A SOUTH AFRICAN PERFORMANCE BASED STANDARDS (PBS) VEHICLE TO TRANSPORT STEEL PIPES

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The preliminary design of a South African PBS vehicle to transport large-bore welded steel pipes is an important milestone in developing local expertise to analyse PBS designs. The design approach has drawn extensively from the PBS measures developed in Australia. Nevertheless, the design conforms to South African axle load and bridge formula legislation. Simple analytical equations, based on geometry and previous empirical research, were used to optimise the payload and PBS performance measures: an efficient and novel design approach. Using the optimisation model, an A-Double design was shown to exceed all of the PBS safety requirements for L2 performance with a 50% increase in payload over the baseline vehicle. This optimised solution was verified using TruckSim 8.0. The predictions from the optimisation model were highly accurate with the exception of SRT and upper limit for RA, which were reasonably accurate.

Keywords: South African Heavy Vehicle legislation, RTMS, PBS, pipe transport, vehicle safety, payloads, vehicle dynamics simulation, Generalized Reduced Gradient optimisation

1. Introduction

A vehicle designed according to Performance Based Standards (PBS) conforms to performance measures which directly assess vehicle safety. The design approach is not constrained by prescriptive mass and dimension limitations which only affect safety in conjunction with a whole host of other variables such as suspension stiffness and fifth wheel lash. The PBS design approach promotes innovation and more productive vehicles, with increased focus on increasing road safety and decreasing road wear.

To prevent the abuse of the PBS approach and the occurrence of *ad hoc*, unregulated PBS designs, all PBS participants in South Africa must first be certified through the RTMS accreditation scheme (Nordengen, Prem, & Mai, 2008). The RTMS programme is an industry-led voluntary self-regulation scheme that seeks to preserve road infrastructure, improve road safety and increase the productivity of transport logistics in South Africa (Standards South Africa, 2007).

1. The South African PBS Strategy

A South African PBS committee was formed in 2004 and enjoys full support and involvement from the Department of Transport (DoT). The PBS strategy allows an RTMS-accredited participant to exceed current dimension and load limits for a single trial PBS vehicle provided safety and road wear are improved or at least not compromised. The demonstration vehicle safety record, loading and productivity is carefully monitored. Once the improved safety performance and payload efficiency are demonstrated, the DoT will consider allowing the RTMS-accredited participant to operate a fleet of such vehicles as part of the PBS demonstration project. These concessions are primarily for the purpose of gathering sufficient data to enable a thorough evaluation of the safety performance of PBS vehicles compared with the baseline vehicles.

Sappi Forests (Pty) Ltd (Sappi) and Mondi Business Paper (Mondi), the two major timber companies in South Africa have successfully trialled PBS demonstration vehicles and plans are underway to expand the PBS projects to include monitoring a fleet of PBS timber vehicles. The PBS analyses of these vehicles were completed by Australian experts in accordance with the PBS measures developed in Australia jointly by the National Transport Commission (NTC) and Austroads. The vehicles pass the Level 2 (L2) performance requirements necessary to drive on significant freight routes but preclude inner city driving. Guidelines on the classification of the road network into four levels are available from the NTC (National Transport Commission, July 2007).

The Sappi vehicle analysed by Mechanical System Dynamics (Pty) Ltd (MSD) has a permissible maximum combination mass (CM) of 67.5 tonnes, an overall length of 27 m and is able to carry a 15% larger payload. The Mondi vehicle analysed by ARRB Group Ltd (ARRB) has a CM of 64 tonnes and an overall length of 24 m. The Mondi vehicle is approximately 15% more fuel efficient and has an improved tonnage throughput per vehicle by 23.4% (Armstrong, 2008). The currently used baseline timber vehicle, legal within the current South African prescriptive legislation (maximum length of 22m and a CM of less than 56 tonnes (Department of Transport, 2000)), did not meet the L2 requirements for Static Rollover Threshold and Rearward Amplification (Nordengen, Prem, & Mai, 2008).

The Mondi and Sappi PBS demonstration vehicles have shown that by using the PBS design approach it is possible to make productivity gains while simultaneously improving vehicle safety in South Africa.

