A PRO-FORMA DESIGN FOR CAR-CARRIERS: LOW-SPEED PERFORMANCE-BASED STANDARDS

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ABSTRACT

The Australian performance-based standards (PBS) scheme is being evaluated in South Africa as an alternative means of regulating heavy vehicles, allowing for a relaxation of length and mass limits. This has proven to provide economic benefits while improving vehicle safety and emissions. Within the PBS scheme, the vehicle is assessed using twelve performance standards which can be grouped together as low-speed directional, high-speed directional, stability and longitudinal performance measures. Compliance with these standards requires expensive and time-intensive computer simulations; a hurdle to the car-carrier industry in particular. We propose a pro-forma car-carrier design in which limits on the most important car-carrier parameters are defined to ensure compliance with the low-speed PBS. It is proposed that new car-carrier designs complying with this semi-prescriptive pro-forma design be exempted from full PBS assessment in the South African PBS project. In this paper the parametric sensitivity of the low-speed performance standards was assessed, and suitable limits on these parameters were found. Tests were carried out on hypothetical designs within these limits. It was found that each of the 10 000 vehicle configurations generated within the constraints of the pro-forma design met the Level 1 requirements of the low-speed PBS. Future work will ensure compliance with the full set of twelve performance standards. It is estimated that the pro-forma approach as compared to doing full assessments would save the South African car-carrier industry an estimated R1,200,000 in one year.

1 INTRODUCTION

1.1 Background

The Australian performance-based standards (PBS) scheme is being evaluated in South Africa as an alternative means of regulating heavy vehicles, allowing for a relaxation of length and mass limits. The PBS scheme has proven to provide economic benefits in South Africa by allowing greater payloads while improving vehicle safety and emissions (Nordengen, 2014). A proposed vehicle is assessed in terms of twelve performance standards which can be grouped together as low-speed directional, high-speed directional, stability and longitudinal performance measures (National Transport Commission, 2008). To demonstrate compliance with these standards, time-intensive computer simulation is required. This has become a hurdle to the car-carrier industry in particular, as these vehicles are often over-length and over-height and are (since recently) required by the relevant authorities to meet Level 1 PBS requirements before any over-length and over-height permits are issued (Abnormal Load Technical Committee, 2014).

1.2 Aim

This paper develops a pro-forma car-carrier design which defines limits on the most critical car-carrier parameters to ensure compliance with the low-speed PBS. Upper and lower bounds are defined for the vehicle geometry and physical properties of a new car-carrier, which should ensure Level 1 PBS compliance. This work forms part of a larger project that aims to develop a pro-forma design for South African car-carriers in terms of the full PBS framework. This will negate the need for costly and time-consuming individual PBS assessments.

1.3 Scope

The scope of this paper is limited to the three applicable low-speed directional PBS for a commercial car-carrier, namely low-speed swept path, frontal swing and tail swing. Similar work has been done in New Zealand where pro-forma designs were developed for three different vehicle types (De Pont, 2010). De Pont only considered the swept width standard which is similar to the low-speed swept path as described in section 2.3.

2 LOW-SPEED DIRECTIONAL PBS

According to the Australian PBS scheme, the low-speed directional standards are measured during a prescribed low-speed 90° turn (National Transport Commission, 2008). The sidewall of the vehicle’s steer tyre is required to follow the 12.5 m radius path as shown in Figure 2.1.

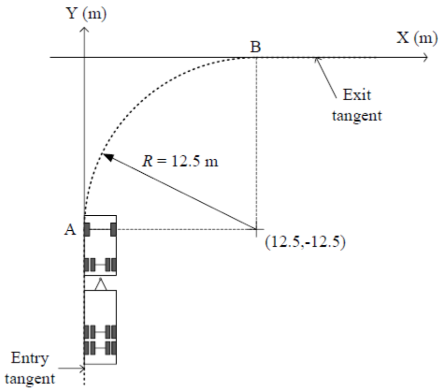

Figure 2.1 NTC prescribed low-speed 90° turn (De Saxe, 2012)

While performing this manoeuvre, frontal swing (FS), tail swing (TS) and low-speed swept path (LSSP) are measured (by simulation or physical testing) as shown in Figure 2.2 and described in sections 2.1 to 2.3.

