PERFORMANCE-BASED STANDARDS: CHALLENGES IN DEVELOPING INFRASTRUCTURE PROTECTION STANDARDS

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ABSTRACT

A set of performance standards covering vehicle mass and dimensions are being developed in Australia in a major project under the control of the National Transport Commission and Austroads, which is known as the Performance-Based Standards (PBS) project. The standards, when finally approved, will be an alternative (optional) method of controlling vehicle size and weight. The proposed standards deal both with vehicle safety standards and infrastructure protection standards. It is the latter standards that are the subject of this paper.

There are four proposed standards for infrastructure protection which are:

- pavement vertical loading;
- pavement horizontal loading;
- tyre contact pressure distribution; and
- bridge loading.

The paper describes the various initial standards and the processes and alternatives considered prior to the selection of the final set of standards. Difficulties with some promising prospective standards are described along with the reasons that led to them being discarded.

BACKGROUND

Introduction

A major project under the control of the National Transport Commission and Austroads is developing a regime of Performance-Based Standards (PBS) as an alternative (optional) method of controlling heavy vehicle mass and dimensions. In a major part of that project, termed A3/A4, the central theme of the proposed performance standards was developed. The resulting performance standards cover both safety (16 standards) and infrastructure protection (4 standards).

In the initial stages of the project a range of potential infrastructure standards were identified. These potential standards were narrowed down to four potential standards:

- pavement vertical loading;
- pavement horizontal loading;
- tyre contact pressure distribution; and
- bridge loading.

The challenge in developing performance standards to cover these four infrastructure protection measures has shown that many problems and pitfalls can be encountered. Not unexpectedly, the vehicle safety standards, taken alone, do not necessarily identify configurations that are undesirable from an infrastructure viewpoint. The four infrastructure protection standards are required to perform this task and to provide sufficient levels of protection to the road and bridge infrastructure in all elements of the interaction of this

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infrastructure with heavy vehicles to satisfy all Australian state road authorities. As an additional constraint, various aspects of the regulation of PBS make it essential that complicated standards are avoided.

Infrastructure protection standards are also central to any productivity gains from PBS and therefore the attractiveness and economic viability of this alternative regulatory regime for the economy and the transport industry. This paper deals with the difficulties encountered in the development of these infrastructure protection standards.

Context

Australia has a wide variety of pavement types throughout the country, ranging from granular pavements with thin chip seals to rigid concrete pavements. Pavements on most intercity routes are granular although a significant proportion of the intercity routes in New South Wales (a major State) are rigid concrete pavements.

Bridges built more than 50 years ago comprise nearly 50 percent of the bridge stock and many of these bridges were built to a 13-tonne design vehicle. More recent bridges, those built up until 1976, were designed for a standard truck weighing 35 tonnes. Today, many of these bridges carry articulated trucks to 45.5 tonnes and B-doubles (B-trains) to 68 tonnes.

Australia also has a wide variety of freight vehicles that are amongst the largest in the world. Apart from rigid trucks and truck-and-trailer combinations, which primarily operate in urban areas, the most common are six-axle articulated vehicles (A123), which carry about 45% of the freight tonne kilometres. Steadily rising in popularity in the last 15 years has been the B-double (called a B-train in many other parts of the world) and the most common today has nine axles with two triaxle trailers. B-doubles carry nearly 25% of Australia's freight in terms of tonne kilometres. Carrying a similar proportion are our unique road trains, generally a prime mover hauling either two or three trailers although some comprise rigid trucks hauling up to three trailers. In recent years a variety of other combinations have been introduced, including B-triples and configurations that are a B-double hauling a dog trailer or a B-double hauling another set of B-double trailers. Gross mass of the larger combinations regularly exceeds 110 tonnes.

Maximum mass limits on vehicles for general access (General Mass Limits – GML) are shown in Table 1 below. In addition, some route-specific Higher Mass Limits (HML) are available for vehicles fitted with road-friendly suspension systems in a number of states and the Northern Territory. Generally, reference is made only to GML in this paper.

Table 1. General and higher mass limits in Australia.

