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Pavement wear analysis of three-axle buses with various axle and tyre configurations

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Summary

Advantia was engaged to determine the marginal pavement wear effects of increasing the maximum axle loads on three-axle buses. To perform this assessment, Advantia compared the pavement wear effects of various loading scenarios and axle/tyre configurations.

The assessment focused on determining the effects of four parameters on pavement wear:

- Gross Vehicle Mass (GVM)
- the mass split between the steer axle and the tandem group
- the mass split between the two axles within the tandem group
- tag/pusher axle tyre width.

In addition, Advantia compared the pavement wear effect of three-axle buses against currently operating two-axle bus configurations.

Advantia determined that three-axle buses produced lower pavement wear per tonne GVM than two-axle buses. Furthermore, increasing the allowable GVM of a three-axle bus up to 22 tonnes (with a floating tonne and tandem group mass splits between 70:30 and 60:40) would not cause more pavement wear than currently-operating two-axle buses.

If instead mass split requirements were removed and the mass split limits were taken from the Heavy Vehicle (Mass, Dimension and Loading) National Regulation definition of a load sharing axle group the most uneven potential mass splits would be 73:27 and 33:67. It would therefore be possible to increase the pavement wear costs above that of currently operating two-axle buses.

However, for the case of a 22-tonne GVM bus (6.5-tonne steer axle and 15.5-tonne tandem axle) the pavement wear per tonne GVM would still be below that of currently operating two-axle buses.

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1. Introduction

It has been determined through previous research that due to a disconnect between the regulations governing bus occupancy limits and those setting axle load limits, current occupancy limits may cause three-axle buses to exceed the axle load limits. This is attributed to the increasing average mass of the Australian population.

Alongside this, additional safety technology being installed in buses has led to an increase in the average tare weight of the vehicles, which then reduces the occupancy limits of the vehicles.

To allow increased occupancy, the allowable axle loads of the vehicles must be increased. However, this will lead to an increased rate of pavement wear and associated costs.

To determine the costs attributable to increasing the axle load limits, Advantia was engaged to perform pavement wear cost calculations for three-axle buses under various loading scenarios and tyre/axle configurations.

In doing so, Advantia determined the effects of changing:

- Gross Vehicle Mass (GVM)
- the mass split between the steer axle and the tandem group
- the mass split between the two axles within the tandem group
- tag/pusher axle tyre width.

Ultimately this will allow decision-makers to understand the repercussions of increasing three-axle bus axle load limits with respect to marginal pavement wear costs.

2. Technical background

The amount of pavement wear induced by a vehicle is a function of the load carried by each tyre and the distribution of tyres throughout the vehicle (i.e. whether there are single or dual tyres on an axle and whether an axle is single or part of a group). Load is transmitted to the deep structural layers of the pavement, which lose strength over time as vehicles repeatedly pass over them.

If everything else remains the same, increased axle loads will result in increased pavement wear, but the choice of tyres can have a significant impact. Tyres with a larger footprint area (i.e. wide-base tyres) put less force on the pavement per unit area and are proven to induce less wear on pavements as a result. It is possible for a vehicle to have higher axle loads without increased pavement wear if it incorporates wide-base tyres or a larger number of axles.

The amount of wear that develops in a pavement due to the passing of a heavy vehicle can be estimated using the Standard Axle Repetition (SAR) approach. The SAR approach considers that one unit of pavement wear is the amount of wear caused by one pass of a standard axle, being a single axle with dual tyres that is laden to 80 kN (8.16 tonnes). According to Austroads (2011) the amount of wear caused by one pass of a vehicle with various axle group types laden to various axle group loads is equal to the wear caused by an equivalent number of passes of a standard axle (i.e. standard axle repetitions, or SAR) using the formula:

$$\mathrm{SAR} = \sum_{i=1}^{m} (\mathrm{L}_i / SL_i)^n$$

where:

L_i = load carried by axle group i in tonnes

SL_i = standard load for axle group i in tonnes (see Table 1) – if the axle group happens to be at this load it produces one unit of pavement wear

n = pavement wear exponent, which may vary from 4 to 12 depending on the pavement distress type (typically 4 for overall wear of unbound granular pavements by rutting, for which the calculation is termed ‘Equivalent Standard Axles’ or ESA)

m = number of axle groups on the vehicle.

