THE PBS ASSESSMENT OF A SOUTH AFRICAN BI-ARTICULATED BUS

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Abstract

A vehicle safety analysis of a bi-articulated bus to be manufactured by MAN Bus and Coach S.A. (Pty) Ltd and operated by Buscor (Pty) Ltd was performed using the Australian performance based standards (PBS) framework. The vehicle analysed has a gross combination mass of 31 744 kg (loaded with 137 seated passengers and the driver weighing 68 kg each), an overall length of 26.940 m and four axles. The original vehicle did not meet the requirements to operate on PBS Level 1 roads with regard to the following performance measures: yaw damping coefficient, high-speed transient offtracking and tail swing. A modified vehicle was proposed in which the wheelbase of the second vehicle unit was increased from 4.45 m to 4.90 m and the wheelbase of the third vehicle unit increased from 4.75 m to 5.40 m. The modified vehicle meets all the requirements to operate on PBS Level 1 roads. A parametric study of the wheelbases of the second and third vehicle unit showed that both wheelbase increases were required for the vehicle to pass the PBS Level 1 safety requirements.

Keywords: Performance Based Standards, Bi-articulated Bus, Vehicle Simulation, Experimental Validation

1. Introduction

1.1 Background to Designing a Bi-articulated Bus in South Africa

An articulated bus (or bendy bus) has a kingpin which allows articulation for improved low-speed performance with respect to cutting of corners when turning. This allows for a longer bus capable of carrying more passengers compared with a conventional bus. The low-speed directional improvement of adding articulation must be balanced by considering the decreased yaw stability, and increased rearward amplification. Interest in articulated bus design has in part been sparked in South Africa through an initiative to introduce Performance Based Standards (PBS) for heavy vehicle design and operations (Nordengen *et al.*, 2008).

A bi-articulated bus (with two articulation joints) designed by MAN Bus and Coach S.A. (Pty) Ltd (MAN) and operated by Buscor (Pty) Ltd was proposed. The South African road authorities requested the vehicle design be assessed using the Australian PBS Level 1 safety requirements (NTC, 2008) as the vehicle does not conform to the current prescriptive dimensional requirements in South Africa. A prototype of the proposed design is shown in Figure 1.

Figure 1- Bi-articulated Bus Prototype Manufactured by MAN

1.2 Literature Review

Sleath *et al.* (2006) detailed a study in New Zealand which investigated the safety and productivity impact of increasing the allowable lengths of buses. In the context of this project, it was decided that "the generally accepted suite of performance based standards (PBS) levels was not required". Only the tail swing and low-speed offtracking performance measures were analysed.

A detailed dynamic analysis of a single articulated bus was conducted by Fancher *et al.* (1981). The under/oversteer gradient, ramp/step steer response time, yaw oscillation reduction factor after a pulse steer input, and rearward amplification during an accident-avoidance lane change were calculated. The study highlighted the poor yaw damping performance of articulated buses. The poor yaw damping performance is because articulated buses have the hitch point located behind the rear axle of the lead unit, in contrast with tractor semitrailer combinations which generally have the hitch point in front of the rear axle of the lead unit.

The docking bay requirements for a 25 m bi-articulated bus were investigated by Zhao *et al.* (2011). The study used the multibody dynamics software package ADAMS to build a model of the bi-articulated bus. The study concluded that the Chinese codes for designing bus terminals would require modification to accommodate the 25 m bi-articulated bus. The study did not include any measured dynamic performance such as yaw stability or rearward amplification or model the suspension.

Little research on bi-articulated bus safety exists and to the authors' knowledge no research on designing and analysing a bus using the PBS approach has been published.

1.3 Study Objectives

The objectives of this study were to:

- Complete a full PBS assessment of the bi-articulated bus (model HB3) designed by MAN using the Australian (NTC, 2008) PBS Level 1 safety requirements.
- Make necessary design changes to the bi-articulated bus to ensure the vehicle meets the Level 1 safety requirements.
- Conduct a parametric study on the influence of wheelbase on the vehicle performance as assessed using the PBS framework.