Configuration	General Mass Limits (GML)	Higher Mass Limits (HML)
single axle – single tyres	6 tonnes	6 tonnes
single axle – dual tyres	9 tonnes	9 tonnes *
tandem axle – single tyres	11 tonnes (with load sharing)	11 tonnes (with load sharing)
tandem axle – dual tyres	16.5 tonnes	17 tonnes
triaxle – dual tyres	20 tonnes	22.5 tonnes

* under review

PAVEMENT VERTICAL LOADING

Initial proposal

The initial proposal developed for pavement vertical loading was termed Gross Mass Per Standard Axle Repetition (GM/SAR) (NRTC 2001). The SAR is conceptually equivalent to an Equivalent Standard Axle (ESA) except that calculation of SARs does not always rely on a fourth power relationship but is otherwise calculated in the same manner. A SAR represents the pavement wear attributable to a single pass of an 8.2t single axle with dual tyres.

For a particular load and axle/group configuration, the SAR value is given by:

$$SAR = (L/L_{eq})^n \qquad (1)$$

where

L = load carried by the axle group (tonne);

L_{eq} = equivalent load for the axle group that produces similar wear as a Standard Axle

(tonne); and

n = the wear exponent, nominally 4 for granular pavements, but which may vary depending on distress mode (NRTC 2003).

The SAR values for each axle/group are summed to provide the SARs corresponding to each passage of the candidate vehicle and divided into the gross mass to provide GM/SAR.

An important principal identified in NRTC 2001 was that the performance levels for GM/SAR should be based on the premise that pavement wear from a freight task being performed for a vehicle under PBS should be no greater than for the task being performed by conventional vehicles. It was suggested that the performance level be set at a minimum of 8.4t/SAR[1], the level of the most common vehicles undertaking the freight task, the six-axle articulated vehicle. This was to be the level for all heavy vehicles operating on granular pavements with thin surfacing but it was noted that other levels would need to be calculated for other pavement types.

Difficulties with GM/SAR

GM/SAR was intended to discourage the use of heavily loaded single axles that are damaging to pavements. High values for GM/SAR imply efficient transport and movement of freight. For a given gross mass, the greater the number of axles the lower is the load on each axle and the lower the pavement damage for each unit of mass transported. For any given gross mass, increasing the number of axles will therefore reduce the SARs and increase GM/SAR. GM/SAR is in effect a pavement efficiency or road-wear efficiency standard, in which the higher the performance level the lower is the pavement damage.

However, there were five major difficulties with using GM/SAR, particularly in the form that it was proposed with a single performance level:

- it proved to be a significant barrier to vehicles meeting the proposed set of PBS standards, with only those vehicles using triaxles tending to meet the GM/SAR standard and with no vehicle with less than six axles being able to meet the standard at currently permitted axle-group masses;
- it did not protect pavements from excessive wear with larger vehicle combinations;
- there was some concern with the implication that GM/SAR was directed more at promoting transport efficiency rather than infrastructure protection;
- both the gross mass and the SAR factor have elements of mass, and this could be seen to have the effect of double counting; and
- it has been a difficult performance measure for many people to conceptualise, to some extent due to the specification of GM/SAR as a minimum level that has to be achieved by a PBS vehicle.

The first point is illustrated in Table 2 below. Vehicles with less than six axles (those shown in italicised bold) tend to have high SARs relative to their gross mass. These vehicles are relatively inefficient in the level of pavement wear they cause. However, the larger vehicles in Table 1 have GM/SARs exceeding the minimum of 8.4.

[1] The value of 8.4 is used in the first part of this paper, based on a tandem equivalency of 13.6t, as this was the figure used in the earlier references. The value of 8.6 was used later in the project based on the correct tandem equivalency of 13.8t.

Table 2. GM/SAR for a selection of vehicles at maximum national mass limits.