2. The Development of South African Expertise to Assess PBS Designs

The capability to carry out PBS analyses in South Africa is limited but this shortcoming is being addressed. In 2008, heavy vehicle experts (Winkler, Gillespie and Radlinski) presented a University of Michigan Transport Research Institute (UMTRI) course on heavy vehicle dynamics in Stellenbosch, South Africa (Kienhöfer, 2008). Attendees included representatives from the CSIR, Afrit, BPW Axles, MAN and Daimler Chrysler SA (all involved in the Sappi and Mondi PBS projects).

In 2009 Hall Longmore, a manufacturer of large-bore welded steel pipes, contracted the University of the Witwatersrand (Wits) to design a PBS vehicle to transport pipes. The Wits team has completed the initial conceptual development, vehicle configuration selection and simulations to determine conformance to the Australian PBS measures. This work will be corroborated by Australian experts before the manufacture of the PBS vehicle commences.

3. Hall Longmore Customer Requirements

Hall Longmore manufactures 6.1 m, 12.2 m and 18.3 m pipes for the local market and 12.2 m and 12.8 m lengths for the export market. The maximum permissible length of a multi-vehicle combination is 22 m and for tractor semi-trailer it is 18.5 m (Department of Transport, 2000). Thus the 12.2 m, 12.8 m and 18.3 m pipes can only be transported with a single trailer configuration. The transport of 18.3 m pipes requires an abnormal load permit.

The transport of 12.2 m and 12.8 m pipes from Johannesburg to Richards Bay for export is a good opportunity to design a PBS vehicle because the route and payload are consistent. Figure shows the export sales for 2007 to 2009 (12.2 m and 12.8 m lengths have been combined).

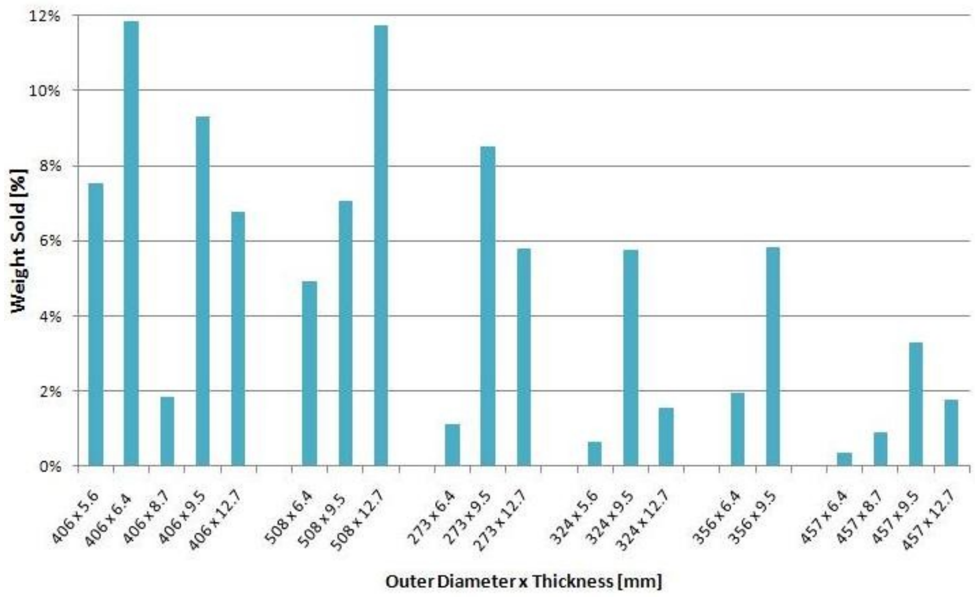

Figure – Hall Longmore Export Sales for 2007 to 2009

A smaller pipe can be nested within a larger pipe if the smaller pipe has a diameter roughly 100 mm less than the larger pipe. Based on the export sales shown in Figure , two nested pipe configurations were selected as potential design payloads (See Table):

- Configuration 1: 273x9.5 nested inside 406x6.4
- Configuration 2: 273x9.5 nested inside 508x12.7

The more challenging configuration 1 was selected as the design payload; configuration 2 results in a lower centre of gravity when fully laden.