2. Methodology

2.1 Vehicle Description

The analysed vehicle had a gross combination mass of 31 744 kg (loaded with 137 seated passengers and the driver), an overall length of 26.940 m and four axles. In Australia, a Level 1 vehicle length is limited to 20 m (NTC, 2008). The permissible maximum length for an articulated vehicle in South Africa is 22 m. The South African Smart Truck Review Panel allow this length requirement to be waived on condition that the low speed directional performance measures are adhered to and route approval is obtained. The original prototype vehicle has wheelbases of 6.05 m, 4.45 m and 4.85 m. This vehicle is referred to as the "original vehicle". In order to improve the yaw stability and tail swing of the original vehicle the wheelbases of the second and third vehicle units were increased to 4.85 m and 5.40 m respectively. This vehicle is referred to as the "modified vehicle". The dimensions of the original and modified vehicles are shown in Figure 2.
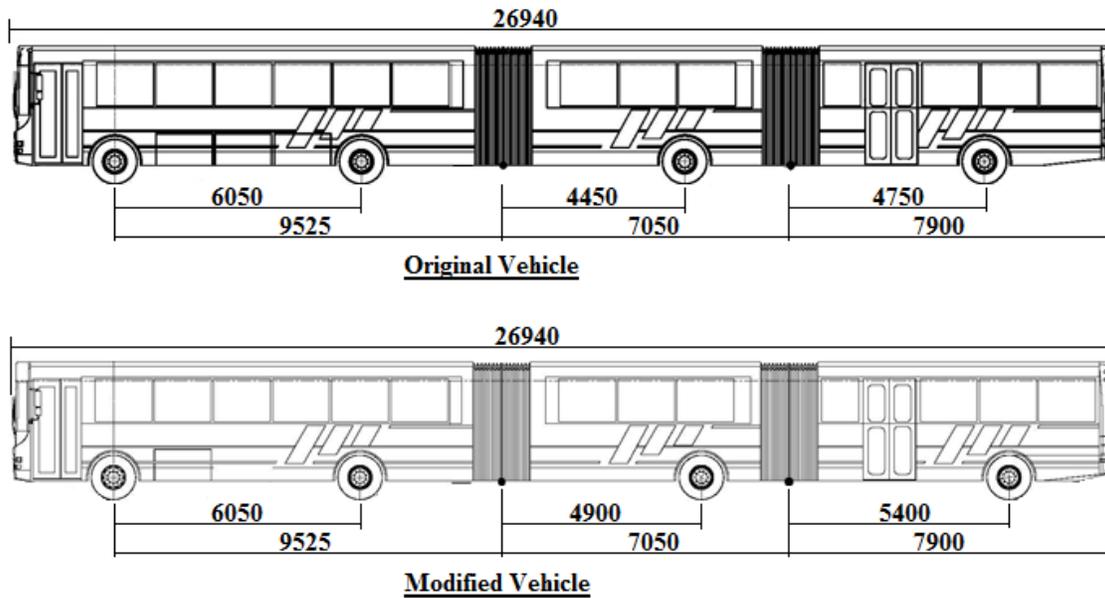
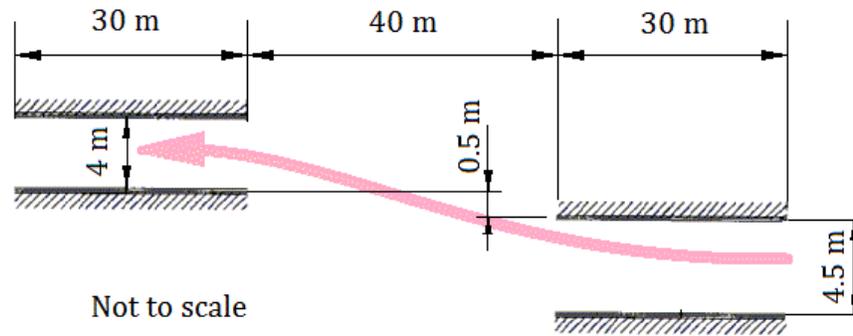**Figure 2 – Wheelbase Dimensions of the Original and Modified Vehicles**

2.2 PBS Safety Assessment Simulation Method

TruckSim 8.0 (a multi-body vehicle dynamics software package) was used to assess the PBS compliance of the bi-articulated bus. Eleven performance measures were considered necessary and sufficient for a safe vehicle in the context of the project: static rollover threshold, yaw damping coefficient, rearward amplification, high-speed transient offtracking, tracking ability on a straight path, tail swing, front swing, maximum of difference, difference of maxima and steer-tyre friction demand.