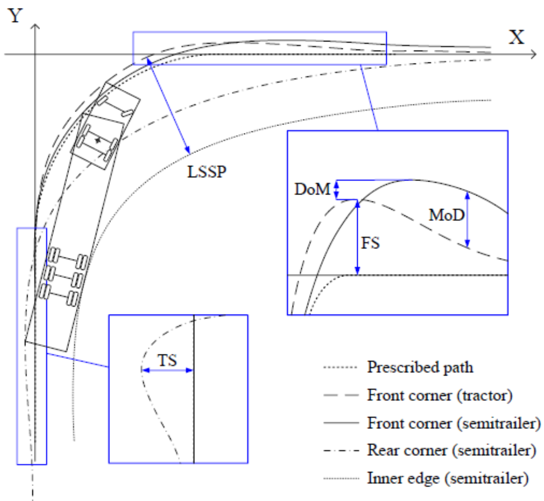

Figure 2.2 Low-speed directional PBS (De Saxe, 2012)

2.1 Frontal swing

Frontal swing is the amount that the front outer corner of the hauling unit swings outside the path followed by the widest section of the vehicle in the exit region of the low-speed 90° turn. Maximum of difference (MoD) and difference of maxima (DoM) pertain to the amount by which the front outer corner of a semitrailer swings out beyond that of the hauling unit or preceding semitrailer (National Transport Commission, 2008).

2.2 Tail swing

Tail swing is the amount that the rear outer corner of a vehicle unit swings out at the commencement of the prescribed low-speed 90° turn (National Transport Commission, 2008).

2.3 Low-speed swept path

Low-speed swept path is the amount of road width required by the vehicle when executing the prescribed low-speed 90° turn as the trailing units track inside of the path followed by the hauling unit (National Transport Commission, 2008).

3 ASSESSMENT OF A COMMERCIAL CAR-CARRIER

A representative commercial car-carrier was assessed according to the low-speed Australian PBS standards using TruckSim® vehicle dynamics simulation software (Benade, Berman and Kienhofer, 2014). The general assembly drawing of the vehicle is shown in Figure 3.1.

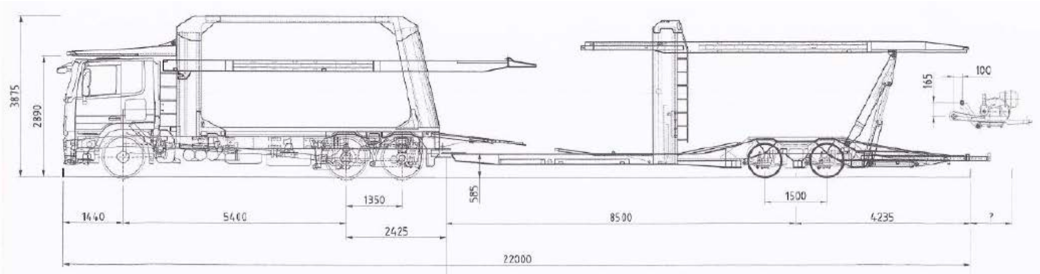

Figure 3.1 Commercial car-carrier

The MoD and DoM standards are not applicable as this trailer configuration does not have a front overhang. The FS, TS and LSSP results from the assessment (Benade, Berman and Kienhofer, 2014) are shown in Figure 3.2 to Figure 3.4.