Table – Potential Design Payloads

	Outer Pipe		Inner Pipe		Mass
	OD	thickness	OD	thickness	
	[mm]	[mm]	[mm]	[mm]	[tonnes]
Configuration 1	406	6.4	273	9.5	1.597
Configuration 2	508	12.7	273	9.5	2.776

2. Design Criteria

The design approach has drawn extensively from the PBS measures developed in Australia (National Transport Commission, July 2007). Nevertheless, the design conforms to South African axle load and bridge formula legislation. The eight performance measures listed below are considered to be necessary and sufficient for a safe vehicle in the context of this project.

Yaw Damping Coefficient (YDC) – The rate at which "sway" or yaw oscillations decay after a severe steering input.
Static Rollover Threshold (SRT) – The maximum steady state lateral acceleration that can be sustained in constant radius high speed turn. This directly measures the vehicle's rollover stability.
Rearward Amplification (RA) – Measures the degree to which the lateral accelerations experienced by trailing units are amplified in comparison to that of the towing unit in a high speed evasive single lane change manoeuvre.
High-Speed Transient Offtracking (HSTO) – The excess lateral displacement, or overshoot, of the rearmost axle of the vehicle when performing the same prescribed lane change manoeuvre as used for the Rearward Amplification test. This indicates the amount which the vehicle will deviate out of its own lane.
Tracking Ability on a Straight Path (TASP) – The amount of road width used by the vehicle when travelling at high speed along a straight road with an uneven surface as the trailing units deviate from the path of the hauling unit.
Low-Speed Swept Path (LSSP) – The amount of road width required by the vehicle when executing a prescribed low-speed 90° turn as the trailing units track inside of the path followed by the hauling unit.
Tail Swing (TS) – The amount which the rear corner of a vehicle unit swings out at the commencement of a tight turn. This may cause collisions with objects in adjacent lanes or on the roadside. This is of particular concern for vehicle units with a large rear overhang.

Frontal Swing (FS) – The amount that the front corner of the hauling unit tracks outside of the path followed by the front outside steer wheel.

The Australian PBS guidelines contain requirements that are specific to the road class to which the vehicle is permitted access (requirements are more lenient for the higher road levels):

- Level 1 (L1) – General Access
- Level 2 (L2) – Significant Freight Routes
- Level 3 (L3) – Major Freight Routes (generally the lowest level met by road trains)
- Level 4 (L4) – Remote Areas

The Sappi and Mondi PBS vehicles were designed to meet L2 performance requirements: improving the safety of currently used baseline timber vehicles that do not meet the L2 requirements for SRT and RA (Nordengen, Prem, & Mai, 2008). L2 performance requirements have thus been used for this PBS vehicle design.

The designed vehicle adheres to the South African restrictions on axle loads thus ensuring no additional pavement deterioration over current legal vehicles. The limits for the axle configurations used as prescribed in Government Gazette No 20963, Part 1 (Department of Transport, 2000) are summarised in Table .

Table – South African Axle Mass Load Limits

Configuration	Limit [kg]	Regulation
2 wheel, 1 axle, steerable	8 000	240 (b)
4 wheel, 1 axle	9 000	240 (c)
8 wheel, 2 axle	18 000	240 (e)
12 wheel, 3 axle	24 000	240 (g)

The proposed vehicle complies with the South African bridge formula, see Equation (1), which limits the concentration of axle loading in the longitudinal direction to prevent bridge overloading (Department of Transport, 2000).

$$P = 2100L + 18000 \quad (1)$$

where: L = distance between the centres of extreme axles of any two axle groups [m]

P = maximum combined mass on all the axles within the distance L [kg]

3. Design Optimisation

Simple analytical equations, based on geometry and previous empirical research, were used to estimate the PBS performance of the vehicle. These simple models were used to optimise the payload and PBS performance measures. The optimised solution was verified using a detailed model developed in TruckSim 8.0, a multi-body vehicle dynamics simulation software package (Mechanical Simulation Corporation, 2009). Using simple models in an optimisation routine was found to be an efficient design approach: no previous reference to such a design approach could be found in the literature.

1. Estimates of Australian PBS Performance

Models were developed to estimate the vehicle axle loads, bridge loading, Static Rollover Threshold (SRT), Low-Speed Swept Path (LSSP) and Rearward Amplification (RA): a vehicle that met the preceding requirements would most likely meet the remaining standards (if not the design could be fine-tuned at the detailed modelling stage).