2.3 Field Testing to Validate the Simulation Model

Field testing was conducted at the Gerotek Test Facilities west of Pretoria. A VBOX 2SX SL3 was mounted on the third vehicle unit of the bi-articulated bus (the antenna was positioned 1 m from the back of the bus, on the centre line and on the roof) to measure: GPS position, longitudinal velocity, heading, yaw rate and roll angle. A single lane change manoeuvre was used for the testing as prescribed by MAN (See Figure 3). Because the bus is 2.438 m wide, a minimum and maximum lateral displacement of 2.938 m and 6.562 m was possible. The average tested lateral displacement was 5.8 m.

The manoeuvre was conducted at seven speeds: 40 km/h, 50 km/h, 60 km/h 70 km/h, 80 km/h, 85 km/h and 90 km/h. Three load cases were tested: empty with only 95 kg driver, partially loaded with a 95 kg driver and 21 seated 70 kg dummies at the rear of the bus and fully loaded with a 95 kg driver and 137 seated 70 kg dummies (See Figure 4).

Figure 3 – MAN Single Lane Change

Load case 1: empty

Load case 2: partially loaded

95 kg driver   70 kg dummy   Load case 3: fully loaded
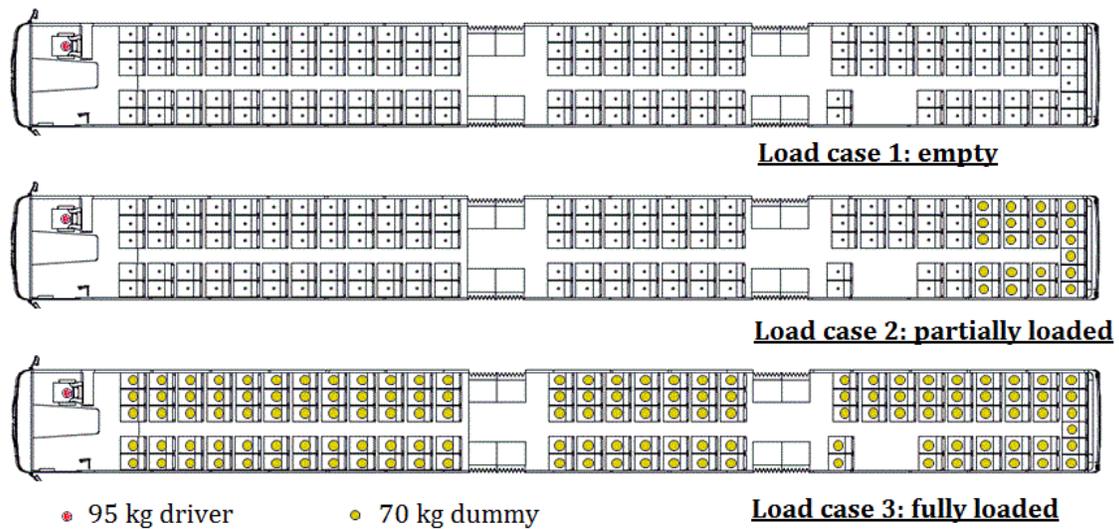
Figure 4 - Loading Cases Considered

2.4 Parametric Study of the Wheelbase on the Vehicle Performance

The performance of the vehicle was simulated with the wheelbase of the second vehicle unit equal to 4.45 m, 4.85 m, and 5.25 m, and the wheelbase of the third vehicle unit equal to 4.75 m, 5.40 m, and 6.05 m (See Table 1).