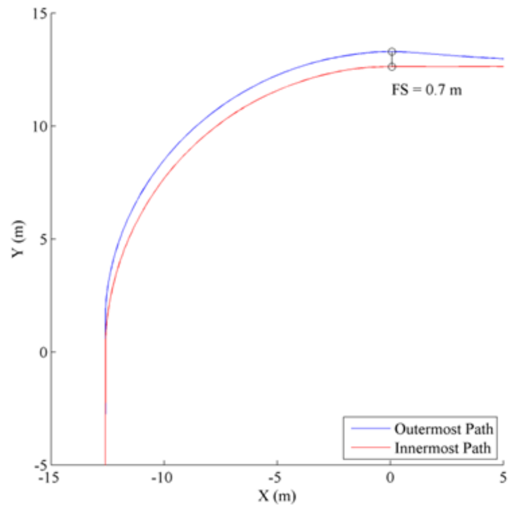

Figure 3.2 FS assessment using TruckSim®

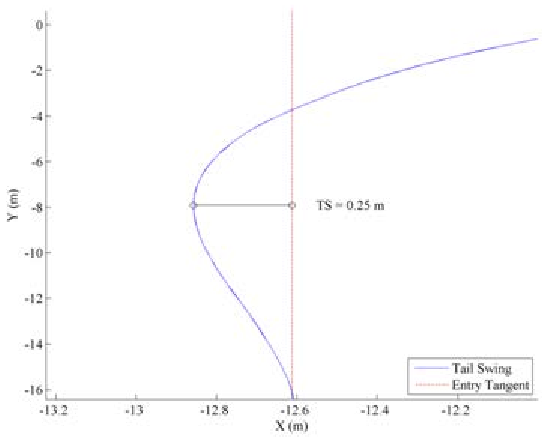

Figure 3.3 TS assessment using TruckSim®

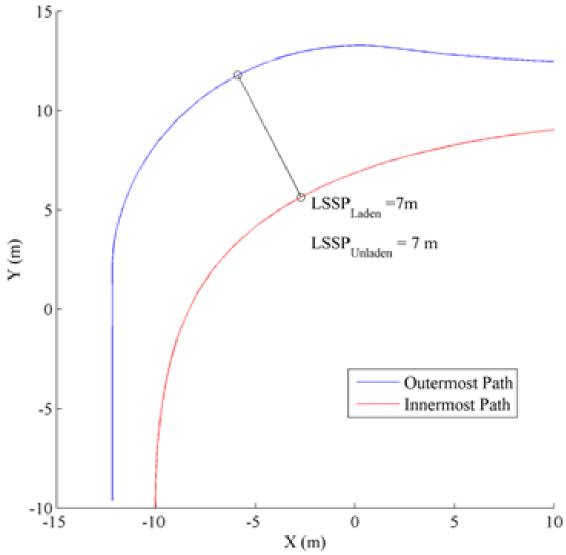

Figure 3.4 LSSP assessment using TruckSim®

Level 1 performance was achieved for all applicable low-speed PBS as shown in Table 3-1. A low-speed mathematical model (LSMM), developed by de Saxe (De Saxe, 2012), allows the low-speed directional standards to be accurately predicted in significantly less time than the TruckSim® model. The commercial car carrier was re-assessed using de Saxe's LSMM. The results (as shown in Table 3-1) correlated well with the TruckSim® results and the LSMM was thus used for all further assessments and optimisations.

Table 3-1 PBS results of commercial car-carrier

Standard	TruckSim Result		LSMM Result		LSMM vs. TruckSim	Required performance			
						Level 1	Level 2	Level 3	Level 4
LSSP (m)	6.912	Level 1	7.080	Level 1	-2.43%	≤ 7.4 m	≤ 8.7 m	≤ 10.6 m	≤ 13.7 m
FS (m)	0.674	Level 1	0.674	Level 1	0.07%	≤ 0.7 m			
TS (m)	0.245	Level 1	0.234	Level 1	4.40%	≤ 0.30 m	≤ 0.35 m	≤ 0.35 m	≤ 0.50 m

The LSMM offers a simplistic approach and requires significantly less input parameters compared to TruckSim®. The required parameters and values used by the LSMM are shown in Table 3-2 and illustrated in Figure 3.5.