The vehicle unit mass properties were calculated based on information supplied by Afrit (a South African trailer manufacturer). Where necessary, vehicle parameters, such as the axle unsprung mass, were taken from the list of properties for the generic truck/trailer configurations investigated by Prem *et al.* (2001).

The Static Rollover Threshold was predicted using the method developed by Elischer and Prem (1998):

$$SRT=T2HF \qquad (2)$$

where: T = track width [m]

H = height of centre of gravity for the vehicle (tare and payload) [m]

F = 1+WPHP-HEHWE+WP

where: W_P = payload mass [kg]

W_E = empty vehicle mass [kg]

H_P = height of centre of gravity of payload [m]

H_E = height of centre of gravity of empty vehicle [m]

The results from an NTC study conducted by Prem *et al.* (2002) were used to estimate Rearward Amplification (RA). The study investigated the sensitivity of PBS measures to vehicle design variables: an example is illustrated in Figure in which the RA sensitivity to wheelbase is shown.

The RA was estimated assuming superposition and a linear relationship with respect to each vehicle design variable:

$$RA=RA'1+\Delta RA20xi'xi'-xi \qquad (3)$$

where: xi = value of vehicle design variable *i*

xi' = value of vehicle design variable *i* for the mid-range baseline vehicle

RA' = RA of mid-range baseline vehicle [-]

ΔRA = corresponding change in RA for a 20% change in vehicle design variable *i* for the mid-range baseline vehicle [%]

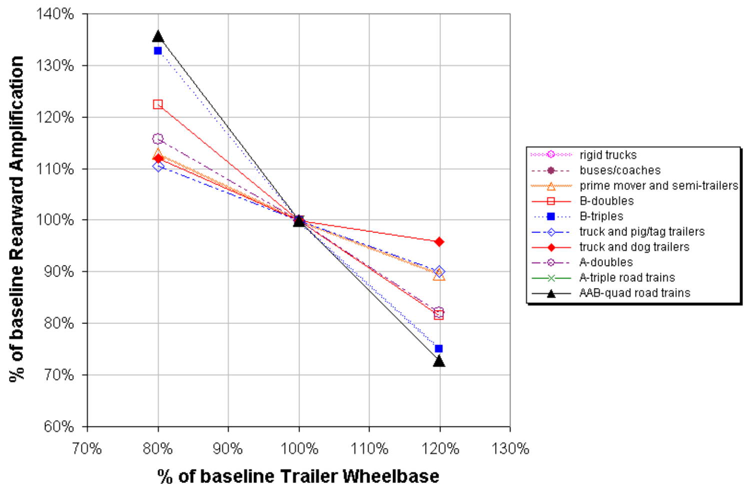

Figure – Sensitivity of RA to Trailer Wheelbase (Prem *et al.*, 2002)

The design variables incorporated in the RA prediction are:

- combination mass
- prime-mover wheelbase as a proportion of total length
- trailer wheelbase as a proportion of total length
- dolly wheelbase as a proportion of total length (for the A-Double)
- centre of gravity height (CoG)

The Low-Speed Swept Path (LSSP) was predicted using the WHI formula (1970). The prediction of the total road usage includes the equivalent wheelbase of the hauling unit, as suggested by Prem *et al.* (2002). The equivalent wheelbase is given by:

$$EqW=WBi-OSi \qquad (4)$$

where: WB_i = wheelbase of vehicle unit i [m]

OS_i = hitch point offsets (fifth wheel and pin type) [m]

Using the WHI formula:

$$LSSP=\beta0+\beta1EqW+\beta2EqW2+\beta3EqW3 \qquad (5)$$

where: $\beta_{0,1,2,3}$ = 1681.5, 197.49, 30.965 and -0.59412 [-]

2. Optimisation Model

A Generalized Reduced Gradient (GRG) nonlinear optimisation code (Lasdon, Waren, Jain, & Ratner, 1978) was used to optimise the vehicle design parameters (such as trailer wheelbase lengths) of a B-Double and an A-Double configuration. The optimisation model was implemented in Excel using an objective function (overall performance measure) which combines wasted axle load and proximity to the limits for LSSP and RA:

$$Z= Pi-CM-kLSSPlim-LSSPRAlim-RA \qquad (6)$$

where: P_i = maximum permissible axle group load in accordance with South African legislation [kg]

CM = vehicle combination mass [kg]

$LSSP_{lim}$	=	maximum permissible LSSP for L2 roads [m]
RA_{lim}	=	maximum permissible RA for L2 roads [-]
k	=	adjustment factor used to ensure that both terms of Z are of similar magnitude [m^{-1}]

The terms and are multiplied rather than added together so that their contribution is large only if the solution does not approach either limit. Since the predictions are estimates, a solution that does not approach the PBS limits is preferable.