Table 1 - Wheelbases for Parametric Study

Vehicle Designation	Second Wheelbase [m]	Third Wheelbase [m]
Vehicle 1 or original vehicle	4.45	4.75
Vehicle 2	4.90	4.75
Vehicle 3	5.35	4.75
Vehicle 4	4.45	5.40
Vehicle 5 or modified vehicle	4.90	5.40

Vehicle 6	5.35	5.40
Vehicle 7	4.45	6.05
Vehicle 8	4.90	6.05
Vehicle 9	5.35	6.05

3. Results and Discussion

3.1 PBS Assessments of the Original and Modified Vehicle

The original vehicle passed eight of the performance standards but failed the yaw damping, high-speed transient offtracking (HSTO) and tail swing performance requirements. The yaw damping coefficient was calculated to be 0.09. This is a dangerously low value. The required minimum yaw damping coefficient as prescribed by the PBS framework is 0.15 for all levels. The HSTO of the vehicle was calculated to be 0.7 m and failed the Level 1 maximum allowed value of 0.6 m. The tail swing of the vehicle was calculated to be 0.42 m and failed the Level 1 maximum allowed value of 0.3 m.

In consultation with MAN, it was proposed to increase the wheelbases of the original vehicle as this would have a significant positive effect on all three failed performance measures. The modified vehicle passed all eleven required performance measures. A summary of the PBS assessment of the original and modified vehicle is shown in Table 2. The wheelbase modifications improved the yaw damping coefficient from 0.09 to 0.26, reduced the high speed transient offtracking from 0.7 m to 0.6 m, and reduced the tail swing from 0.42 m to 0.30 m. The rearward amplification also improved. These improvements were at the expense of low-speed swept path which was degraded. The modified vehicle low-speed swept path was still well within the Level 1 bounds.

**Table 2 - Summary of PBS Assessment: Original and Modified Vehicle**

Standard	units	Original Vehicle		Modified Vehicle		Level 1 Limit	Level 2 Limit	Level 3 Limit	Level 4 Limit
		Result	Level	Result	Level				
Static Rollover Threshold	g	0.45	All	0.45	All	≥0.4	≥0.4	≥0.4	≥0.4
Yaw Damping Coefficient	-	0.09	None	0.26	All	≥0.15	≥0.15	≥0.15	≥0.15
Rearward Amplification†	-	2.26	All	1.88	All	$\leq2.574^1$ $\leq2.591^2$	≤2.574 ≤2.591	≤2.574 ≤2.591	≤2.574 ≤2.591
High-speed Transient Offtracking	m	0.7	L2	0.6	All	≤0.6	≤0.8	≤1.0	≤1.2
Tracking Ability on a Straight Path	m	2.7	All	2.7	All	≤2.9	≤3.0	≤3.1	≤3.3
Low-speed Swept Path	m	6.2	All	6.6	All	≤7.4	≤8.7	≤10.6	≤13.7
Tail Swing	m	0.42	L4	0.30	All	≤0.3	≤0.35	≤0.35	≤0.5
Frontal Swing	m	1.4	All	1.4	All	≤1.5	≤1.5	≤1.5	≤1.5
Maximum of Difference	m	0.01	All	0.01	All	≤0.4	≤0.4	≤0.4	≤0.4
Difference of Maxima	m	0.01	All	0.01	All	≤0.2	≤0.2	≤0.2	≤0.2
Steer-Tyre Friction Demand	-	25%	All	25%	All	$\leq80\%$	$\leq80\%$	$\leq80\%$	$\leq80\%$

†RA limits are calculated 5.7SRT$_{rrcu}$ for all levels ^{1} = 2.574 for the original vehicle ^{2} = 2.591 for the modified vehicle

3.2 Experimental Testing and Validation of the Model

A comparison between the measured trajectory of the 3rd vehicle unit (measure point 1 m forward from the back of the bus) and the same simulated point is shown in Figure 5. The low-speed results conducted at 40 km/h are shown in red and the high speed results conducted at 85 km/h are shown in blue. The experimental results are shown as points and the simulated results are shown as lines. The experimental results for the empty bus are shown as squares and the experimental results for the fully loaded bus as triangles. The simulated results for the empty bus are shown as dashed lines and the simulated results for the fully loaded bus as solid lines. The solid black lines indicate the cones or marked lines through which the drive was required to drive.