Class	Vehicle configuration	Gross Mass	SARs	GM/SAR
Rigids	*R11*	*15.0*	*2.98*	*5.04*
	R12	*22.5*	*3.69*	*6.10*
	R22	*27.5*	*4.21*	*6.53*
Single semi-trailer	*A111*	*24.0*	*4.43*	*5.42*
	A112	*31.5*	*5.14*	*6.13*
	A113	*35.0*	*4.34*	*8.06*
	A122	*39.0*	*5.86*	*6.66*
	A123	42.5	5.06	8.40
Truck/trailers	*R12T11*	*40.5*	*6.59*	*6.14*
	R12T12	42.5	5.06	8.40
B-doubles	B1222	55.5	8.02	6.92
	B1232	59.0	7.22	8.17
	B1233	62.5	6.42	9.73
A-doubles	A122T22	72.0	10.19	7.07
	A123T22	75.5	9.39	8.04
	A123T23	79.0	8.59	9.20
	A123T33	82.5	7.79	10.59

Note that shaded vehicles meet the GM/SAR standard

The effect of allowing higher mass for the larger vehicles based on a single GM/SAR requirement for all roads is shown in Table 3. For the B-double, B-triple and A-triple vehicles, a GM/SAR threshold of 8.4 would allow mass to increase, increasing pavement wear on a per-vehicle basis for any given transport task, which was against the principle of no additional pavement wear.

Tables 2 and 3 are drawn from the preliminary draft Regulatory Impact Statement (NRTC 2002).

Table 3. Effects on pavement wear of increased mass for PBS vehicles.

	Single artic (A123)		**B-double (B1233)**		**B-triple (B12333)**		**A-triple (A123T33T33)**	
	present	**possible**	**present**	**possible**	**present**	**possible**	**present**	**possible**
Steer	6	5	6	5	6	5.5	6	6
Drive	16.5	16.1	16.5	16	16.5	16.4	16.5	18
Trailing group 1	20	23.5	20	24	20	23.5	20	23
Trailing group 2			20	23.7	20	23.5	20	23
trailing group 3					20	23.5	20	23
trailing group 4							20	23
trailing group 5							20	23
Gross	42.5	44.6	62.5	68.7	82.5	92.4	122.5	139
SARs/vehicle	5.06	5.30	6.42	8.18	7.79	11.00	10.52	16.54
GM/SAR	8.40	8.41	9.73	8.40	10.59	8.40	11.64	8.40
Tare (approx)	17	17	23	24	29	30	35	36
Trips/10^6 tonnes	39,216	36,232	25,316	22,371	18,692	16,026	11,429	9,709
total SARs	198,302	192,128	162,599	182,921	145,581	176,309	120,234	160,563
Change in wear		-3.1%		12.5%		21.1%		33.5%

Notes: (1) All masses in tonnes (2) Steer axle masses and tare masses are illustrative only.

Alternatives considered

Successive efforts during the main A3/A4 study process did not yield a better performance standard. Possible alternatives that were considered included different GM/SAR standards for different road classifications based on typical vehicles using each road type and even a proposal to adjust road-access pricing structures to reflect the costs of the increased pavement wear that would be attributable the increased axle masses. A further alternative extending this approach was to allow operators to choose to operate at different GM/SAR levels, and pay for the associated level of road wear via a charging system. Even reverting to prescriptive mass limits was considered.

It became obvious, however, that a better means to limit pavement wear was required and further extensive investigations resulted in further options being considered, as described in NRTC and Pearson (2002) and Pearson and NRTC (2002). The first 2 options were variations on GM/SAR, based on different exponents and different reference vehicles. These options are shown in Table 4.

Table 4. Alternatives to the use of GM/SAR.

Option	Comment
Use a table of multiple reference vehicles taken from the existing fleet with respective GM/SAR values. The tabulated GM/SAR values must be exceeded by PBS vehicles within a range of gross mass from the GCM of the nearest existing fleet vehicle	See Figure 1 for an illustration of the outcomes. To use these values as they are, as a basis for determining a performance level for PBS vehicles, leaves open the question of whether to use GM/SAR values from the peaks, the troughs or the mid range of the curves. PBS vehicles may not be tied to current axle groupings and it was therefore considered that not all of the vehicles are sensibly eligible to be used as reference vehicles to set a GM/SAR performance level.
Use a schedule of axle numbers (as a proxy for GCM) with a corresponding minimum GM/SAR that is derived from the better performing or mid-range vehicles in the current fleet.	Similar to the option above but using either mid-range or high-range values. Figure 2 shows the 4th power GM/SAR curve taken from Figure 1 with two lines superimposed. The line designated "High" is interpolated from the peaks of the base GM/SAR curve, and the line designated "Mid" is a line of best fit by geometric regression for the base GM/SAR curve.
Require that the GM/SARs related to the passage of any vehicle is no greater than the GM/SAR related to the passage of that vehicle loaded to statutory mass limits.	Still retains the conceptual difficulties of GM/SAR as noted above.