Table 3-2 Parameters required by LSMM

Parameter	Value	Unit	Parameter	Value	Unit
T	2.351	m	H_2	0	m
WB_1	6.075	m	WB_2	8.5	m
$FC_{long,1}$	1.352	m	$FC_{long,2}$	0	m
$FC_{wid,1}$	2.596	m	$FC_{wid,2}$	0	m
$RC_{long,1}$	10.025	m	$RC_{long,2}$	12.735	m
$RC_{wid,1}$	2.3	m	$RC_{wid,2}$	2.58	m
n_1	2		n_2	2	
d_1	1.35	m	d_2	1.5	m
$IE_{wid,1}$	2.58	m	$IE_{wid,2}$	2.58	m
H_1	7.825	m			

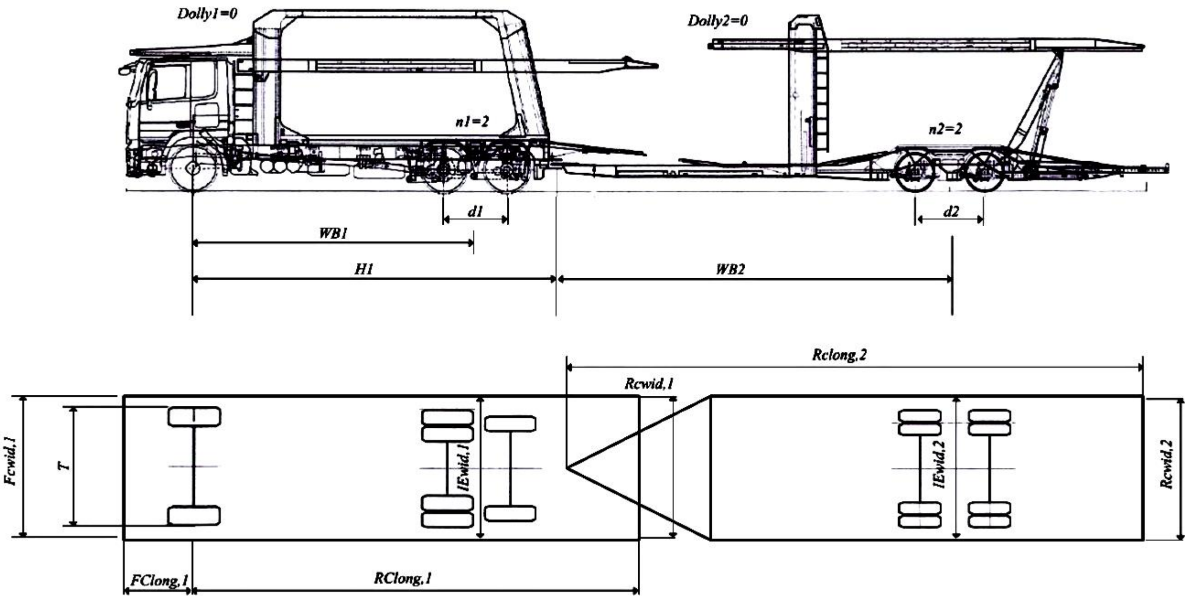

Figure 3.5 Parameters required by LSMM

4 SENSITIVITY ANALYSIS AND PARAMETER LIMITATION

A study conducted on the Australian heavy vehicle fleet by Prem et al (2002) revealed the typical effects of key vehicle parameters on PBS performance. The low-speed findings are summarised in Table 4-1 and correlated well with our findings.

Table 4-1 Broad summary of parametric effects

Standard	Effect of increasing			
	Prime mover wheelbase (WB_1)	**Front overhang** ($FC_{long,1}$)	**Trailer wheelbase** (WB_2)	**Rear overhang** (RC_{long})
FS	Significantly increases	Significantly increases		
TS			Moderately decreases	Significantly increases
LSSP	Significantly increases	Moderately increases	Significantly increases	

We performed a detailed sensitivity analysis considering all of the parameters in Table 3-2. Each parameter was varied by ±10% to determine the parameters which affect FS, TS and LSSP and the degree thereof. A so-called "parameter significance factor (PSF)" was calculated by dividing the percentage deviation from the original performance (as result of the 10% parameter change) by the percentage change in input parameter (10%). Based on the PSFs, certain parameters were limited to ensure Level 1 low-speed PBS performance whilst allowing a vehicle designer maximum freedom w.r.t. vehicle layout.