At low speeds (40 km/h) there is excellent agreement between the experimental and simulated results. There is only a slight discrepancy in the measured trajectory at the entry to the manoeuvre of the fully loaded bus. At high speeds (85 km/h) the agreement between experimental and simulated results is good. The physical bus driver attempted to swing out first before manoeuvring the vehicle through the lane change. Because the driver model did not capture this behaviour, it is unrealistic to expect the results to match exactly. The excessive overshoot and unstable vehicle behaviour at high speed (85 km/h) is importantly captured by the simulation.
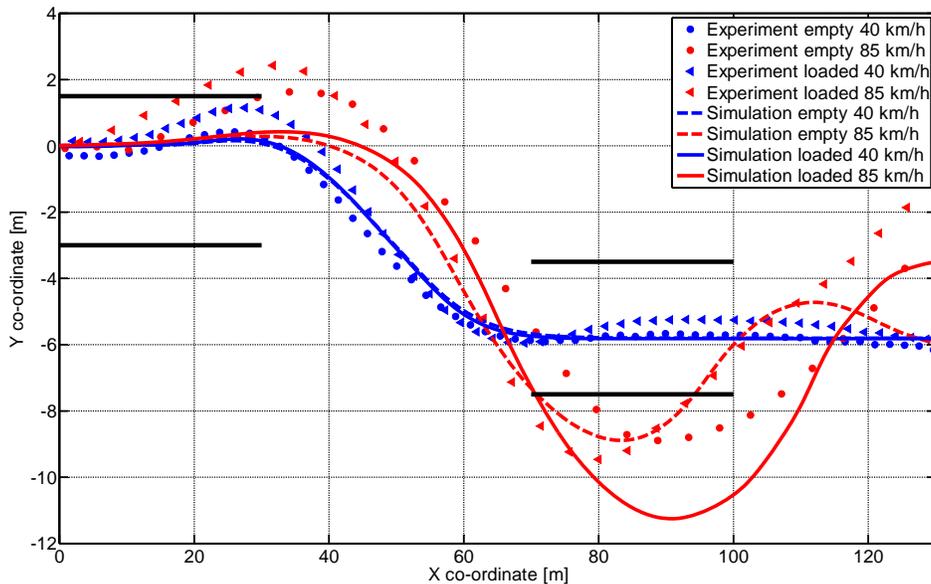

Figure 5 – 3rd Vehicle Unit Trajectory: Agreement between Experiment and Simulation

The maximum measured roll of the 3rd vehicle unit is compared to the simulated results in Figure 6. The experimental results are shown as circular points and the simulated as lines. The empty, partially loaded and fully loaded bus results are represented by blue, mauve and red respectively.

There is good agreement in the results and the simulation is able to capture the characteristic behaviour of the real bus. For the empty bus, the maximum roll increased linearly with the vehicle speed for the range of speeds investigated. For the partially loaded bus, the maximum

roll was slightly greater than the empty bus given the same speed. For the fully loaded bus the maximum roll was increased further but the behaviour became non-linear. The fully loaded bus at high speeds experienced excessive maximum roll during the single lane change.
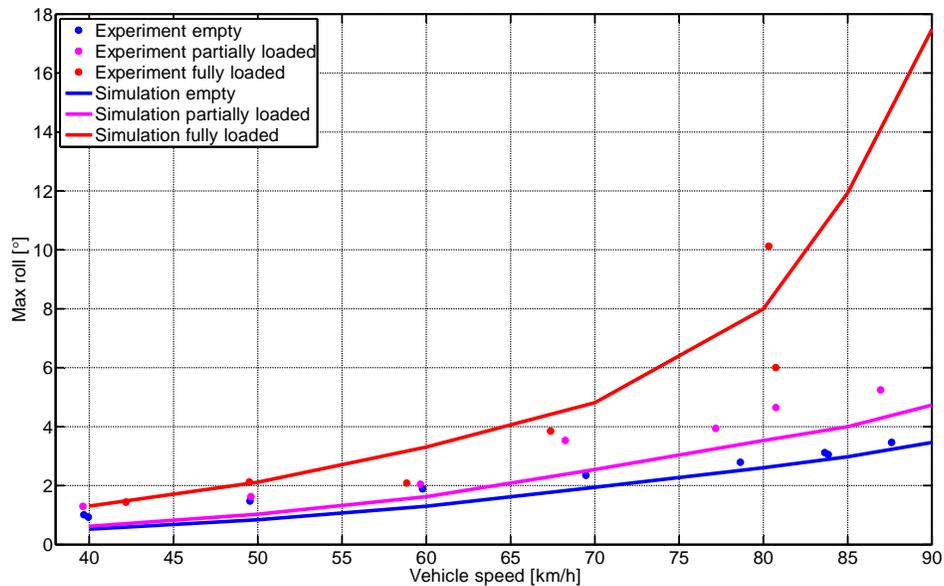