The model was constrained using applicable mass and dimension restrictions from Government Gazette No 20963, Part 1 (Department of Transport, 2000) in spite of the freedom offered by the PBS design approach to ignore these limits. The prescriptive legislation constraints that were included in the model were vehicle overall width, rear overhang, axle loads and bridge loading. The upper limit of 1.8 m for trailer front overhang was not included. The model was further constrained with limits for SRT, RA and LSSP and limited to an overall vehicle length of less than 30m (to ensure safe overtaking) in accordance with the Australian PBS for L2 performance (National Transport Commission, July 2007).

3. Optimisation Results

Table summarises the results for the baseline tractor semi-trailer configuration and the optimised B-Double and A-Double configurations. In order to meet the LSSP of 8.7 m the axle locations of the B-Double have to be placed such that the axle load limits are not well utilised. This results in a wasted axle load capacity of 19% and a payload increase of only 15% over the baseline vehicle. Although the B-Double has an improved SRT and RA compared with the baseline vehicle, the comparatively poor payload efficiency considering the investment of an added trailer to the vehicle precludes the B-Double as a viable option.

The A-Double configuration was selected for further investigation as the optimisation model predicted it will exceed all the safety requirements with a 50% increase in payload over the baseline vehicle. Figure shows the baseline vehicle and the proposed PBS design A-double configuration.

Table – Comparison of Optimised Vehicle Configurations to Baseline Vehicle

			Baseline	B-Double	A-Double
Payload			20 pipes	23 pipes	30 pipes
Configuration			12s3	12s3s3	12s2-2s2
Number of axles		[-]	6	9	9
Overall length		[m]	17.3	29.5	30
Tare mass		[kg]	17 050	23 155	24 400
Payload mass		[kg]	31 965	36 760	47 950
CM		[kg]	49 015	59 920	72 350
Wasted axle load capacity		[kg]	685	13 780	7 350
SRT	(SRT_{min} = 0.35)	[g]	0.36	0.45	0.42
RA/RA_{max}	(RA_{max} = 5.7SRT)	[-]	67%	54%	92%
LSSP	($LSSP_{max}$ = 8.7)	[m]	6.65	8.68	8.03