Table 1 Standard load by axle group type

Axle group type	Tyre width ‘W’ (mm)	Standard load (tonnes)
Single axle with single tyres	W < 375 375 ≤ W < 450	5.40 5.92
Single axle with dual tyres	W < 375	8.16

Austroads (2011) recommended treating a six-tyre tandem group as the summation of a single axle with dual tyres and a single axle with single tyres.

To determine the cost of the pavement wear, a pavement wear cost factor of 15 c/ESA-km travelled was used. This is applicable where the specific routes and road types the buses are operating on are not known. Fifteen cents is considered to be conservative, but not unreasonable in the context of the routes that buses may be expected to operate on.

To calculate the pavement wear cost from 100 km of travel, one must multiply the vehicle's total ESA by 100, to determine the ESA-km, and then multiply this by the 15 c/ESA-km value to determine the cost per 100 km of travel.

For example:

If a fully-laden vehicle has a total of 3 ESA, then over one hundred kilometres of fully laden travel it would be responsible for 300 ESA-km of pavement wear. To then determine the cost per 100 km of travel, 300 ESA-km is multiplied by 15 c/ESA-km. This would give a cost of $45 per 100 km of fully laden travel.

The marginal cost of a mass increase can be determined by subtracting the results of two calculations (before and after).

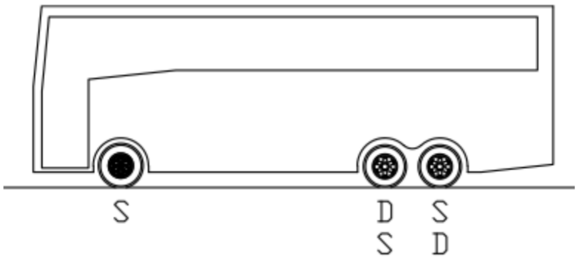
3. Subject vehicles

This assessment primarily considered the ESA performance of a three-axle bus, however, a two-axle bus has also been included for comparison. The three-axle bus has a single steer axle, and a six-tyred tandem group comprising a driven axle and a 'lazy' tag or pusher axle with single tyres. The two-axle bus has a single steer axle and a single drive axle with dual tyres. In all cases the steer and drive tyres were fitted with either 275 mm or 295 mm section width tyres, while the tyre width on the tag/pusher axle was varied between 275/295 mm and 375+ mm.

This assessment is considered applicable to both single-deck and double-deck buses as pavement wear is only affected by the load being transmitted through the tyres to the road.

Figure 1 shows the three-axle bus included in this assessment. 'S' and 'D' represent single and dual tyres respectively.

Figure 1 Three-axle bus tyre configurations



4. Pavement wear calculations

Pavement wear calculations for buses in various loading and axle/tyre configurations are shown in Table 2 to Table 8. The mass split between the drive and tag axle is shown in brackets next to the axle loads where applicable.

The loading scenarios are described below:

- 20-tonne GVM (current practise)
- 21-tonne GVM
- 22-tonne GVM
- 22-tonne GVM (floating tonne)
- 23-tonne GVM
- 23-tonne GVM (floating tonne)
- 18-tonne GVM (2-axle bus included for comparison)
- 22-tonne GVM (HVNL MDL[1] regulation for load sharing)

While it is expected that most axles would load-share so that the load is equally split across each of the tyres in the tandem axle group (a 67:33 mass split), a mass split of 70:30 and 60:40 has also been included to account for expected variations in the load sharing. Additional analysis of mass splits possible under the HVNL MDL regulation has also been included in Table 9. This is described in further detail in later sections of the report.

[1] Heavy Vehicle National Law (Mass, Dimension and Loading) National Regulation

Table 2 20-tonne GVM loading scenarios (current practise)

Axle loads (t)	Tag/pusher axle tyre width (mm)	Total ESA	ESA per tonne GVM	$/100 km of travel
6.0 + 14.0 (70:30)	275 or 295	3.97	0.20	59.56
6.0 + 14.0 (67:33)	275 or 295	3.79	0.19	56.90
6.0 + 14.0 (60:40)	275 or 295	3.80	0.19	57.06

It can be seen from Table 2 that a 67:33 split produces the least amount of pavement wear when using 275 or 295 mm width tag/pusher tyres. This is because it represents an even split of mass across each of the tyres in the tandem group.

