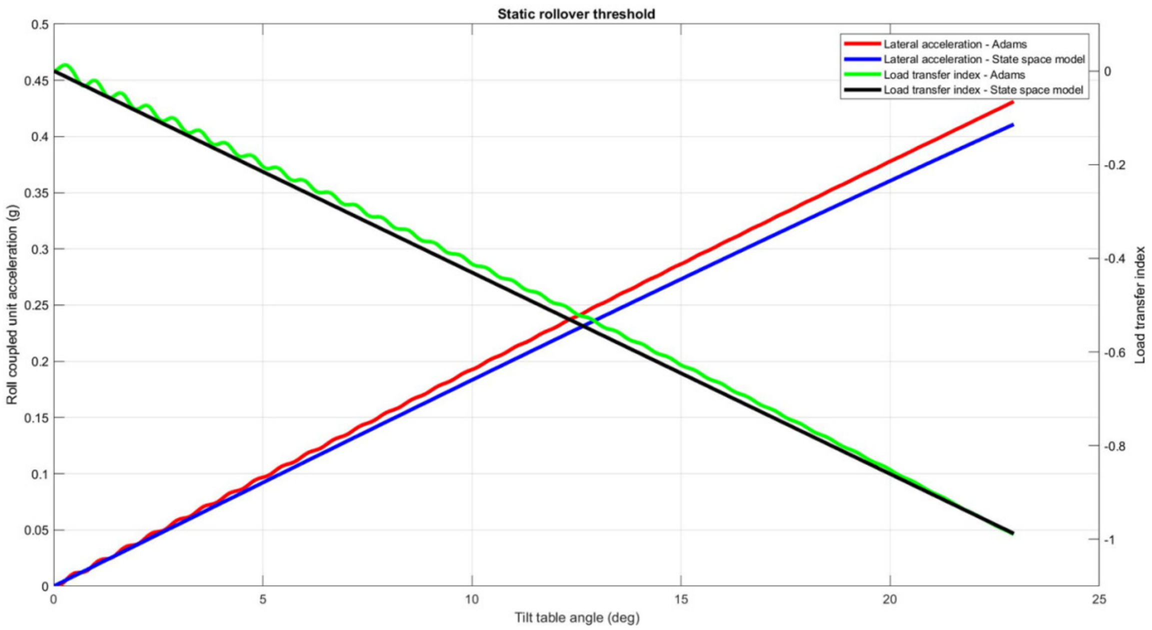

Figure 5: Static Roll Threshold

Table 2 summarises the accuracy of the simplified model when performing these PBS tests. Both the Adams model and the simplified mode achieved a level 2 PBS performance. The simplified model is a conservative model that significantly overestimates the FS and TS. It should be noted that although the error percentage is high the error magnitudes are low. The simplified model significantly underestimates the HSTO and YD, however, the model indicates that the proposed design will likely not roll-over in an emergency manoeuvre and that the yaw oscillations will decay thereafter. The simplified model is able to estimate the SWP, SRT and RA with an error a 5% error.

Table 2: PBS performance levels and simplified model accuracy

<table>
<tr><th></th><th colspan="3">Low Speed Performance</th><th colspan="4">High Speed Performance</th></tr>
<tr><th>Road class</th><th>SWP (m)</th><th>FS (m)</th><th>TS (m)</th><th>SRT(g)</th><th>HSTO (m)</th><th>RA</th><th>YD</th></tr>
<tr><td>Level 1</td><td>≤ 7.4</td><td rowspan="4">Trucks - $\leq$ 0.7, Busses - ≤ 1.5</td><td>≤ 0.3</td><td rowspan="4">Trucks transporting Dangerous goods & Busses - ≥ 0.40 Other - ≥ 0.35</td><td>≤ 0.6</td><td rowspan="4">$\leq 5.7 \times SRT = 2.56$</td><td rowspan="4">$\geq 0.15$</td></tr>
<tr><td>Level 2</td><td>≤ 8.7</td><td>≤ 0.35</td><td>≤ 0.8</td></tr>
<tr><td>Level 3</td><td>≤ 10.6</td><td>≤ 0.35</td><td>≤ 1.01</td></tr>
<tr><td>Level 4</td><td>≤ 13.7</td><td>≤ 0.5</td><td>≤ 1.2</td></tr>
<tr><td colspan="8">Simplified model accuracy</td></tr>
<tr><td>Adams</td><td>8.5</td><td>0.37</td><td>0.04</td><td>0.43</td><td>0.3</td><td>0.537</td><td>0.27</td></tr>
<tr><td>Simplified</td><td>8.1</td><td>0.58</td><td>0.05</td><td>0.41</td><td>0.05</td><td>0.513</td><td>0.18</td></tr>
<tr><td>Error</td><td>-0.4</td><td>$+0.21$</td><td>$+0.01$</td><td>-0.02</td><td>-0.25</td><td>-0.024</td><td>-0.09</td></tr>
<tr><td>Error (%)</td><td>-5</td><td>$+57$</td><td>$+25$</td><td>-5</td><td>-83</td><td>-5</td><td>-33</td></tr>
</table>

8. CONCLUSION

A major deterrent to the wide-spread adoption of PBS heavy vehicles over traditional heavy vehicles is the associated higher costs and longer developmental cycle of PBS heavy vehicles compared to a traditional heavy vehicle. Participants in the Smart Truck Pilot Project have suggested that a simplified heavy vehicle model that operators and trailer manufacturers can use during the design phase to predict the vehicle's performance will reduce the PBS heavy vehicles developmental cycle. Such a model will allow operators and trailer manufacturers to conduct majority of the developmental work in-house, thus reducing the design iteration phase between the operator and a vehicle dynamics specialist performing the PBS evaluation on the proposed design. Also, operators can use this model to conduct feasibility studies in-house to determine if a PBS vehicle will have a positive Return on Investment (RIO) for the operator.

In this study a simplified reconfigurable multi-axle, multi-articulation heavy vehicle linear state space model capable of performing PBS evaluations was developed in MATLAB. An Adams View model with the same vehicle parameters was created to evaluate the accuracy of the simplified model. The simplified model correlates well with the Adams model for the SWP, SRT and RA achieving a 5% error, but poorly estimated the FS, TS, HSOT and YD with a 57%, 25%, 83% and 33% error. These tests show that a simplified model cannot be used to perform PBS evaluations in accordance with the standard, however the simplified model can be used as a designing tool to reduce the associated time and costs of developing a PBS vehicle. The simplified model can be used by designers and operators to do the majority of the feasibility and early stage design in-house. The simplified model can be used by non-vehicle dynamics specialist to select suitable vehicle hardware, given simple vehicle parameters such as vehicle dimensions, payload, etc. Thereafter, a vehicle dynamics specialist can be consulted to refine the proposed design with a high fidelity software such as Adams or Trucksim to ensure that the proposed design complies with the PBS standard. The simplified model reduces the time and costs associated with the design iteration phase between operators and the vehicle dynamics specialist.

9. FUTURE WORK

- The simplified model's accuracy can be improved by using an adaptive tyre to include the non-linear characteristics of the tyre (stiffness and damping) and taking load transfer effect into consideration.
- Create models for the common truck-trailer combinations in South Africa that are prescriptively regulated and investigate how the productivity of these vehicle's productivity and safety can be improved, while infrastructure damage and environmental impact can be reduced.
- The simplified model can be used to perform an eigenvalue analysis to study directional stability of articulated vehicles.
- The simplified model can be used as a reference model to develop vehicle active systems.

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