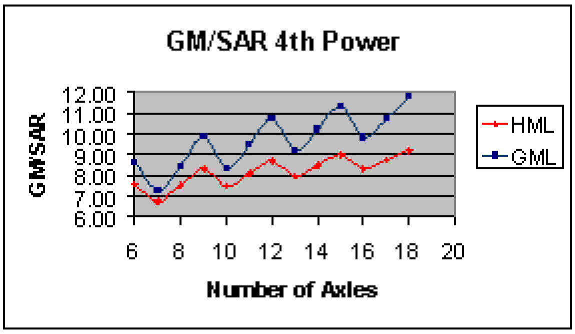

Figure 1. Variation of GM/SAR with Axle Numbers from Representative Vehicles.

In addition to these options, the possibility of using 12th power relationships rather than 4th power relationships was considered, and this issue is discussed later.

Both the second and third options considered above raised the possibility of multiple reference vehicles, using numbers of axles as the basis for selection of reference vehicles. However, because SARs are calculated for axle groups rather than for axles within a group, it is the number of axle groups rather than the number of axles that was considered to be the more influential parameter.

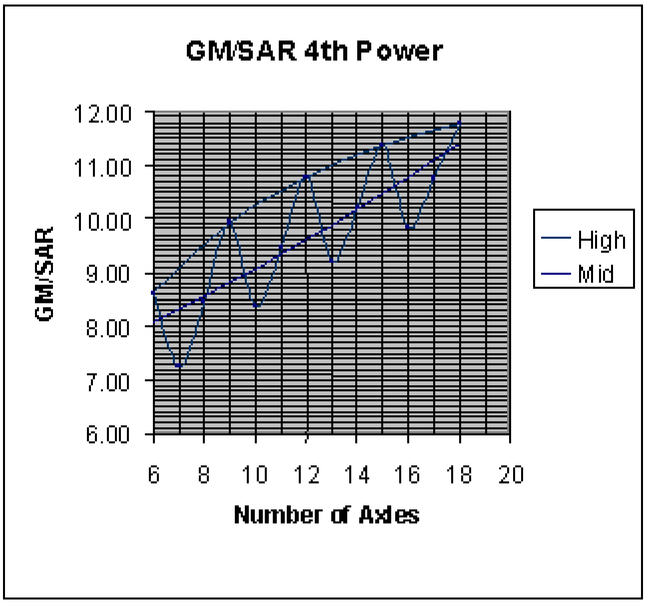

Figure 2. High range and mid range GM/SAR values.

Using this approach, a potential performance measure of Average SARs per Axle Group was investigated. SARs per axle group (SARs/AG) is calculated by:

$$\text{SARs per Axle Group} = \sum(L/L_{eq})^n/N_{ag} \qquad (2)$$

where N_{ag} is the number of axle groups in the vehicle or combination

and n is the selected damage exponent.

Three options using this potential measure were considered:

- limit the average SARs per axle group for a PBS vehicle to that for an equivalent vehicle loaded to statutory limits;
- establish a general performance level for Average SARs per Axle Group to cover the entire fleet rather than retain the level for each vehicle derived from prescriptive mass limits; and
- use trendlines to determine a formula based on numbers of axles.