4.1 Frontal swing

For the case of decreasing the parameter values by 10%, no parameter was found to increase the FS - hence only the "increased parameters" chart is shown in Figure 4.1

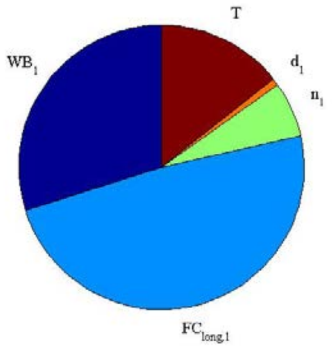

Figure 4.1 PSF w.r.t. FS for increased parameters

$FC_{long,1}$ was found to be the dominant PSF and needed to be constrained in order to ensure Level 1 FS performance. By constraining this parameter to a maximum value equal to that of the commercial vehicle, a larger range of the less-significant parameters can simultaneously be tolerated as presented in Table 4-2. The less-significant parameters were assigned practical maximum values, after which WB_1 was increased and modelled up to just before non-compliance in terms of FS.

Table 4-2 Parameter limits w.r.t. FS

Parameter	Minimum	Maximum	Comments
FClong,1		1.352	Equal to commercial vehicle
n_1		2	Number of drive axles for a car-carrier will unlikely exceed this
d_1		1.36	Maximum axle spacing according to the CSIR database of car-carrier hauling units
T		2.542	Based on the axle spacing of the commercial vehicle while also allowing for 385mm wide tyres to be used plus an additional 5% for further uncertainty
WB_1		6.185	Modelled up to the point of FS failing to meet Level 1 standards

4.2 Tail swing

The PSFs with respect to TS are shown in Figure 4.2. The parameters that when increased were found to increase TS were assigned an upper limit. Of these parameters, the parameter with the most significant influence on TS was found to be $RC_{long,2}$. By constraining $RC_{long,2}$ to a value equal to that of the benchmark vehicle, a larger range of less-significant parameters can be tolerated while complying with the TS requirements as described in Table 4-3. The parameters that when decreased were found to increase TS were assigned a lower limit. Of these, the parameter with the greatest impact on TS was WB_2. By constraining this parameter to a value equal to that of the benchmark vehicle, a larger range of less-significant parameters can be tolerated as described in Table 4-3.

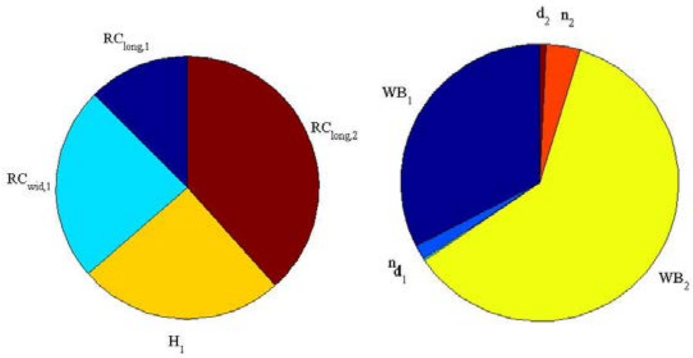

Figure 4.2 PSF w.r.t. TS for increased (left) and decreased (right) parameters

Table 4-3 Parameter limits w.r.t. TS

Parameter	Minimum	Maximum	Comments
WB_1	5.665		Modelled up to the point of the hauling unit failing to meet Level 1 for the TS standard, after the limits described below were set
n_1	1		It would be useful to also allow single drive axles
d_1	1.34		No significant influence. Minimum limit chosen 20mm smaller than maximum that is stated in Table 4-1 to allow some freedom.
WB_2	8.5		Equal to commercial vehicle
n_2	1		No significant influence and it would be useful to also allow single axles on the trailer
d_2	1.34		No significant influence, equal to d_1
$RC_{long,1}$		10.025	Equal to commercial vehicle
$RC_{wid,1}$		2.3	Equal to commercial vehicle
H_1		8.025	Modelled up to the point of the trailer failing to meet Level 1 TS standards
$RC_{long,2}$		12.735	Equal to commercial vehicle