Figure 6 – 3rd Vehicle Unit Roll: Agreement between Experiment and Simulation

### 3.3 Parametric Study on the Influence of Wheelbase on Bi-articulated Bus Safety

The preceding results highlighted that the original vehicle did not pass Level 1 requirements for the following measures: yaw damping coefficient, high-speed transient offtracking and tail swing. The parametric study focuses on these performance measures as well as the low speed swept path as this performance measure was slightly degraded.

The yaw damping parametric study (See Figure 7) shows that increasing the wheelbase of the second vehicle unit from 4.45 m to 4.90 m increases the damping of the vehicle combination from 0.096 to 0.188 (above the minimum requirement of 0.15). Increasing the wheelbase of only the third vehicle unit from 4.75 m to 5.40 m only increases the damping of the vehicle combination from 0.096 to 0.104. Making both the above changes (i.e. comparing the original vehicle with the modified vehicle) increases the yaw damping from 0.096 to 0.269, which is an effective modification.

The high-speed transient offtracking (HSTO) study (See Figure 8) shows that increasing the wheelbase of the second vehicle unit from 4.45 m to 4.90 m decreases the HSTO of the vehicle combination from 0.668 m to 0.562 m (below the maximum limit of 0.6 m). Increasing the wheelbase of only the third vehicle unit from 4.75 m to 5.40 m increases the HSTO of the vehicle combination from 0.668 m to 0.702 m. Increasing the wheelbase of only the third vehicle unit is detrimental to the HSTO performance of the vehicle. Making both the above changes (i.e. comparing the original vehicle with the modified vehicle) decreases the HSTO from 0.668 m to 0.563 m, which is an effective modification.
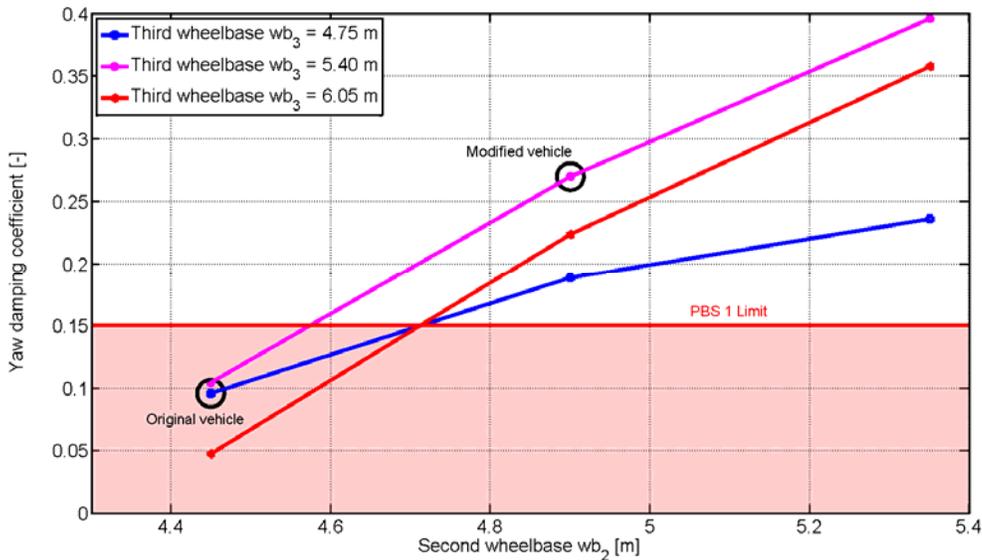
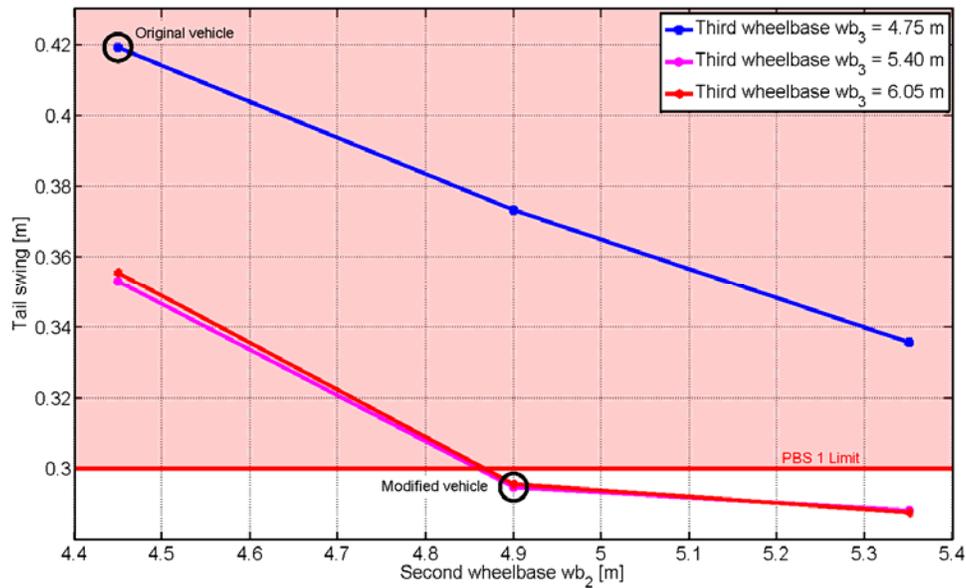**Figure 7 – Yaw Damping Parametric Study**
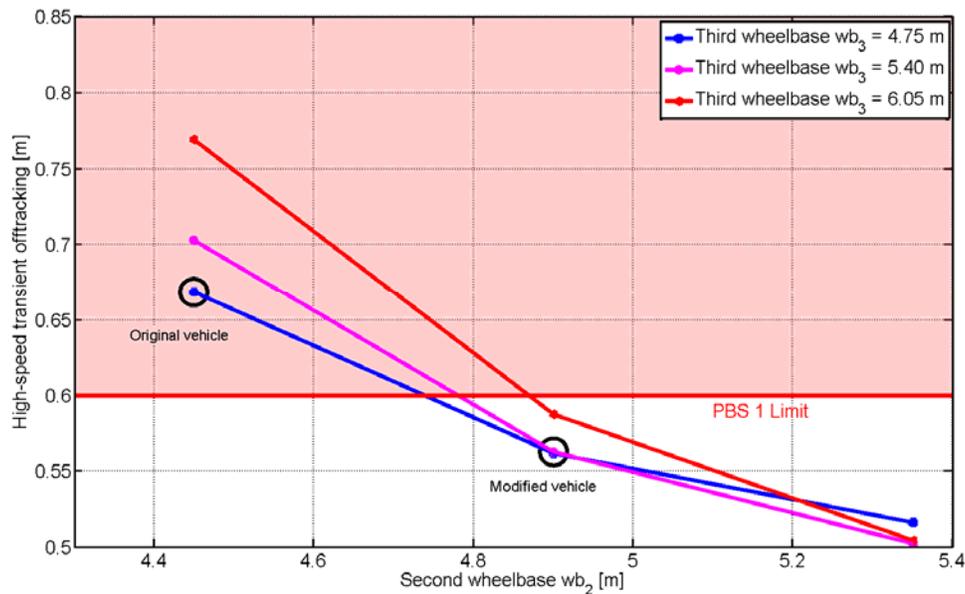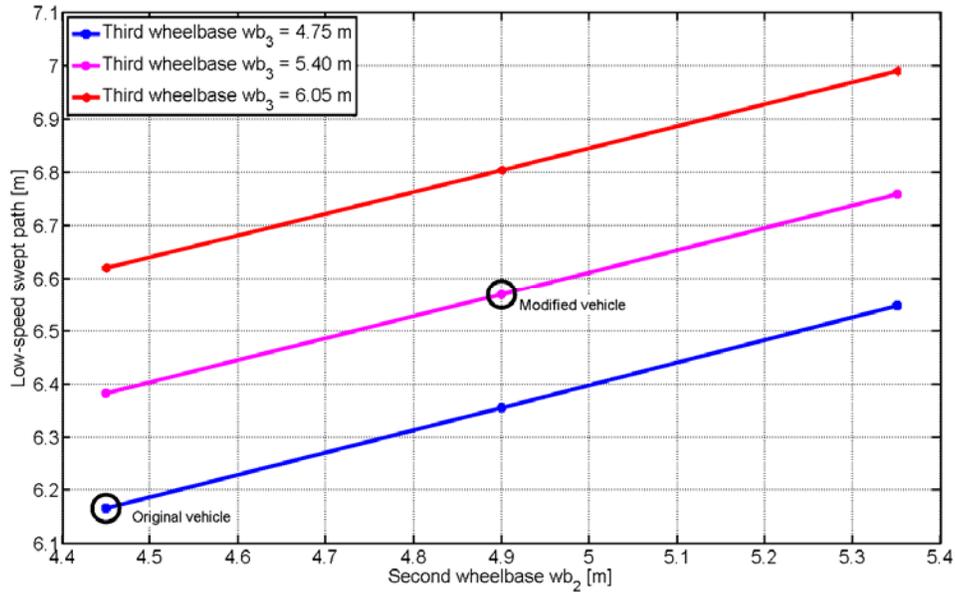