Table 3 21-tonne GVM loading scenarios

Axle loads (t)	Tag/pusher axle tyre width (mm)	Total ESA	ESA per tonne GVM	$/100 km of travel
6.5 + 14.5 (70:30)	275 or 295	4.91	0.23	73.71
6.5 + 14.5 (67:33)	275 or 295	4.71	0.22	70.66
6.5 + 14.5 (60:40)	275 or 295	4.72	0.22	70.84
7.0 + 14.0 (70:30)	275 or 295	5.27	0.25	79.05
7.0 + 14.0 (67:33)	275 or 295	5.09	0.24	76.39
7.0 + 14.0 (60:40)	275 or 295	5.10	0.24	76.55

It can be seen from Table 3 that increasing the mass on the steer axle results in more pavement wear than a corresponding increase on the tandem axle group. This is because when you add mass to the steer axle it is spread over two tyres, while in the case of the tandem group, the mass is spread over six tyres, leading to a smaller increase per tyre.

Table 4 22-tonne GVM loading scenarios

Axle loads (t)	Tag/pusher axle tyre width (mm)	Total ESA	ESA per tonne GVM	$/100 km of travel
6.5 + 15.5 (70:30)	275 or 295	5.77	0.26	86.62
6.5 + 15.5 (67:33)	275 or 295	5.51	0.25	82.63
6.5 + 15.5 (60:40)	275 or 295	5.52	0.25	82.86
7.0 + 15.0 (70:30)	275 or 295	6.05	0.27	90.71
7.0 + 15.0 (67:33)	275 or 295	5.81	0.26	87.21
7.0 + 15.0 (60:40)	275 or 295	5.83	0.26	87.42
6.5 + 15.5 (70:30)	375+	5.61	0.25	84.09
6.5 + 15.5 (67:33)	375+	5.25	0.24	78.77
6.5 + 15.5 (60:40)	375+	4.99	0.23	74.84
7.0 + 15.0 (70:30)	375+	5.90	0.27	88.49
7.0 + 15.0 (67:33)	375+	5.59	0.25	83.82
7.0 + 15.0 (60:40)	375+	5.36	0.24	80.38

It can be seen from Table 4 that the wide-base tyre on the tag/pusher axle reduces pavement wear and also skews the preferred mass split across the tandem axle group to 60:40.

Table 5 22-tonne GVM (floating tonne) loading scenarios

Axle loads (t)	Tag/pusher axle tyre width (mm)	Total ESA	ESA per tonne GVM	$/100 km of travel
6.0 + 16.0 (70:30)	275 or 295	5.70	0.26	85.46
6.0 + 16.0 (67:33)	275 or 295	5.40	0.25	80.93
6.0 + 16.0 (60:40)	275 or 295	5.41	0.25	81.19
6.5 + 15.5 (70:30)	275 or 295	5.77	0.26	86.62
6.5 + 15.5 (67:33)	275 or 295	5.51	0.25	82.63
6.5 + 15.5 (60:40)	275 or 295	5.52	0.25	82.86
7.0 + 15.0 (70:30)	275 or 295	6.05	0.27	90.71
7.0 + 15.0 (67:33)	275 or 295	5.81	0.26	87.21
7.0 + 15.0 (60:40)	275 or 295	5.83	0.26	87.42
6.0 + 16.0 (70:30)	375+	5.51	0.25	82.58
6.0 + 16.0 (67:33)	375+	5.10	0.23	76.54
6.0 + 16.0 (60:40)	375+	4.81	0.22	72.09
6.5 + 15.5 (70:30)	375+	5.61	0.25	84.09
6.5 + 15.5 (67:33)	375+	5.25	0.24	78.77
6.5 + 15.5 (60:40)	375+	4.99	0.23	74.84
7.0 + 15.0 (70:30)	375+	5.90	0.27	88.49
7.0 + 15.0 (67:33)	375+	5.59	0.25	83.82
7.0 + 15.0 (60:40)	375+	5.36	0.24	80.38

It can be seen in Table 5 that the benefits of wide single tyres and lower mass on the steer axle overlap. The 22-tonne GVM combination with the lowest pavement wear costs has 6 tonnes on the steer axle and wide single tyres on the tag/pusher axle.