4.3 Low-speed swept path

Figure 4.3 compares the relative magnitude of all positive PSF of LSSP for the case of increasing parameter values as described earlier. Upper limits were assigned to these parameters as described in Table 4-4. For the case of decreasing the parameter values only the H_1 parameter was found to increase the LSSP and subsequently a lower limit was assigned to this parameter.

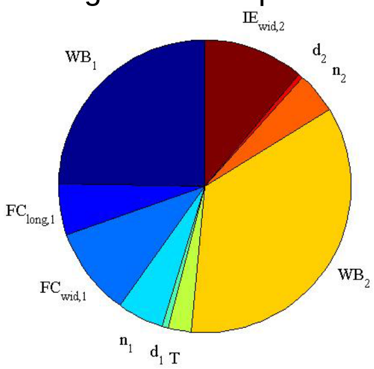

Figure 4.3 PSF w.r.t. LSSP for increased parameters

Table 4-4 Parameter limits w.r.t. LSSP

Parameter	Minimum	Maximum	Comments
H_1	7.8		To allow some deviation from the commercial vehicle
WB_1		6.185	From Frontal swing limit (Table 4-2)
$FC_{long,1}$		1.352	From Frontal swing limit (Table 4-2)
$FC_{wid,1}$		2.596	Equal to commercial vehicle
n_1		2	From Frontal swing limit (Table 4-2)
d_1		1.36	From Frontal swing limit (Table 4-2)
T		2.542	From Frontal swing limit (Table 4-2)
WB_2		8.85	Modelled up to the point of LSSP failing to meet Level 1 requirements
n_2		3	No significant influence and it would be useful to also allow tridem axles on the trailer
d_2		1.6	Not a significant influence, offers reasonable range
$IE_{wid,2}$		2.6	Legal limit in terms of maximum vehicle width (Department of Roads and Transport, 1996)

4.4 Combined limitations

The limits as described in Table 4-2 to Table 4-4 were combined into a preliminary low-speed pro-forma as shown in black in Table 4-5. The limits in green are not part of the formal requirements but were imposed to provide realistic bounds so that test simulations could be performed as described in the following section.

Table 4-5 Preliminary low-speed pro-forma

Parameter	Min	Max	Unit	Parameter	Min	Max	Unit
T	2.3	2.542	m	H_2	0	0	m
WB_1	5.665	6.185	m	WB_2	8.5	8.85	m
$*FC_{long,1}$	0.5	1.352	m	$FC_{long,2}$	0	0	m
$*FC_{wid,1}$	1.8	2.596	m	$FC_{wid,2}$	0	0	m
$*RC_{long,1}$	7	10.025	m	$*RC_{long,2}$	9	12.735	m
$*RC_{wid,1}$	1.8	2.3	m	$*RC_{wid,2}$	1.8	2.6	m
n_1	1	2		n_2	1	3	
d_1	1.34	1.36	m	d_2	1.34	1.6	m
$IE_{wid,1}$	2.3 (2.55)	2.6	m	$IE_{wid,2}$	2.3 (2.55)	2.6	m
H_1	7.8	8.025	m				