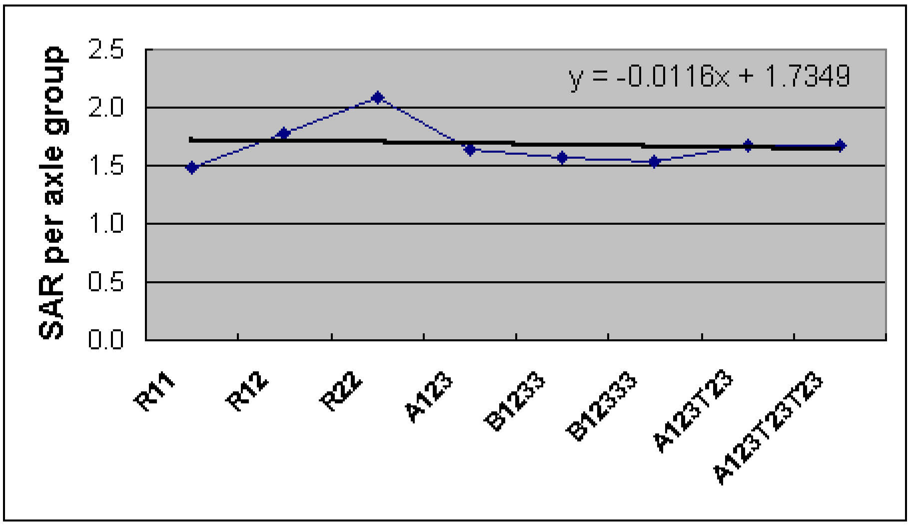

Figure 3. SAR per axle group (GML – 4^{th} power).

The first option in this group is similar to the last option in the GM/SAR group (detailed in Table 4) but overcomes most of the difficulties that were encountered with GM/SAR. Figure 3 illustrates the possible levels for the second and third options (using a 4^{th} power exponent), where a single level of around 1.75 could apply or use a formula based on the trendline.

Exponent

The results of research into pavement wear more recent than the AASHO road trials have suggested that for different pavement types, particularly bound pavements, pavement wear resulting from vertical loadings is related to vertical load by other than a fourth power law. Alternative exponent values of 2, 5, 7 and 12 have been suggested (Vuong, Tepper and Sharp, 2002), with the higher values attributable to bound pavements.

As noted earlier, while the national road system is predominantly comprised of granular pavements with sprayed bituminous seals, there are a number of important routes where there is an increasing use of bound granular pavements together with an increasing use of concrete pavements. Therefore, it seemed logical to adopt the exponent that would provide the most complete access for PBS vehicles across the road network and, if possible, the entire network. This would obviate the need to assess a route for pavement type prior to ascertaining the allowable GCM, and the need to re-assess routes after there had been construction and/or maintenance activities on the route, which may have altered the predominant pavement type. Use of the twelfth power pavement wear rule would appear to achieve this for network PBS approvals. It would still be open for road authorities to grant approvals for specific routes using other powers down to the fourth power if a route is comprised entirely of granular pavement.

Adoption of the twelfth power has the following effects:

- more tightly limit the potential for one axle group to be more heavily laden relative to another axle group, reducing the possibility of significant pavement wear with a small number of passes of a PBS vehicle;
- restrict the possible gross combination mass to a level that is below that which would be available if lower exponents were used; and
- eliminate the dependence on the bridge infrastructure measure (see later) to protect pavements for combinations with large numbers of axles.

If PBS encourages the use of more pavement efficient vehicles than those detailed in Table 2, such as vehicles with steerable quadaxles, then pavement wear will decrease in comparison to that which would occur in the absence of PBS.

Present position

The present proposal is to limit the SARs/AG to the maximum that is incurred by an equivalent vehicle operating under prescriptive mass limits, with SARs based on a 12^{th} power exponent. It was considered that the use of the SAR per axle group with twelfth power pavement wear rule as the standard would provide:

- an adequate level of infrastructure protection without the difficulties associated with the GM/SAR standard;
- application to vehicles with less than 6 axles; and
- coverage for the total road network including concrete pavements.

A disadvantage is that potential productivity increases are marginally lower.

A number of supplementary rules are also under development to ensure that the principle of no additional road wear under PBS is retained.

PAVEMENT HORIZONTAL LOADING

This measure was originally termed horizontal tyre forces and was defined as "The degree to which horizontal forces are applied to the pavement, primarily in a low-speed turn and at constant speed on uphill grades, by the tyres of multi-axle groups (drive-axle group tyres in particular) and the effect on remaining pavement life."

This measure was introduced because of concern for excessive forces on pavement surfacings, particularly chip seals, and the effects of traction on uphill grades and large side forces generated during tight low speed turns. Experience with road trains in particular, which generate high tractive forces on uphill grades, was influential in including a horizontal forces requirement. Research into relative pavement damage (Prem et al 2000) found that, relative to a conventional 19m articulated vehicle, the horizontal forces generated by very large combination vehicles can be a factor of 2 greater on small radius turns and a factor of 3 greater for operation on up-grades. The initial level assigned to pavement horizontal forces was that pavement wear for PBS vehicle for a particular freight task be no greater than for the same task being performed by conventional vehicles.