Table 6 23-tonne GVM loading scenarios

Axle loads (t)	Tag/pusher axle tyre width (mm)	Total ESA	ESA per tonne GVM	$/100 km of travel
6.5 + 16.5 (70:30)	275 or 295	6.82	0.30	102.29
6.5 + 16.5 (67:33)	275 or 295	6.48	0.28	97.17
6.5 + 16.5 (60:40)	275 or 295	6.50	0.28	97.46
7.0 + 16.0 (70:30)	275 or 295	7.00	0.30	104.96
7.0 + 16.0 (67:33)	275 or 295	6.70	0.29	100.43
7.0 + 16.0 (60:40)	275 or 295	6.71	0.29	100.69
6.5 + 16.5 (70:30)	375+	6.60	0.29	99.03
6.5 + 16.5 (67:33)	375+	6.15	0.27	92.20
6.5 + 16.5 (60:40)	375+	5.81	0.25	87.16
7.0 + 16.0 (70:30)	375+	6.80	0.30	102.07
7.0 + 16.0 (67:33)	375+	6.40	0.28	96.03
7.0 + 16.0 (60:40)	375+	6.11	0.27	91.58

Table 7 23-tonne GVM (floating tonne) loading scenarios

Axle loads (t)	Tag/pusher axle tyre width (mm)	Total ESA	ESA per tonne GVM	$/100 km of travel
6.0 + 17.0 (70:30)	275 or 295	6.84	0.30	102.64
6.0 + 17.0 (67:33)	275 or 295	6.46	0.28	96.87
6.0 + 17.0 (60:40)	275 or 295	6.48	0.28	97.20
6.5 + 16.5 (70:30)	275 or 295	6.82	0.30	102.29
6.5 + 16.5 (67:33)	275 or 295	6.48	0.28	97.17
6.5 + 16.5 (60:40)	275 or 295	6.50	0.28	97.46
7.0 + 16.0 (70:30)	275 or 295	7.00	0.30	104.96
7.0 + 16.0 (67:33)	275 or 295	6.70	0.29	100.43
7.0 + 16.0 (60:40)	275 or 295	6.71	0.29	100.69
6.0 + 17.0 (70:30)	375+	6.60	0.29	98.97
6.0 + 17.0 (67:33)	375+	6.08	0.26	91.27
6.0 + 17.0 (60:40)	375+	5.71	0.25	85.60
6.5 + 16.5 (70:30)	375+	6.60	0.29	99.03
6.5 + 16.5 (67:33)	375+	6.15	0.27	92.20
6.5 + 16.5 (60:40)	375+	5.81	0.25	87.16
7.0 + 16.0 (70:30)	375+	6.80	0.30	102.07
7.0 + 16.0 (67:33)	375+	6.40	0.28	96.03
7.0 + 16.0 (60:40)	375+	6.11	0.27	91.58

Much like the 22-tonne scenarios, Table 6 and Table 7 show the same trends for 23-tonne GVM scenarios; pavement wear is reduced most with wide single tyres and a

6-tonne steer axle. However, as the overall mass is greater, the pavement wear costs are higher, as expected.

Table 8 18-tonne GVM (2-axle bus included for comparison)

Axle loads (t)	Total ESA	ESA per tonne GVM	$/100 km of travel
7.0 + 11.0	6.13	0.34	91.89
6.0 + 12.0	6.20	0.34	93.02

For comparison, a two-axle bus was also included in the pavement wear cost analysis. Table 8 shows that because a two-axle bus splits mass over only six tyres, compared to eight tyres on the three-axle buses, the ESA per tonne GVM is higher than that of all three-axle buses included in this assessment.

Interestingly, in the case of the two-axle bus with an 18-tonne GVM, having a 7-tonne load on the steer axle creates slightly less pavement wear than a 6-tonne load on the steer axle. While in the case of three-axle buses, the opposite was observed.

Comparing Table 8 and Table 5, it can be seen that for all 22-tonne GVM (floating tonne) three-axle bus scenarios, the pavement wear cost was lower than both two-axle bus scenarios included in this assessment.

It should be noted however that this assessment only considered buses operating at their axle load limits. If two-axle buses are routinely underloaded but three-axle buses are routinely at full load, then this straight comparison may not be applicable.