5 TESTING OF THE PRO-FORMA DESIGN

A test module was developed using Matlab to generate 10 000 car-carrier designs at random within the individual parameter constraints as described in Table 4-5. The 10 000 designs were then evaluated using the LSMM. The results are shown in Figure 5.1. A total of only 13 (0.13%) combinations were found not to comply with Level 1 low-speed standards. In each case, it was the TS performance that failed to meet the Level 1 requirement. The worst TS performance was 0.354 m, 18% above the Level 1 TS limit of 0.3 m. Further investigation revealed that each of the 13 non-complying combinations was assigned a relatively small IE_{wid} value by the random generator. In these unique cases, the IE_{wid} represented the widest point of the respective vehicle unit. Considering that the widest point is used as reference when determining TS, the small IE_{wid} values were suspected to be the cause the poor TS performance. It was found that by increasing the minimum IE_{wid} of both the first and second units to 2.55 m (from 2.3 m), level 1 standards were met for all 13 combinations. With these new constraints, a further 10 000 randomly generated combinations were assessed, of which all were found to meet Level 1 performance.

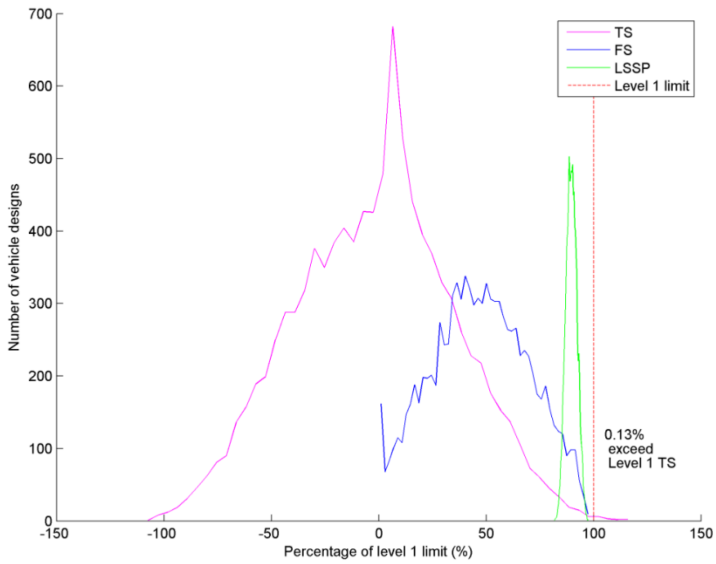

Figure 5.1 Performance of designs tested

The preliminary pro-forma is however limited in that the front and rear corner longitudinal positions and width were limited to that of a commercial car-carrier while in reality, the longitudinal position and width are related, that is if the width is decreased, the longitudinal position can be increased. Further work is currently being done to find the relationship between these parameters in order to offer the car-carrier designer even greater flexibility. Future work will also include testing vehicles featuring parameters at the limit of those proposed.

6 ESTIMATED FINANCIAL BENEFIT OF USING A PRO-FORMA DESIGN

Currently three commercial car-carrier manufacturers, Unipower (Natal), Lohr Transport Solutions ZA, and Rolfo South Africa, are pursuing PBS vehicle designs in South Africa and have developed eight PBS car-carrier designs or configurations. If each trailer design is assessed with three prime-movers during a year, this would require twenty-four assessments. If each assessment is roughly estimated to cost R60,000 in consulting fees, the PBS car-carrier assessments would cost the industry R1,440,000. If the Pro-forma design is estimated to cost R240,000 in consulting fees it is estimated that the pro-forma approach as compared to doing full assessments would save the South African car-carrier industry an estimated R1,200,000 in one year.

7 CONCLUSION

A preliminary pro-forma design was developed for a commercial car-carrier in terms of the low-speed Australian PBS. This was done by investigating parameter sensitivity, determining individual parameter limits and testing hypothetical designs within these limits. It was found that each of the 10 000 vehicle configurations generated within the constraints of the pro-forma design met the Level 1 requirements of the low-speed PBS. Future work will ensure compliance with the full set of twelve performance standards. It is estimated that the pro-forma approach as compared to doing full assessments would save the South African car-carrier industry an estimated R1,200,000 in one year.

8 ACKNOWLEDGEMENTS AND LIABILITY DECLARATION

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