Figure 8 – HSTO Parametric Study

The tail swing study (See Figure 9) shows that increasing the wheelbase of the second vehicle unit from 4.45 m to 4.90 m decreases the tail swing of the vehicle combination from 0.419 m to 0.373 m. Increasing the wheelbase of only the third vehicle unit from 4.75 m to 5.40 m decreases the tail swing of the vehicle combination from 0.419 m to 0.352 m. Making both the above changes (i.e. comparing the original vehicle with the modified vehicle) decreases

the tail swing from 0.419 m to 0.295 m (below the required limit of 0.3 m), which is an effective modification.

The low-speed swept path (LSSP) parametric study results are shown in Figure 10. The LSSP increases as the wheelbase of either the second or third vehicle unit is increased. The graphs are equidistant, parallel, straight lines illustrating that the LSSP increases linearly with respect to both the second and third unit wheelbase length. Increasing the wheelbase of the second vehicle unit from 4.45 m to 4.90 m and increasing the wheelbase of only the third vehicle unit from 4.75 m to 5.40 m (i.e. comparing the original vehicle with the modified vehicle) increases the LSSP of the vehicle from 6.17 m 6.56 m. The performance measure has been degraded slightly but is still well below the required Level 1 PBS limit of 7.4 m.

Figure 9 – Tail Swing Parametric Study

Figure 10 – Low-speed Swept Path Parametric Study

4. Conclusions

- A bi-articulated bus designed by MAN Bus and Coach S.A. was assessed using the Australian NTC PBS Level 1 safety requirements. The original vehicle failed the yaw damping, high-speed transient offtracking and tail swing performance requirements.
- It was proposed to increase the wheelbases of the original vehicle. The modified vehicle was calculated to have an improved yaw damping coefficient of 0.26, high-speed transient offtracking of 0.6 m and tail swing of 0.30 m. The modified vehicle passed all eleven required performance measures.
- The simulation model used to conduct the PBS assessment was validated using field test data of a single lane change. The experimental and simulated results show good agreement.
- A parametric study of the wheelbases of the second and third vehicle unit showed that both wheelbase increases were required for the vehicle to pass the PBS Level 1 safety requirements.
- This study is a significant and a valuable research contribution because:
  - very little or no research on the dynamic performance of bi-articulated buses has been published
  - very little or no research on assessing the safety of buses using the PBS framework has been published
  - this study will further the PBS initiative in South Africa to improve heavy vehicle safety and productivity.

5. Acknowledgements

6. References

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