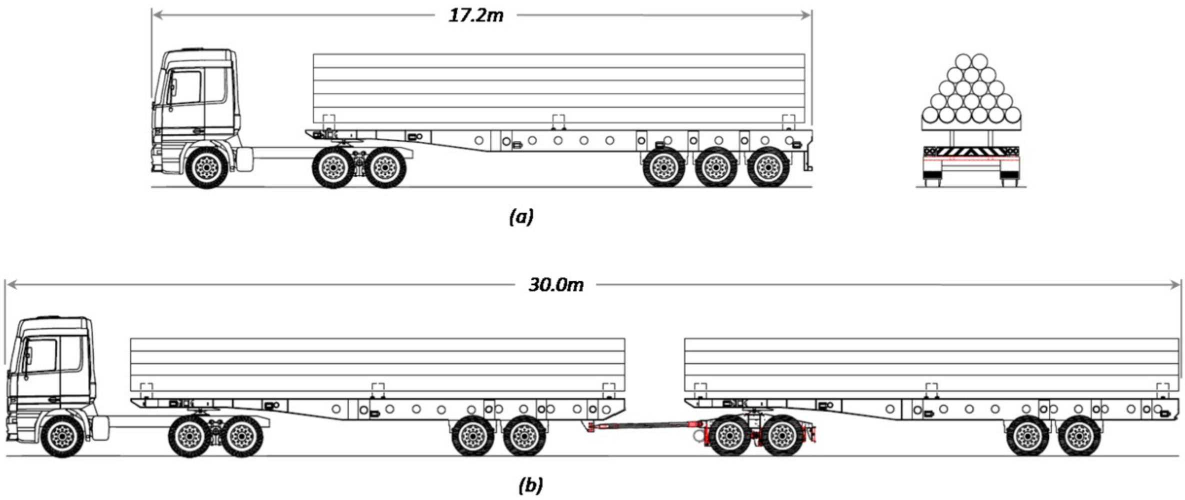

Figure – (a) Baseline vehicle at 49 t CM and (b) Optimised A-Double at 72.4 t CM

4. Detailed PBS Assessment

A numerical model of the selected A-Double configuration was developed in TruckSim 8.0. As with the optimisation model, the vehicle unit mass properties were calculated based on information supplied by Afrit. All axle, spring, tyre, damper and turntable parameters were taken from Prem *et al.* (2001). The comparison study by Prem *et al.* was further used to validate the use of the TruckSim software in this work. The TruckSim results compared well with the results from Prem *et al*.

The manoeuvres prescribed in the Australian PBS guidelines (National Transport Commission, July 2007) were simulated:

- a low-speed 90° turn
- high-speed travel along a 1.0km long straight road with uneven road surface
- a pulse-steer test
- a constant radius turn at slowly increasing speed
- an evasive lane change manoeuvre

The TruckSim simulated PBS values are compared to the analytical optimisation values in Table . The values are not rounded off as prescribed in the standards to allow for a more meaningful comparison.

Table – PBS Results for Optimised A-Double Configuration (72.4 t, 30.0 m)

PBS Standard	units	TruckSim Model	Optimisation Model	Error	NTC L2 Specification
Yaw Damping Coefficient	[-]	0.191	-	-	≥ 0.15
Static Rollover Threshold	[g]	0.386	0.424	9.8%	≥ 0.35
Rearward Amplification	[-]	2.202	2.212	0.5%	≤ 2.28 (5.7SRT_{rrcu})
High-Speed Transient Offtracking	[m]	0.897	-	-	≤ 0.8
Tracking Ability on a Straight Path	[m]	2.771	-	-	≤ 3.0
Low-Speed Swept Path	[m]	7.999	8.025	0.3%	≤ 8.7
Tail Swing	[m]	0.155	-	-	≤ 0.35

Frontal Swing	[m]	0.526	-	-	≤ 0.7

Note: SRT_{rrcu} denotes the *SRT* of the rearmost roll-coupled unit which in this case differs from the *SRT* for the entire vehicle

The optimisation predictions are highly accurate with the exception of SRT and the upper limit for RA, which are reasonably accurate. The vehicle meets all of the Australian PBS requirements for L2 performance with the exception of High-Speed Transient Offtracking (HSTO) which is exceeded by 0.097 m.

As suggested by the discussions under RA and HSTO in the Australian PBS document (National Transport Commission, July 2007) the HSTO performance measure can be improved using:

- tyres with a higher cornering stiffness
- turntables with stiffer roll coupling
- longer trailer wheelbases

5. Conclusions

The preliminary assessment and design of a South African PBS vehicle to transport large-bore welded steel pipes has been completed: an important milestone in developing local expertise to analyse PBS designs. Based on export sales data, 273x9.5 pipes nested inside 406x6.4 pipes were selected as the design payload. The design approach has drawn extensively from the PBS measures developed in Australia. Nevertheless, the design conforms to South African axle load and bridge formula legislation.

Simple analytical equations, based on geometry and previous empirical research, were used to give an estimate of the PBS performance of the vehicle. These simple models were used to optimise the payload and PBS performance measures: an efficient and novel design approach.

Using the optimisation model, an A-Double design was shown to meet all of the PBS requirements with a 50% increase in payload over the baseline vehicle. This optimised solution was verified using a detailed model developed in TruckSim 8.0.

The predictions from the optimisation model were highly accurate, with the exception of SRT and the upper limit for RA, which were reasonably accurate. The vehicle meets all of the Australian PBS requirements for L2 performance with the exception of High-Speed Transient Offtracking (HSTO) which is exceeded by 0.097 m. Future work will improve the HSTO using methods suggested by NTC such as using tyres with a higher cornering stiffness.

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