A second attempt at defining the standard arose from extrapolation of some limited research, which predicated that damage was related to forces by a 5^{th} power relationship. This resulted in a proposal that the pavement wear for PBS vehicles for a particular freight task be no greater than 1.8 times damage caused by conventional vehicles performing the same task. However, this proposal caused concern for regulatory authorities and was replaced by prescriptive requirements until further research can be undertaken to establish a more reliable and better accepted wear relationship.

At this time, the prescriptive provisions proposed require, inter alia, steering axles for quad axle groups, equal sharing of the tractive power to driven axles and tri drive axles for combinations above specified gross mass limits.

TYRE CONTACT PRESSURE DISTRIBUTION

Traditional design and evaluation of pavements assumes the vertical contact pressure between the tyre and the roadway is uniformly distributed over a contact area that is circular. However, the actual pressure distribution varies with many parameters, particularly carcass construction, inflation pressure and load. Australia, which commonly uses relatively thin pavements, is susceptible to variations in tyre pressure.

A major difficulty arises in establishing an appropriate performance level given that little is known about the relationship between pressure and road wear. Research for CSIR in South Africa (De Beer, 1996) has resulted in a system to measure vertical and horizontal forces under a moving tyre load, but how these forces relate to desirable practice has yet to be determined.

It was noted that informed operators take considerable efforts to achieve correct tyre pressures, as tyre wear is a major cost in road transport. An under inflated or over inflated tyre will lead to non-uniform pressure and lead to greater tyre wear as well as greater road wear. One of the reasons for the modern dominance of radial ply tyres is because of more even distribution and lower tyre wear than bias ply tyres.

Present prescriptive regulations provide for a maximum tyre pressure of 700 kPa for bias ply tyres and 825 kPa for radial ply tyres. Given that it is likely that axle group loads for PBS vehicles will not differ markedly for PBS vehicles than for current prescriptively regulated vehicles, it is therefore proposed to retain these requirements for PBS vehicles pending further research.

BRIDGE LOADING

At the time of the commencement of the PBS project, Australian bridge design manuals specified a load factor for live loads of 1.8 in ultimate strength design.

The 80% increase in the design load caters for:

- the inherent variability in live loads;
- deterioration of the bridge through aging over its design life;
- the passage of loads over the life of the bridge; and
- the support of vehicles carrying indivisible loads and for the occasional overloaded vehicle to traverse the bridge without failure.

The first attempt at a performance measure for bridge loading was to specify that the measure would be “the maximum stress that a bridge can sustain under repeated loading without incurring damage”. The initial performance level specified was a load factor of 1.8, i.e. the same level as specified in the design manual.

Although the logic was sound, significant difficulties with the level of 1.8, including lack of data on many older bridges and the costly process of assessing bridges, led to the search for a measure that would be more easily comparable for PBS vehicles.

The alternative method now proposed is to assess bridges by using a series of comparative design vehicles. Using this methodology, each bridge would be assessed using a standard vehicle and the load distribution effects on the bridge of a PBS vehicle would be compared to the load effects imposed by a design vehicle.

The Austroads Bridge Assessment Group (ABAG) has produced typical live-load (truck) configurations to be used for the consistent assessment of the load capacity of bridges throughout Australia. The configurations are for a six-axle articulated vehicle, a nine-axle B-double and double and triple road trains, and these vehicles are known as ABAG vehicles. The present proposal is that the forces imposed by potential PBS vehicles would be no greater than those imposed by ABAG vehicles, with the appropriate vehicle depending on the proposed route and present level of loading.

The currently proposed standard has an advantage over the earlier proposal in that it does not require a detailed knowledge of the structural characteristics or condition of bridges in a particular road class or on a particular route.

CONCLUSIONS

The development of four infrastructure protection standards under PBS has presented many challenges. Initial standards were in three cases found not to be satisfactory while the fourth proposal, for prescriptive limits, remains. While confident that most pitfalls have been identified, certainty that all problems have been solved in the totally new regulatory environment of PBS would be premature. The challenge remains to implement standards that can provide incentives by means of productivity benefits yet still ensure adequate infrastructure protection.

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