It was also requested that an investigation be undertaken to determine the effects of removing specific requirements around the mass split ratio in the tandem group. Instead, the definition of load-sharing suspension from the HVNL MDL Regulation which defines a load-sharing suspension system of an axle group to mean:

- *Built to divide the load between the tyres on the group so no tyre carries a mass more than 10% above the mass it would carry if the load were divided equally; and*
- *With effective damping characteristics on all axles of the group.*

Under the HVNL MDL regulation definition, additional loading scenarios are possible, shown in Table 9. Note that only scenarios based on a 22-tonne GVM (6.5 + 15.5) with 295 mm width tyres, and a nominal 67:33 mass split were requested for inclusion.

Table 9 22-tonne GVM loading scenarios (HVNL MDL regulation)

Axle loads (t)	Tag/pusher axle tyre width (mm)	Total ESA	ESA per tonne GVM	$/100 km of travel
6.5 + 15.5 (73:26)	275 or 295	6.21	0.28	93.11
6.5 + 15.5 (67:33)	275 or 295	5.51	0.25	82.63
6.5 + 15.5 (63:37)	275 or 295	5.42	0.25	81.31

Compared with the other loading scenarios shown in Table 2 to Table 7, using the HVNL MDL regulation definition of mass splits allows for a more uneven mass split between the dual tyred axle and the single tyred axle. This is because increasing the mass on the dual tyred axle by 10 per cent decreases the mass on the single tyred axle by over 20 per cent; the HVNL MDL regulation only places a maximum load limit of +10 per cent on individual tyres and not a minimum load limit.

As such, the loading case with a 73:26 mass split on the tandem group caused an increase in the ESA pavement wear when compared to other 22-tonne GVM loading scenarios. Note that the ESA per tonne GVM was still below that of 18-tonne GVM two axle buses.

Conversely, if additional load is instead placed on the single tyred axle (i.e. the 63:37 split), it will actually result in a marginal improvement in pavement wear compared to equal loading. The increased load on the single tyred axle will increase the ESA of the individual axle, but by decreasing the dual tyred axle load there is a net positive overall effect.

It is expected that this marginal improvement is due to the empirical source for the reference loads used in the ESA calculation, which favour slightly more load on the single tyred axles. However as shown in Table 2 to Table 7, increasing the load on the single tyred axle too much (i.e. to a 60:40 split) will then worsen the pavement wear compared to the equal case.

Conclusions and recommendations

The assessment determined that the existing practise of operating a bus at 6 tonnes on the steer axle and 14 tonnes split across the drive and tag/pusher axles resulted in the lowest ESA values out of all the scenarios tested.

When comparing two similar loading scenarios, using wide single tyres on the tag/pusher axle reduced the pavement wear costs due to spreading the mass over a larger pavement/tyre contact area.

In addition, the assessment determined that when using 275 or 295 mm width tyres on the tag/pusher axle, having a 67:33 split (drive and tag/pusher respectively) on the tandem group was generally optimal. However, if using a 375+ mm width tyre on the tag/pusher axle, a 60:40 split was optimal as the mass was more evenly spread on the tandem group relative to the contact area of the tyres.

When comparing three-axle bus pavement wear costs (with mass splits varying from 70:30 to 60:40) against those of two-axle buses, it was found that a 22-tonne GVM (floating tonne) three-axle bus will have a lower pavement wear cost than an 18-tonne GVM two-axle bus. Furthermore, when considering ESA per tonne GVM, the three-axle buses assessed (including 23-tonne GVM) had lower pavement wear than the two-axle buses included in this assessment.

If mass split requirements were removed and only the HVNL MDL regulation definition of a load sharing axle group was used, it would be possible to increase the pavement wear costs further. However, the ESA per tonne GVM of the assessed 22-tonne GVM bus would still be below that of 18-tonne GVM two-axle buses.

Based on the results of this assessment, Advantia recommends that wide single tyres (>375 mm) be fitted on the tag/pusher axles of three-axle buses operating at increased mass limits)

In addition, Advantia recommends increasing the axle loads of three-axle buses to 22-tonne GVM (with a floating tonne), as it would be comparable (in terms of pavement wear) with two-axle buses being operated currently.

However, further research may be required to determine what proportion of travel each bus configuration would be operating at the stated axle load limits.

5. References

Austroads 2011, *Pavement Wear Assessment Method for PBS Vehicles*, AP-R372/11, Austroads, Sydney